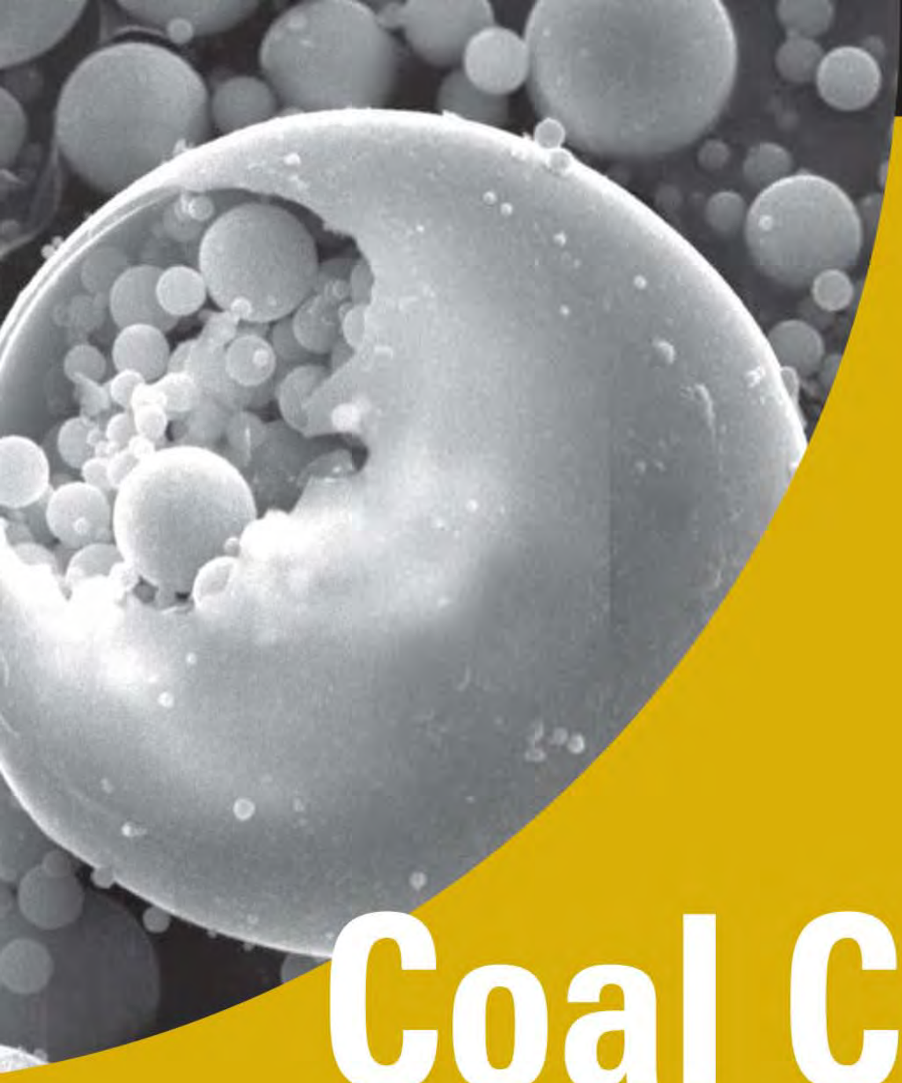

Coal Combustion Products Utilization Handbook

Ramme - Tharaniyil

Third Edition

A We Energies Publication

Ramme – Tharaniyil

We Energies Coal Combustion Products Utilization Handbook

3rd Edition

A We Energies Publication

This book is dedicated to all the individuals who have worked in
support of the development of beneficial utilization of
We Energies' coal combustion products.

Special thanks go to our teacher, Professor Tarun Naik, Director
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Disclaimer: The coal combustion products information presented in this product handbook is based on experience with various other materials and is provided as an overview of product data and construction techniques. We Energies makes no guarantee, implied or otherwise in reference to this information.

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Preface

This third edition of the coal combustion products utilization handbook is developed with the intent of providing practical, technical and regulatory compliance information to the users of We Energies' coal combustion products. This edition has been expanded to include additional information on FGD gypsum applications in manufacturing and agriculture. We hope that this book will serve as a ready reference tool for engineers, architects, construction managers and contractors in using We Energies coal combustion products (CCPs) in various construction applications. This handbook contains chapters dedicated to major product categories and their applications.

The information in this handbook will help develop an understanding of the generation, properties, construction applications and performance of CCPs. It also contains sample specifications that can be used as references in developing project specifications that utilize CCPs. A list of cited as well as additional references is provided at the end of this handbook for the reader who is looking for a deeper understanding of the material.

The authors invite your questions and comments via e-mail or mail for consideration in future editions, and can be contacted at:

Bruce W. Ramme, Ph.D., P.E.
Vice President
We Energies
333 West Everett Street
Milwaukee, WI 53203
E-mail : bruce.ramme@we-energies.com

Mathew P. Tharaniyil, P.E.
President

Bloom Companies, LLC
10501 West Research Drive, Suite 100
Milwaukee, WI 53226
E-mail : mtharaniyil@bloomcos.com

Chapter 1

Background and History of We Energies Coal Combustion Products (CCPs)

Figure 1-1: Fly ash "flying away" from We Energies' Lakeside Power Plant prior to the advent of collection in electrostatic precipitators and bag houses.

In the early days of the power generation industry, coal combustion products (CCPs) were considered to be a waste material. The properties of these materials were not studied or evaluated seriously and nearly all of the coal combustion products were landfilled. In the course of time, the cementitious and pozzolanic properties of fly ash were recognized and studied by several individuals and institutions. The products were tested to understand their physical properties, chemical properties and suitability as a construction material. During the last few decades these "waste" materials have seen a transformation to the status of "by-products" and more recently "products" that are sought for construction and other applications.

During the past several decades, generation of electricity through various coal combustion processes has grown to accommodate increased population and associated industrial and commercial development in the United States and other parts of the world. These coal combustion processes leave behind residues that are referred to as CCPs.

The initial CCPs were called cinders and were formed from burning lump coal on grates in stoker furnaces. These cinders were sometimes used as road gravel and as a lightweight aggregate in manufacturing masonry "cinder" blocks.

Figure 1-2: Bottom ash "cinders" from We Energies' Wells Street Power Plant destined for road surfacing and other applications.

In the 1920's, more effective methods of firing power plant boilers were invented. These new processes involved burning pulverized coal instead of lump coal. While the process was a more efficient method of firing, the process generated an increased stream of fine combustion products and lower quantities of cinders. This fine combustion product is called fly ash, and the cinders that are relatively coarser are called bottom ash. As environmental awareness and landfilling costs have grown, CCP generators and government regulators have encouraged the beneficial use of industrial by-products, including coal ash.

According to the American Coal Ash Association (ACAA), combustion of coal in the United States alone generated approximately 130 million tons of coal combustion products in 2010, including approximately 68 million tons of fly ash, 18 million tons of bottom ash, 32 million tons of flue gas desulfurization (FGD) materials, and 2 million tons of boiler slag. Of the fly ash produced, approximately 13 million tons were used in cement, concrete, and grout applications; and another 13 million tons were used in various other applications (1).

In some parts of the world, CCP utilization rates are much higher than that of the United States with a utilization rate of 42.5% in 2010, per ACAA. For example, in the European Union (EU15) the CCP utilization rate was 89% in 2007[1]. CCP utilization in Japan was 97% in 2006[2], and was

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[1] European Coal Ash Association (ECOBA), "Production and Utilization of CCPs in 2007 in Europe (EU 15)"

[2] Japan Coal Energy Center, "Status of coal ash production", 2005

58% in China in 2000[3]. According to ECOBA, EU15 generated 61.2 thousand metric tons of coal combustion products (including 41.8 tons of fly ash, 5.7 tons of bottom ash, 10.8 tons of FGD and 1.5 tons of boiler slag) in 2007.

The United States is the world's second largest producer of fly ash with 68 million tons (second only to China with 70 million tons)[4]. Opportunities exist to make use of these valuable mineral resources (2) with approximately 43% of coal combustion products used in the United States in 2010. The ACAA survey reported the usage included a number of applications, with construction industries and civil engineering at 32.0%, followed by mining applications with 9.9% and other applications with 1.1%. These percentages are expected to increase, as a result of the development of new uses for CCPs, increased awareness of proven technologies, and global focus on sustainable development for the remaining 57% of the total CCPs produced in the USA that are being stockpiled or disposed in landfills.

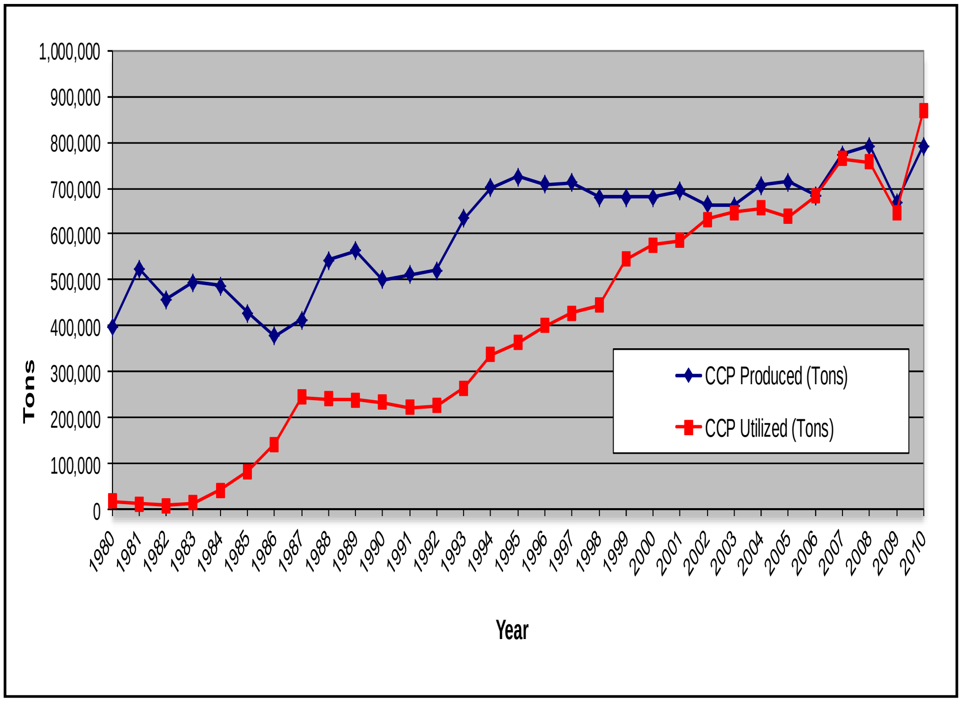

Figure 1-3: We Energies CCP Production and Utilization

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[3] Wang,F., &WU,Z, "A Handbook For Fly Ash Utilization (2ed.)", Beijing: China Power Press, 2004.

[4] Fu, J., "Challenges To Increased Use of Coal Combustion Products in China", Spring 2010

Coal fired power generation has gone through several process modifications to improve efficiency, control the quality of air emissions, and to improve the quality of CCPs. The variety of coal that is burned influences the chemistry of CCPs significantly. The introduction of low sulfur coal has improved the quality of air emissions and also generally improved the quality of fly ash.

The provisions of the Clean Air Act Amendments (CAAA) have also affected nitrogen oxide (NO_x) emissions and its controls for the electric utility industry. Further reductions are possible if the Cross State Air Pollution Rule (CSAPR) is implemented.

The process for reducing NOx emissions through combustion control technologies has generally increased the amount of unburned carbon content and the relative coarseness of fly ash at many locations. In particular, post-combustion control technologies for NOx emissions such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) both utilize ammonia injection into the boiler exhaust gas stream to reduce NOx emissions. As a result, the potential for ammonia impacts of the fly ash due to excessive ammonia slip from SCR/SNCR operation is an additional concern. An SCR installed at We Energies Pleasant Prairie Power Plant (P4) began operation in 2003 and at the Oak Creek Site Units in 2010-2012. Ammonia impacts can occur especially near the end of an SCR catalysts life, and daily fly ash testing is in place to ensure that ammonia levels are acceptable for the intended use of the fly ash. We Energies has also developed and patented a fly ash beneficiation process to remove and reuse ammonia if needed in the future.

Regulations to reduce sulfur dioxide emissions have resulted in the introduction of either dry or wet scrubber flue gas desulfurization (FGD) systems which can produce calcium sulfite or calcium sulfate (gypsum) as a by-product, respectively. The scrubbers capture more than 97% of the sulfur dioxide (SO_2) from combustion exhaust gas. According to the U.S EPA, in 2005, the overall annual SO_2 emissions from power plants were 9% lower than the year 2000 and 41% lower than 1980. In 2010, the total SO_2 emissions were reduced by over 10 million tons since 1990 (67%). The Clean Air Interstate Rule (CAIR) was issued by U.S. EPA in 2005. The U.S Clean Air Act Amendments of 1990 established the Acid Rain Program (ARP). The former NO_x Budget Trading Program (NBP) was promulgated by U.S. EPA in 1998. From the CAIR, ARP, and Former NBP 2010 progress report, the electric utility companies nationwide emitted about 5.2 million tons of SO_2 (well below the statutory annual cap of 8.95 million tons). Many western coals and some eastern coals are naturally low in sulfur and have been used to help meet SO_2 compliance requirements. Blending coals of different sulfur contents to achieve a mix that is in compliance with applicable regulations is also common. Nearly more than 200 coal-fired power plants in more than 35 states use compliance coals such as low sulfur Powder River Basin coal to achieve the SO_2 emission level currently mandated[5]. Wet FGD systems are currently installed on about 25% of the coal-fired utility generating capacity in the United States (3). Currently, there are wet FGD systems operating on We Energies new supercritical Oak Creek Units 1-2, Oak Creek Units 5-8 and Pleasant Prairie Power Plants.

Figure 1-4: This 170-acre coal ash landfill is located in Oak Creek, Wisconsin, where over 3,700,000 cubic yards of coal ash are stored.

In the 1990 Clean Air Act Amendments, mercury is also identified to be an air toxic metal, and this element is emitted in three forms from the coal-fueled power plants. About 60% of mercury is typically in the elemental form (Hg^0), 40% in the oxidized (Hg^{2+} or $HgCl_2$) form, and the remainder is condensed mercury on ash particles (Hg_p). Since the oxidized mercury is water-soluble, small amounts end up in waste water treatment residuals. Under the right conditions mercury can form a toxic organic form called Methylmercury (which can be taken in by fish). The U.S. EPA conducted as analysis on mercury emissions from coal-fueled power plants and regional deposition patterns in U.S waters. A case study was conducted for Wisconsin in 2002 as part of the state rule-making process, and has concluded that all of the state's coal-fueled power plants combined contribute approximately 1-4 % of the mercury being deposited in Wisconsin's lakes and rivers. A significant reduction of mercury emissions was achieved through existing pollution controls such as fabric filters (for particulate matter), scrubbers (for SO_2) and SCRs (for NO_x). The Presque Isle Power

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[5] Ward Jr.,K., "Powder River Basin not a 'coal producing region'?", Coal Business in Legal Actions, February 11, 2011.

Plant installed the TOXECON process that uses a fabric filter in conjunction with sorbent (activated carbon) injection to remove mercury and other emissions downstream of the plant's existing particulate control devices. Results have shown that TOXECON has been able to capture 90% of the mercury in the flue gas. One of the disadvantages of injecting activated carbon is its impact on the salability or reuse of ash. Tests have shown that the activated carbon interferes with admixtures used in concrete. However, if a TOXECON baghouse is placed downstream of an Electrostatic Precipitator (ESP) to capture the spent sorbent, the fly ash quality is then preserved for subsequent use. We Energies Oak Creek (Units 5-8), Pleasant Prairie (Units 1 & 2) and Presque Isle Power Plants (Units 7-9) use sub-bituminous coal and these power plants increase the capture process of mercury by using calcium bromide ($CaBr_2$) as an additive to the coals. $CaBr_2$ is a cost effective method to oxidize mercury for facilitating its absorption in the wet FGD slurry. The adsorbed mercury is then primarily captured within the FGD waste water treatment system solids.

The Oak Creek Expansion, Units 1 - 2 burn Eastern bituminous coal with the use of advanced air quality control equipment including selective catalytic reduction to remove nitrogen oxides, baghouse filters to remove particulate matter (ash in the exhaust gas), scrubbers to remove sulfur dioxide, and wet electrostatic precipitators (WESP) to remove sulfuric acid mist, aerosols and ultrafine particulates from the flue gas. The WESP consists of a series of electrically charged collecting plates located in the casings of the WESP where discharge electrodes between the plates create the electrical field which in turn repels the sulfuric acid mist, aerosols and ultrafine particulates toward the collecting plates. The plates are continuously (or intermittently, depending on the gas condition) washed with spray water to remove the collected material. This wash water is collected and returned either to the WESP spray wash system or added to the FGD system for neutralization. The WESP captures more than 94% of the sulfuric acid mist, aerosols and ultrafine particulates on collection plates from the flue gas (4).

It is important to distinguish fly ash, bottom ash, and other CCPs from incinerator ash. CCPs result from the burning of coal under controlled conditions. The U.S EPA (RCRA orientation manual, 2008) has conclusively determined CCPs being non-hazardous after studying the coal-fired utility wastes in 1993 that excluded large volume of coal fired utility wastes (inclusive of fly ash, bottom ash, boiler slag and flue gas desulfurization materials) from the definition of hazardous waste. In December of 2008, an impoundment dike failed at the Kingston Plant in Tennessee that has resulted in EPA proposing both hazardous and non-hazardous rules for comment. The outcome will likely establish federal standards for disposal of CCPs. Even though trace elements of mercury are retained in the coal-combustion residue, it is unlikely to be leached at levels of environmental concern (U.S. EPA, January 2006).

The other constituents of coal ash are commonly found in everyday products and natural materials, including soil (ACAA Educational Foundation, March 2009). Incinerator ash is the ash obtained as a result of burning combinations of municipal wastes, medical waste, paper, wood, etc. and sometimes will test as hazardous waste. The mineralogical composition of coal ash and incinerator ash consequently are very different. The composition of ash from a single coal source is typically very consistent and uniform, unlike the composition of incinerator ash, which varies tremendously because of the wide variety of waste materials burned.

The disposal cost of CCPs has escalated significantly during the last couple of decades due to significant changes in landfill design regulations. Utilization of CCPs helps preserve existing licensed landfill capacity and thus reduces the demand for additional landfill sites. Due to continued research and marketing efforts, We Energies was able to utilize 110% of coal combustion products in 2010 compared to only 5% in 1980. Increased commercial use of CCPs translates to additional revenues and reduced disposal costs for We Energies, which in turn translates to lower electric bills for electric customers. The use of CCPs in construction reduces the need for quarried raw materials, manufactured aggregates and Portland cement. Replacement of these virgin and manufactured materials with CCPs helps to conserve energy and reduce emissions associated with manufacturing and processing. When fly ash and bottom ash are used beneficially as engineered backfill material, these materials are replacing sand or gravel that would otherwise have been quarried and transported from various locations. The use of CCPs helps preserve mineral materials from sand and gravel pits and quarries as well as provides construction cost savings associated with operation. It is also important to keep in mind that every time Portland cement is replaced or displaced with fly ash, CO_2 and other emissions to the atmosphere from cement production are reduced by decreasing the need for limestone calcination as well as the fossil fuel that is consumed for production. Beginning in 2006, We Energies began production of flue gas desulfurization (FGD) gypsum at Pleasant Prairie Power Plant. The FGD gypsum produced has all been used in place of natural mined gypsum in the manufacture of wallboard products and in agricultural applications.

The Wisconsin Department of Natural Resources (WDNR) has been monitoring the progress of beneficial utilization of industrial by-products, including CCPs. In 1998, the WDNR introduced a new chapter to the Wisconsin Administrative Code - Chapter NR 538 “Beneficial Use of Industrial Byproducts”, to encourage the environmentally responsible use of industrial by-products. According to the WDNR, the purpose of Chapter NR

538 is “to allow and encourage to the maximum extent possible, consistent with the protection of public health and the environment and good engineering practices, the beneficial use of industrial by-products in a nuisance-free manner.

The department encourages the beneficial use of industrial by-products in order to preserve resources, conserve energy, and reduce or eliminate the need to dispose of industrial by-products in landfills.”

Figure 1-5: Landfilling of fly ash can seem overwhelming.

We Energies has made significant progress in finding uses for its coal ash, and it is interesting to look back at this quote from *Path of a Pioneer* page 210 (5):

> Solving one problem in the air created another on the ground: what to do with millions of tons of fly ash. Recycling had provided an early solution to some of the company’s waste problems. In the late 1920’s, cinders from the Commerce and East Wells plants had been mixed in a building material called Cincrete, which was used in the Allen-Bradley plant, the Tripoli Shrine, and other Milwaukee landmarks. Cinders were in short supply after the system converted to pulverized coal, but fly ash found some acceptance as a concrete additive after World War II. Hard, heat-resistant, and convincingly cheap, it was used in everything from oil well casings to airport runways. Demand, however, never threatened to outstrip supply; most of WEPCO’s “used smoke” ended up in landfills.

We Energies, doing business as Wisconsin Electric, and its past affiliate Minergy Corporation also produced several light weight aggregate products such as structural-grade light weight aggregate suitable for use in a broad range of concrete products and geotechnical applications, light weight concrete masonry with higher fire rating and higher R-values, and light weight soils for roof top gardens and parks. However, Minergy Corporation was closed in 2000.

Concrete continues to be the leading utilization application today; however many new and promising technologies have also been introduced and proven which are discussed in the balance of this handbook.

Chapter 2

CCPs and Electric Power Generation

Coal is one of the most commonly used energy sources for the generation of electricity. In the process of generating power from coal, large quantities of CCPs are produced. CCPs are the solid residues that remain after the combustion of coal within a furnace, and are collected in emission control processes.

In the early years of power generation at coal-fueled generating plants, coal was fired in a furnace with stoker grates. Today most coal-fueled power plants are fired with pulverized coal.

Electric Power Generation

In the most simplified form, a coal-fired power plant process can be described as follows. Coal is first passed through a pulverizer where it is milled to the consistency of flour. The powdered coal is mixed with a steady supply of air and is blown to the furnace where it burns like a gas flame. Pulverized coal firing is more efficient than stoker firing. With stoker firing, there is always a bed of coal on the grate, which contains a considerable amount of heat that is lost when it is removed. With pulverized coal, the coal burns instantly, and in this way the heat is released quickly and the efficiency of the process is higher. If the coal supply is cut off, combustion ceases immediately (6).

The heat generated by burning pulverized coal in the furnace in the presence of air is used to generate steam in a boiler. In its simplest form, the boiler consists of steel tubes arranged in a furnace. The hot gases pass through the banks of tubes, heating the tubes. The boiler is supplied with a steady flow of water, which is turned to steam in the tubes. The steam is collected in the upper drum of the boiler and is directed to pipes leading to a turbine (6).

The turbine can be compared to a windmill. The steam generated in the boiler is directed to the fan blades in the turbine and causes the rotor assembly to turn. The blades are arranged in groups or stages and the steam is forced to flow through the different stages. In doing so, the steam loses some of its energy at each stage, and the turbine utilizes the steam energy efficiently to spin the rotor shaft.

The turbine rotor shaft is coupled to an electric generator. When the steam from the boiler pushes against the blades fitted to the turbine rotor, it spins together with the generator rotor. The generator rotor is simply a large electromagnet. The electromagnet rotates inside a coil of wire. The magnetic field issuing from the rotating electromagnet travels across the turns of wire in the stationary coil and generates electric current in the wire.

Depending on the number of turns in the coil, the magnitude of the current in the coil will increase or decrease. The electric voltage and current generated in the generator can be increased or decreased using a power transformer for transmission to consumers. Figure 2-1 is a basic flow diagram of a typical coal-fired power plant. The above description of the turbine/generator is very simple, but in a real power plant, the system is more complex with multiple stages and additional equipment to increase efficiency and protect the environment.

In addition to the above pulverized coal technology, an alternate power generation technology is Integrated Gasification Combined Cycle (IGCC). The IGCC process is designed to break down coal into its basic constituents and obtain a synthetic gas (syngas) that is burned in combustion turbines. The gas conditioning process enables the separation of any contaminants from the syngas prior to its use as fuel. Excess heat is also utilized to produce steam for steam turbine use. The IGCC system consists of coal gasifiers, air separation units, gas conditioning systems, steam turbine generators, and sulfur recovery systems, etc. Figure 2-2 shows a basic diagram of an IGCC plant process. One of the most significant advantages of IGCC is that the technology can easily capture CO_2 and also achieve greater emissions reductions. An IGCC unit was proposed as part of the company’s Power the Future plan, but was not approved due to the immaturity of the processes at the time. As of 2012, IGCC generation units have not been added to the We Energies fleet of power generation units.

CCPs Generation

The description in the past few paragraphs summarizes the primary operations taking place in a coal-fueled power plant for the generation of electricity. In the coal combustion process, CCPs are also generated in direct proportion to the variety, quantity and ash content of coal consumed. The pulverized coal is burned in the furnace to generate heat, and the hot gases then pass around the bank of tubes in the boiler and are eventually cleaned and discharged through the plant chimney. In large power plants that consume large quantities of coal, substantial quantities of coal ash are produced. The ash that is collected in electrostatic precipitators or baghouses is called fly ash.

In electrostatic precipitators the flue gas is passed between electrically charged plates where the fly ash particles are then attracted to the plates. Baghouses can also be used to collect ash with bags that filter the fly ash out of the flue gas stream. The fly ash particles are periodically knocked off the plates or bags and fall into the hoppers located at the bottom of the electrostatic precipitators or baghouses. The fly ash is then pneumatically transported to storage silos. The storage silos are equipped with dry unloaders for loading dry bulk semi tankers or rail cars, and wet unloaders for conditioned ash or disposal applications.

Bottom ash is formed when ash particles soften or melt and adhere to the furnace walls and boiler tubes. These larger particles agglomerate and fall to hoppers located at the base of the furnace where they are collected and normally ground to a predominantly sand size gradation. Some bottom ash is transported to storage dry, but most is transported wet from the furnace bottom to dewatering bins where water is removed prior to unloading and transport to construction sites or storage stockpiles. Figure 2-3 shows the typical ash generation process in a coal-fueled power plant.

The ash collected from pulverized-coal-fired furnaces is fly ash and bottom ash. For such furnaces, fly ash constitutes a major component (80 to 90%) and the bottom ash component is in the range of 10 to 20%. Boiler slag is formed when a wet-bottom furnace is used. The non-combustible minerals are kept in a molten state and tapped off as a liquid. The ash hopper furnace contains quenching water. When the molten slag contacts quenching water, it fractures, crystallizes, and forms pellets, resulting in the coarse, black, angular, and glassy boiler slag. The boiler slag constitutes the major component of cyclone boiler by-products (70 to 85%). The remaining combustion products exit along with the flue gases. Currently, We Energies power plants do not produce boiler slag.

Flue gas desulfurization (FGD) material is the solid material resulting from the removal of sulfur dioxide gas from the utility boiler stack gases in the FGD process. The material is produced in the flue gas scrubbers by reacting slurried limestone or lime with the gaseous sulfur dioxide to produce calcium sulfite. At We Energies, “wet” FGD systems are installed where the sulfur dioxide removal takes place downstream of the fly ash removal device. Then the calcium sulfite is further oxidized to calcium sulfate (synthetic gypsum) which has the same chemical composition as natural gypsum. The dewatering system removes water from the calcium sulfate leaving the FGD absorber modules into hydrocyclone centrifuges and onto belt filter presses. Vacuum pumps beneath the belt, siphon the water out of the material, leaving it with about a 10 percent moisture content. A belt conveyor system transports the dewatered materials from the dewatering building to an adjacent storage shed.

In the FGD process, a small fraction of the calcium sulfate slurry is regularly removed to a water treatment system for dewatering to remove chlorides and fines from the process. The solids from the water treatment system are captured and removed in a filter press. This material is typically referred to as waste water system filter cake (a second by-product) and consists of fine gypsum particles, unreacted limestone fines, calcium sulfite particles and a minor amount of fly ash. It is a brown clay-like chunky material with a high (107% ±) water content. Due to the high content of water, chlorides, sulfites and trace metals, filter cake cannot be used in pavements or other applications without stabilization.

The CCPs described above are produced in pulverized coal-fueled plants. In IGCC facilities, the sulfur-containing gases from the acid gas removal system are converted to elemental sulfur or sulfuric acid. Sulfur dioxide combines with oxygen and water to form sulfuric acid; the reaction of hydrogen sulfide and sulfur dioxide forms water and elemental sulfur. Elemental sulfur or sulfuric acid in sufficiently pure forms can be suitable for sale to other industries for various uses. If elemental sulfur is produced, a storage tank is provided to hold molten sulfur until it can be transferred to railcars for shipment off-site. Sulfur can be used in bituminous mixtures, sulfur-concrete, and in the manufacture of fertilizer, paper, etc. If sulfuric acid is produced, above ground storage tanks are constructed to temporarily hold the acid until it is transported off site by specially designed rail cars or trucks for commercial use, such as wastewater treatment or in the production of phosphate fertilizers.

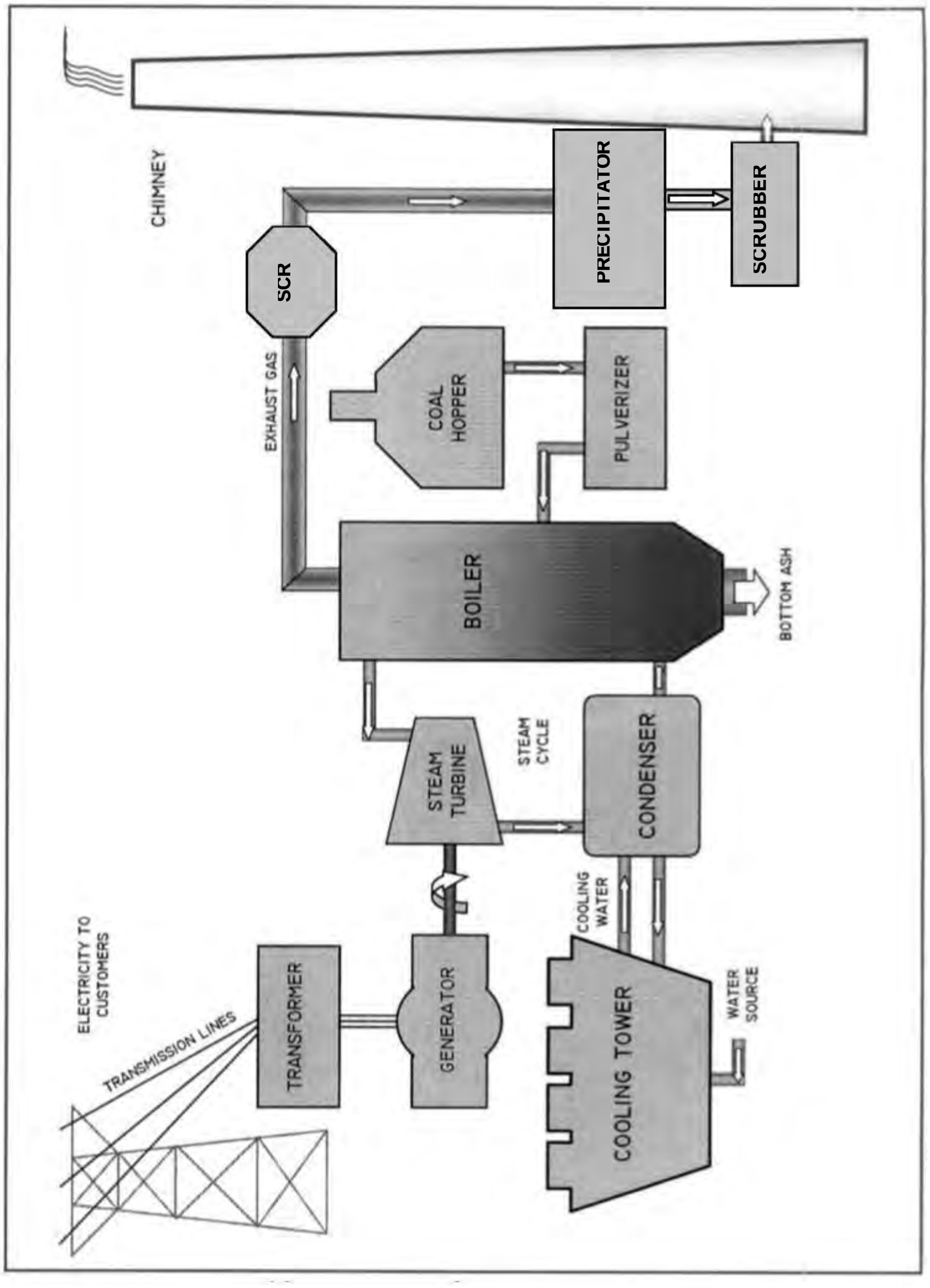


Figure 2-1: Diagram of Pulverized Coal-Fueled Power

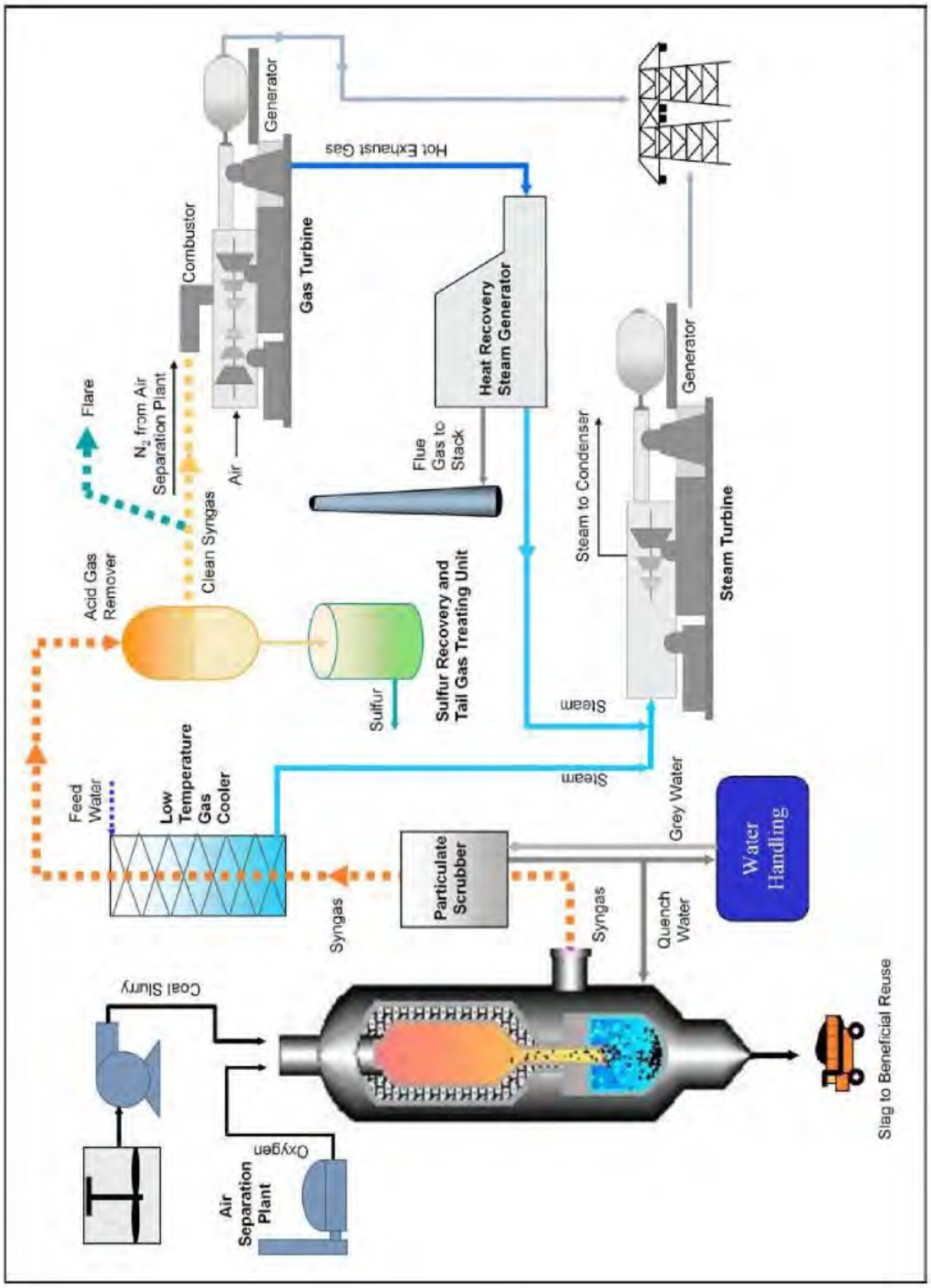


Figure 2-2: Diagram of an IGCC Plant Process (7)

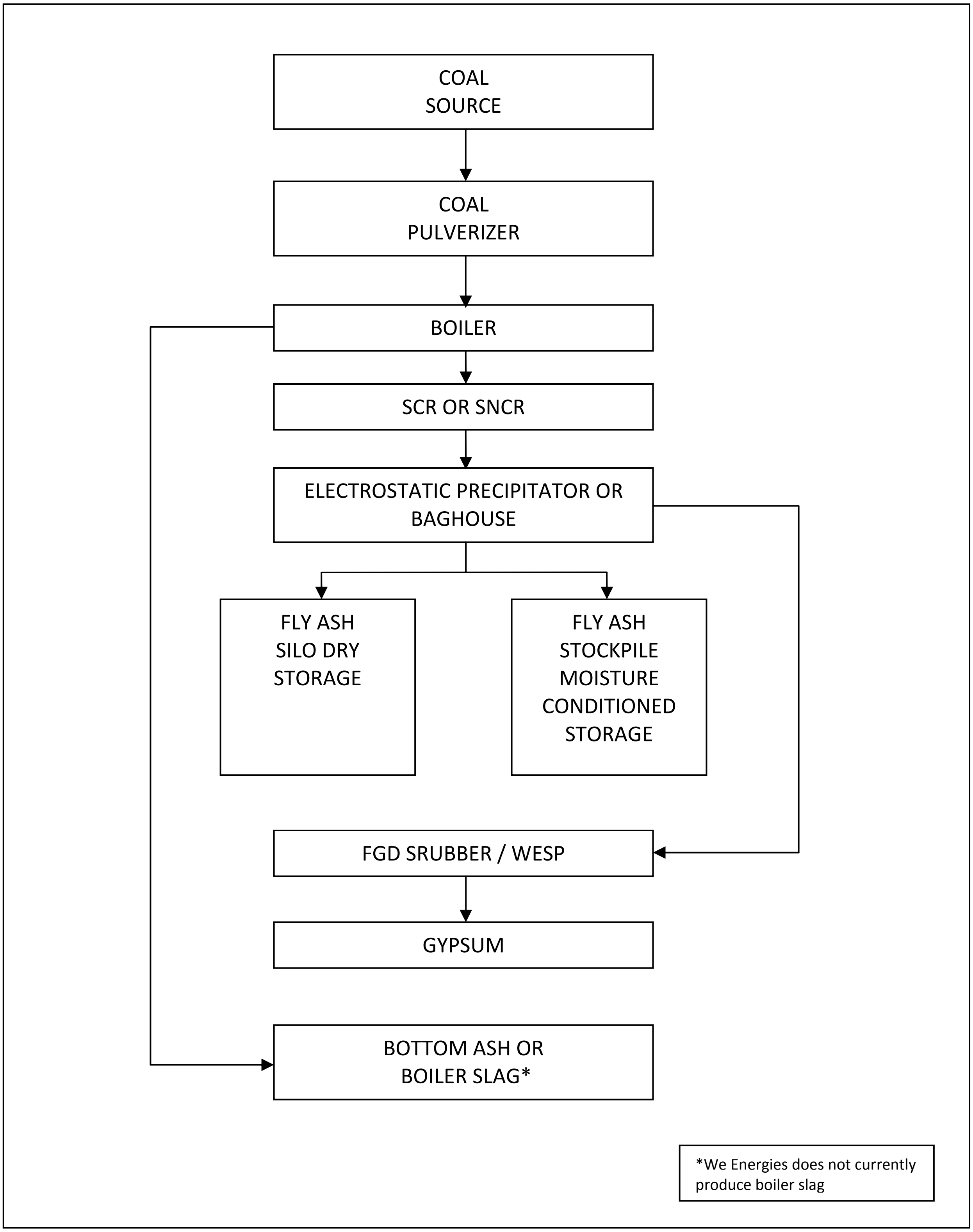


Figure 2-3: Typical Ash Generation Process in a Coal Fired Power Plant

Properties of Fly Ash

Fly ash is a fine powder that is collected from the combustion gases of coal-fueled power plants with electrostatic precipitators and/or baghouses. Fly ash particles are very fine, mostly spherical and vary in diameter. Under a microscope they look like tiny solidified bubbles or spheres of various sizes. The average particle size is about 10µm but can vary from <1µm to over 150µm (8).

The properties of fly ash vary with the mineral make-up of coal used, grinding equipment, the furnace and the combustion process itself. ASTM C618 (American Society for Testing and Materials) “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete”, classifies fly ash into two categories – Class F and Class C fly ash. Combustion of bituminous or anthracite coal normally produces Class F (low calcium) fly ash and combustion of lignite or sub-bituminous coal normally produces Class C (high calcium) fly ash. Table 2-1 shows the normal range of the chemical composition for fly ash produced from different coal types.

Table 2-1: Normal Range of Chemical Composition for Fly Ash Produced from Different Coal Types (%)

Compounds	Bituminous Coal	Sub-bituminous Coal	Lignite
SiO_2	20- 60	40- 60	15- 45
Al_2O_3	5- 35	20- 30	10- 25
Fe_2O_3	10- 40	4- 10	4 - 15
CaO	1- 12	5- 30	15- 40
MgO	0- 5	1- 6	3 - 10
SO_3	0- 4	0- 2	0 - 10
Na_2O	0- 4	0- 2	0 - 6
K_2O	0- 3	0- 4	0 - 4
LOI	0- 15	0- 3	0 - 5

Although ASTM does not differentiate fly ash by CaO content, Class C fly ash generally contains more than 15% CaO, and Class F fly ash normally contains less than 5% CaO. In addition to Class F and Class C fly ash, ASTM C618 defines a third class of mineral admixture - Class N. Class N mineral admixtures are raw or natural pozzolans such as diatomaceous earths, opaline cherts and shales, volcanic ashes or pumicites, calcined or uncalcined, and various other materials that require calcination to induce pozzolanic or cementitious properties, such as some shales and clays (9).

Table 2-2 gives the typical composition of Class F fly ash, Class C fly ash and Portland cement.

Table 2-2: Typical Chemical Composition of Fly Ash

Compounds	Class F Fly Ash		Class C Fly Ash		Portland Cement	
	Typical*	ASTM C-618	Typical**	ASTM C-618	Typical***	ASTM C-150
SiO_2	48.0	---	37.3	---	20.25	---
Al_2O_3	24.3	---	21.4	---	4.25	---
Fe_2O_3	15.6	---	5.7	---	2.59	---
$SiO_2+Al_2O_3+Fe_2O_3$	87.9	70.0 (min%)	64.3	50.0 (min%)	---	---
CaO (Lime)	3.2	---	22.4	---	63.6	---
MgO	---	---	---	---	2.24	6.0 (max%)
SO_3	0.4	5.0 (max%)	2.5	5.0 (max%)	---	3.0 (max%)
Loss on Ignition	3.2	6.0 (max%)	0.4	6.0 (max%)	0.55	3.0 (max%)
Moisture Content	0.1	3.0 (max%)	0.1	3.0 (max%)	---	---
Insoluble residue	---	---	---	---	---	0.75 (max%)
Available Alkalies as Equivalent Na_2O	0.8	1.5 (max%)	1.4	1.5 (max%)	0.20	---

* Class F Fly Ash from OCXP
** Class C Fly Ash from PPPP
*** Type 1 Portland Cement from Lafarge Corporation

Determining Fly Ash Quality (99)

The loss on ignition (LOI) is a very important factor for determining the quality of fly ash for use in concrete. The LOI values primarily represent residual carbonaceous material that may negatively impact fly ash use in air-entrained concrete. A low and consistent LOI value is desirable in minimizing the quantity of chemical admixtures used and producing consistent durable concrete. Activated carbon powder is sometimes now being used in power plant air quality control systems to remove mercury from combustion gases. Ordinary activated carbons that are commingled with fly ash can present two issues when used as a cementitious material in concrete. First, conventional activated carbon has a high affinity for air entraining admixtures, making predictable air content in concrete very difficult. This phenomenon may also be true for other chemical admixtures as well. Secondly, carbon particles can present aesthetic issues for architectural concrete in terms of a darker color or black surface speckles.

Another important fly ash parameter with respect to affecting concrete quality is fineness, which is a measure of the percent of material retained on the no. 325 sieve. The condition and the type of coal crusher can affect the particle size of the coal itself. A coarser ground coal may leave a higher percentage of unburned residues. Also, a coarser resulting fly ash gradation means there is less particle surface area of contact, which leads to a less reactive ash.

Uniformity of fly ash is important in most applications. The characteristics of the fly ash can change when a new coal source is introduced in the power plant. Each generating station's fly ash is different and it is important to determine its chemical and physical properties before it is used in commercial applications.

Based on the Unified Soil Classifications System, fly ash particles are primarily in the silt size range with the low end falling in the clay category and top end in the sand range. For geotechnical applications, fly ash is sometimes classified as a sandy silt or silty sand, having a group symbol of ML or SM (10).

The specific gravity of fly ash is generally lower than that of Portland cement, (SG = 3.15). We Energies fly ash sources typically range from a specific gravity of 2.05 to 2.68. Table 2-3 shows some typical geotechnical engineering properties of fly ash. These properties are useful when fly ash is designed for use in applications such as backfilling for retaining walls or constructing embankments.

Table 2-3: Typical Geotechnical Properties of Fly Ash

Testing Descriptions	Results
Internal Friction Angle (10)	26° - 42°
Initial Stress-Stain Modules (triaxial test) (9)	30 MPa
Stress-Stain Modules (plate load tests) (9)	100 MPa
Modules of Subgrade Reactions (300 mm diameter plates [Ks]) (9)	130 KPa/mm
California Bearing Ratio, Unsoaked (Low Lime Fly Ash) (11)	10.8-15.4
California Bearing Ratio, Soaked (Low Lime Fly Ash) (11)	6.8-13.5
Cohesion*	0
Permeability (10)	10^{-4} cm/sec – 10^{-6} cm/sec
Maximum Dry Density (60-110 lb/cu ft) (10)	960-1760 kg/m^3

* C = 0 recommended for Class F fly ash. When hydrated, Class C Fly Ash will self-harden and gain strength over time.

Major Fly Ash Uses

Class C fly ash has been widely used for soil stabilization. It can be incorporated into the soil by disking or mixing (12). Fly ash can increase the subgrade support capacity for pavements and increase the shear strength of soils in embankment sections when proportioned, disked and compacted properly.

One of the ways that fly ash stabilizes soil is by acting as a drying agent. Soil with high moisture content can be difficult to compact during Spring and Fall. Adding fly ash to the soil and mixing will quickly reduce the moisture content of the soil to levels suitable for compaction. Fly ash has been widely used to reduce the shrink-swell potential of clay soils. The cementitious products formed by the hydration of fly ash bond with the clay particles. The swell potential is substantially reduced to levels comparable to lime treatment.

When fly ash is used to stabilize subgrades for pavements, or to stabilize backfill to reduce lateral earth pressure or to stabilize embankments to improve slope stability, better control of moisture content and compaction is required. The construction equipment needed for proper placement and compacting fly ash includes a bulldozer for spreading the material, a compactor (vibrating or pneumatic tired roller), a water truck to provide water for compaction (if needed) and to control dusting, and a motor grader, where final grade control is critical.

Class C and F fly ashes are pozzolanic and Class C fly ash is also cementitious. It reacts with calcium hydroxide produced by the hydration of cement in the presence of water to form additional cementitious compounds. This property of fly ash gives it wide acceptance in the concrete industry.

Class C fly ash has been successfully used in reconstructing and/or upgrading existing pavements. In this process, commonly known as cold-in-place recycling (CIR) or full depth reclamation (FDR), existing asphalt pavement is pulverized with its base, and the pulverized mixture is stabilized by the addition of fly ash and water. The cementitious and pozzolanic properties of fly ash enhance the stability of the section. Fly ash recycled pavement sections have structural capacities substantially higher than crushed stone aggregate base. A new asphaltic concrete or other wearing surface is then installed above the stabilized section.

Fly ash is a by-product pozzolan. The pozzolanic property of volcanic ash was known to the Romans almost 2000 years ago. Pozzolans are the vitamins that provide specific benefits to a particular mixture (13). The word “pozzolan” comes from the village of Pozzuoli, near Vesuvius, where volcanic ash was commonly used. The Romans used a mixture of lime and volcanic ash or burnt clay tiles in finely ground form as a cementing agent. The active silica and alumina in the ash combined with the lime and was used to produce early pozzolanic cement. Some of the old Roman structures like the Coliseum and the Pont du Gard are good examples of structures built with early volcanic ash cements (14).

Extensive research has been conducted in utilizing fly ash in concrete, masonry products, precast concrete, controlled low strength materials (CLSM), asphalt and other applications. These applications are discussed in the following chapters.

Properties of Bottom Ash

Bottom ash particles are much coarser than fly ash. The grain size typically ranges from fine sand to gravel in size. The chemical composition of bottom ash is similar to that of fly ash but typically contains greater quantities of carbon. Bottom ash tends to be relatively more inert because the particles are larger and more fused than fly ash. Since these particles are highly fused, they tend to show less pozzolanic activity and are less suited as a binder constituent in cement or concrete products. However, bottom ash can be used as a concrete aggregate or for several other civil engineering applications where sand, gravel and crushed stone are used. Table 2-4 shows the typical chemical composition of bottom ash obtained by burning bituminous coal and sub-bituminous coal.

Table 2-4: Chemical Composition of Bottom Ash

Compound	Symbol	Bottom Ash from Bituminous Coal % (Mass*)	Bottom Ash from Sub-bituminous Coal % (Mass*)
Silicon Dioxide	SiO_2	61.0	46.7
Aluminum Oxide	Al_2O_3	25.4	18.8
Iron Oxide	Fe_2O_3	6.6	5.9
Calcium Oxide	CaO	1.5	17.8
Magnesium Oxide	MgO	1.0	4.0
Sodium Oxide	Na_2O	0.9	1.3
Potassium Oxide	K_2O	0.2	0.3

* Mass percentage values shown may vary 2 to 5% from plant to plant.

Table 2-5 shows the gradation of bottom ash from two We Energies power plants. The gradation of bottom ash can vary widely based on the coal pulverization and burning processes in the power plant, the variety of coal burned, and the bottom ash handling equipment. Table 2-6 gives typical geotechnical properties of bottom ash produced from the combustion of bituminous coal. These values are based on research conducted in Australia (10). Table 2-7 shows some geotechnical properties of bottom ash from two We Energies power plants, based on studies performed by Gestra Engineering, Inc. in the USA.

Table 2-5: Gradation of Bottom Ash*

% Passing Sieve Size	MCPP	PPPP
3/4”	100	100
1/2”	96	97
#4	87	90
#8	77	83
#16	65	72
#30	53	57
#50	41	42
#100	31	26
#200	22	13

*Actual figures for 2011
MCPP - Milwaukee County Power Plant (stoker units)
PPPP - Pleasant Prairie Power Plant (pulverized coal units)

Table 2-6: Geotechnical Properties of Bottom Ash (10)

Test Description	Results	Test Method [a]
Liquid Limit (lower) (16 samples)	Mean Value: 45.5 Maximum: 52.0 Minimum: 40.0	T108
Plastic Limit (lower)	Non-Plastic (All 16 Samples)	T109
Linear Shrinkage	Nil	T113
Coefficient of Saturated Permeability	3.47×10^{-6} m/sec hydraulic gradient 2 unstabilized 3.47×10^{-7} m/sec hydraulic gradient 1.3 (+6% lime)[b] 6.94×10^{-8} m/sec hydraulic gradient 1.3 (+6% lime)[c]	Constant Head Permeameter
Maximum Dry Density	1.06t/m^3 at 35% moisture content (unstabilized) 1.165 t/m^3 at 20% moisture content (with 6% lime)	T11 T140
Unconfined Compressive Strength	Unstabilized: 0 - 0.3 MPa With 6% lime: 3.30 MPa (mean 28 day strength)	T141
California Bearing Ratio	Mean: 70% Standard Deviation: 13.5%	T142
Modified Texas Triaxial	Standard Deviation: 13.5% Unstabilized: Class 2.9 @ 25.2% moisture content Class 3.0 @ 23.2% moisture content Class 3.3 @ 28.2% moisture content Tests with lime added gave Class 0 after 11.2 days	T171

[a] Test methods refer to RTA (Road and Traffic Authority, New South Wales, Australia) procedures.

[b] This sample was compacted at 25% moisture content and cured 24 hours prior to testing.

[c] This is the same sample after 72 hours continuous testing. Leaching of lime was evident.

Table 2-7: Geotechnical Properties of Bottom Ash

Property	Bottom Ash		Test Method
	Bituminous Coal [a]	Sub-bituminous Coal [b]	
Specific Gravity	2.33	2.28	ASTM C127 ASTM C128
Minimum Dry Density (lb/cu.ft)	64.8	47.9	ASTM D4254
Maximum Dry Density (lb/cu.ft)	84.2	67.1	ASTM D4253
Plasticity	None	None	---
Optimum Moisture Content (%)	28.7% Air Dry: 15.6%	32.3% Air Dry: 16.5%	ASTM D2216
Los Angeles Abrasion (%)	49.2	50.4	ASTM C131
Linear Shrinkage	1.09	0.59	ASTM D4943
Permeability of granular soils (Constant Head) @ 20°C (cm/sec)	2.40×10^{-3} 2.28×10^{-3}	5.51×10^{-3} 5.25×10^{-3}	ASTM D2434
California Bearing Ratio (%) @ 95%	26.0	22.0	ASTM D1883
Coefficient of Lateral Pressure – determined from internal friction angle	Cohesion: 6.97 psi Friction angle: 39.1° K_o: 0.39, K_a: 0.23, K_p: 4.42	Cohesion: 8.83 psi Friction angle: 43.9° K_o: 0.31, K_a: 0.18, K_p: 5.52	ASTM D3080

[a] Test method performed on Oak Creek Expansion Plant (OCXP) bottom ash

[b] Test method performed on Pleasant Prairie Power Plant (PPPP) bottom ash

Properties of Boiler Slag

Boiler slags are predominantly single-sized and within a range of 5.0 to 0.5 mm. Ordinarily, boiler slag particles have a smooth texture, but if gases are trapped in the slag as it is tapped from the furnace, the quenched slag will become somewhat vesicular or porous. Boiler slag from the burning of lignite or subbituminous coal tends to be more porous than that of the bituminous coals. The gradation of typical boiler slag is shown in Table 2-8. Compared to natural granular materials, the maximum dry density values of boiler slag are from 10 to 25% lower; while the optimum moisture content values are higher.

Table 2-8: Gradation of Boiler Slag (11)

% Passing Sieve Size	Boiler Slag
3/4”	100
3/8”	99
#4	97
#8	85
#16	46
#30	23
#50	12
#100	6
#200	4

Table 2-9 shows the chemical composition of boiler slag. The chemical composition of boiler slag is similar to that of bottom ash, as shown in Table 2-4, though the production process of boiler slag and bottom ash is relatively different.

Table 2-10 gives the typical geotechnical properties of the boiler slag. The friction angle of boiler slag is within the same range as those for sand and other conventional fine aggregates. Boiler slag exhibits high CBR value, comparable to those of high-quality base materials. Compared to bottom ash, boiler slag exhibits less abrasion and soundness loss because of its glassy surface texture and lower porosity (11).

Table 2-9: Chemical Composition of Selected Boiler Slag (11)

Compound	**Symbol**	**Boiler Slag from Bituminous Coal % (Mass)**	**Boiler Slag from Lignite Coal % (Mass)**
Silicon Dioxide	SiO_2	48.9	40.5
Aluminum Oxide	Al_2O_3	21.9	13.8
Iron Oxide	Fe_2O_3	14.3	14.2
Calcium Oxide	CaO	1.4	22.4
Magnesium Oxide	MgO	5.2	5.6
Sodium Oxide	Na_2O	0.7	1.7
Potassium Oxide	K_2O	0.1	1.1

Table 2-10: Geotechnical Properties of Boiler Slag (11)

Property	Boiler Slag
Specific Gravity	2.3 - 2.9
Dry Unit Weight (lb/cu.ft)	60 - 90
Plasticity	None
Maximum Dry Density (lb/cu.ft)	82 - 102
Optimum Moisture Content (%)	8 - 20
Los Angeles Abrasion (%)	24 - 48
Friction Angle (°)	38 - 42 36 - 46 (< 0.37 in.)
Coefficient of Permeability (cm/sec)	$10^{-2} – 10^{-3}$
California Bearing Ratio (%)	40 - 70

Boiler slag has been frequently used in hot mix asphalt because of its hard durable particles and resistance to surface wear. It can also be used in asphalt wearing surface mixtures because of its affinity for asphalt and its dust-free surface, thus increasing the asphalt adhesion and anti-stripping characteristics. Since boiler slag has a uniform particle size, it is usually mixed with other size aggregates to achieve the target gradation used in hot mix asphalt. Boiler slag has also been used very successfully as a seal coat aggregate for bituminous surface treatments to enhance skid resistance.

Properties of FGD Gypsum

FGD scrubber material is initially generated as calcium sulfite; but We Energies' plants use wet FGD systems that utilize calcium-based sorbents and forced oxidation that converts calcium sulfite ($CaSO_3$) to calcium sulfate ($CaSO_4$). Since this process is carried out in the aqueous phase, FGD gypsum is produced. Calcium sulfite FGD scrubber material can be expansive and needs to be fixated or stabilized prior to most construction uses. FGD gypsum is frequently used for wallboard, in agriculture, and as a cement additive. Table 2-11 shows the typical physical properties (particle size and specific gravity) of calcium sulfite and calcium sulfate (gypsum), indicating gypsum is typically coarser than calcium sulfite (11). The purity of FGD gypsum typically ranges from 96%-99%, depending on the sorbent used for desulfurization. Table 2-12 presents the typical chemical composition of FGD gypsum (15) and Table 2-13 shows the typical geotechnical properties (16).

Table 2-11: Typical Particle Size (%) Properties of FGD Material

Property	Calcium Sulfite	Synthetic Gypsum (Calcium Sulfate)
Sand Size	1.3	16.5
Silt Size	90.2	81.3
Clay Size	8.5	2.2
Specific Gravity	2.57	2.36

Compared to mined rock gypsum, the handling of fine grained FGD gypsum is more difficult because FGD gypsum is abrasive, sticky, compressive, and considerably finer (<0.2 mm). The adhesiveness of FGD gypsum decreases with the increase in particle size and the decrease of free water content. Temperature has little effect on the adhesiveness of FGD gypsum in storage. High temperatures, however, can cause a significant amount of degradation of FGD gypsum particles (15). The bulk physical properties of FGD gypsum are similar to silty sand and can be handled similarly. FGD gypsum is primarily crystalline in its morphology. The typical moisture content of FGD gypsum is in the range of about 5-15%. FGD gypsum can be transported by rail, truck, or barge and is easily transferred using mechanical conveyors.

Table 2-12: Typical Chemical Composition of FGD Gypsum

Constituent	Weight Fraction (%)
Ca	24.0
SO_4	54.0
CO_3	3.0
SiO_2	2.7
Inert	1.3
H_2O	15.0
PH=7	

Table 2-13: Typical Geotechnical Properties of Dewatered FGD Gypsum

Testing description	Results
Maximum Dry Density (lb/cu.ft)	81.5 at 35% optimum moisture content
Permeability (cm/sec @ one month)	1.0×10^{-5}
Unconfined Compressive Strength (psi @ one month)	31-52
Plasticity	None
Compressibility, strain	0.9-2.4
Cohesion (psi)	0 @ consolidated drained condition 8 @ unconsolidated undrained condition
Internal Angle of Friction *	39

The quantity of gypsum produced is directly proportional to the sulfur content of the fuel being used. Quality FGD gypsum material produced from wet scrubbers is currently being used for wallboard manufacture and for agricultural applications. Gypsum has reportedly been also utilized for road base or structural fill construction by blending with quicklime and pozzolanic fly ash, cement, or self-cementitious fly ash. Approximately 5% gypsum is used in the manufacturing of Portland cement to control the time of set. FGD gypsum in wet form can benefit the cement grinding process by introducing the inherent moisture into the ball mill, thus providing additional cooling.

Current We Energies CCP Sources

Fly ash, bottom ash and FGD gypsum are the predominant CCPs produced at We Energies' six coal-fueled power plants. These power plants generate electricity for use by residential, industrial and commercial customers and also generate fly ash, bottom ash and gypsum as end products. We Energies together with regulators, universities, consultants and research institutions are committed to developing alternative environmentally protective beneficial use applications for fly ash, bottom ash and gypsum materials.

During the past three decades, several construction products have been developed and marketed. The beneficial utilization of these materials in agriculture, concrete and other construction products can preserve virgin resources, lower energy costs and yield high-performance materials. We Energies has conducted extensive testing of these products to evaluate their properties. The product test information is given in the following chapters to help potential users better understand the materials and potential applications.

Annual fly ash and bottom ash production at We Energies typically totals approximately 625,000 tons of which nearly 491,000 tons of fly ash and 100,000 tons of bottom ash was beneficially used in 2010 (18). In the same year, FGD Gypsum production at We Energies' two power plants (PPPP and OCXP) totaled approximately 166,000 tons of which nearly 102,000 tons of gypsum were utilized in 2010. The breakdown by power plant is shown in Table 2-14. The primary uses of We Energies bottom ash include pavement and foundation sub-base materials and landfill drainage layer construction. For We Energies fly ash, the primary uses include cementitious material for concrete and concrete products, feedstock for Portland cement manufacture, and subsidence prevention in underground mines. Uses for We Energies FGD gypsum presently include agriculture and wallboard manufacturing.

Table 2-14: Annual Coal Combustion Products Production*

Source	Total Ash (Tons)	FA (Tons)	BA (Tons)	FGD Gypsum (Tons)
MCPP	6,862	2,728	4,134	0
PPPP**	276,928	224,239	52,689	76,220
OCPP	120,285	98,577	21,708	***
VAPP	61,140	55,016	6,124	0
PIPP U5-6	49,866	44,865	5,002	0
PIPP U7-9**	44,096	34,788	9,308	0
OCXP	65,963	59,355	6,608	90,263
Total	**625,140**	**519,568**	**105,574**	**166,483**

*Actual production figures for 2010

**Ash production from ash fuel is included

***Gypsum production begins in 2012

The following coal-fueled power plants are owned and operated by We Energies:

1. Milwaukee County Power Plant (MCPP)
2. Oak Creek Power Plant (OCPP)
3. Oak Creek Expansion Units (OCXP)
4. Pleasant Prairie Power Plant (PPPP)
5. Valley Power Plant (VAPP)
6. Presque Isle Power Plant (PIPP)

Of the above power plants, the first five are located in southeastern Wisconsin and the last, Presque Isle Power Plant, is located in upper Michigan.

Milwaukee County Power Plant (MCPP)

9250 Watertown Plank Road, Wauwatosa, Wisconsin 53226

This 11 MW, thermal coal-based power plant is located in Milwaukee County, adjacent to the Milwaukee Regional Medical Complex. MCPP generates heating steam and electricity and supplies steam to a chiller plant generating chilled water for cooling. Combustion products are primarily bottom ash with some fly ash that are commingled and stored in three 250-ton capacity coal silos. Annual coal ash production is approximately 6,900 tons. The MCPP burns low-sulfur western bituminous coal. The fly ash and bottom ash are typically transported for use as ash fuel at PPPP.

Oak Creek Power Plant Units 5-8 (OCPP)

11060 S. Chicago Road, Oak Creek, Wisconsin 53154

This 1,135 MW pulverized coal-fired plant is located in the city of Oak Creek, Milwaukee County, near the Milwaukee-Racine county line. It supplies electrical energy to the company's power grid and produced approximately 99,000 tons of fly ash, 22,000 tons of bottom ash in 2010 and 50,000 tons of FGD gypsum is projected in the future. The plant burns western sub-bituminous coals in Units 5-8. Fly ash, bottom ash and gypsum are handled by separate conveyance/storage systems.

Oak Creek Power Plant also has a 20,000 ton fly ash storage facility for winter production.

Oak Creek Expansion Units 1 and 2 (OCXP)

10800 S. Chicago Road, Oak Creek, Wisconsin 53154

This 1,230 MW pulverized coal-fueled plant is located along the shore of Lake Michigan near the existing Oak Creek Power Plant (OCPP). The OCXP was formerly known as Elm Road Generating Station (ERGS). Based on current projections, it is estimated that by burning eastern bituminous coal, it will normally produce approximately 140,000 tons of fly ash, 20,000 tons of bottom ash, and 230,000 tons of FGD gypsum.

The fly ash is removed by a baghouse and can be used in various construction activities (replacement for Portland cement in concrete, an ingredient in controlled low strength materials, and as a raw feed material for manufactured products). The bottom ash is removed from the bottom of the boiler and is used primarily as base material in place of aggregates beneath pavement and foundations. The FGD gypsum is used in wallboard manufacturing and agriculture.

The OCXP has installed Air Quality Control Systems (AQCS) on the new units to reduce nitrogen oxides by more than 85 percent, capture more than 99 percent of particulate matter, 97 percent of sulfur dioxide, and more than 90 percent of mercury. The AQCS consists of baghouses, Selective Catalytic Reduction (SCR), Wet Flue Gas Desulfurization (WFGD), and wet precipitator emission control components.

All bottom ash (from both OCPP and OCXP) is used by the company's designated bottom ash marketer, A.W. Oakes & Son. An on-site stock pile allows for beneficial use activities that require larger quantities of materials.

Pleasant Prairie Power Plant (PPPP)

8000 95th Street, Kenosha, Wisconsin 53142

This 1,210 MW, pulverized coal-fueled plant is located in the town of Pleasant Prairie in Kenosha County. Each year the plant produces approximately 225,000 tons of fly ash, 53,000 tons of bottom ash and 76,000 tons of FGD gypsum by burning a blend of low sulfur western sub-bituminous coals from the Wyoming Powder River Basin. Each CCP is handled by separate conveyance/storage systems.

PPPP was the first power plant in Wisconsin to get an advanced combustion technology, Air Quality Control System (AQCS) installed to reduce nitrogen oxide (NOx), sulfur dioxide (SO_2) and mercury emissions. The AQCS consists of Selective Catalytic Reduction (SCR) and Wet Flue Gas Desulfurization (WFGD) emission control components.

The flue gas desulfurization (FGD) gypsum is produced in the wet scrubbing process for SO_2 removal from coal combustion gases. It is used in wallboard manufacturing and agriculture. The FGD gypsum and the bottom ash are shipped to users or stored on a compacted high recycled content concrete “Eco-Pad” at this site.

Fly ash that is not immediately transported offsite by the Company’s designated fly ash marketer, Lafarge, can be stored on site in a company-owned 12,000 ton capacity storage building. All bottom ash is removed as necessary by the company's designated bottom ash marketer, A.W. Oakes & Son, who manages a stockpile for this product on site. The stockpile allows for beneficial use activities that require larger quantities of material.

Port Washington Generating Station (PWGS) replaced Port Washington Power Plant (PWPP) – Retired in 2004

146 South Wisconsin Street, Port Washington, Wisconsin 53074

The former pulverized coal-fired plant that was located in the city of Port Washington in Ozaukee County was retired from operation in the year 2004. As of 2005, PWPP generates 1,150 MW from combined cycle natural gas-fueled units pictured here.

Valley Power Plant (VAPP)

1035 West Canal Street, Milwaukee, Wisconsin 53233

This 280 MW, pulverized coal-fired plant is located in downtown Milwaukee. The plant supplies both electric energy to the company's power grid and low-pressure steam to the downtown heating district. It produces approximately 55,000 tons of fly ash and 6,100 tons of bottom ash by burning bituminous coal. The fly ash is captured in bag houses using fabric filters and the bottom ash is removed by a hydraulic removal system. The fly ash and bottom ash are typically transported for use as ash fuel at PPPP.

Presque Isle Power Plant (PIPP)

2701 Lake Shore Boulevard, Marquette, MI 49855

This 431 MW coal-fueled power plant is located on the shores of Lake Superior in Marquette, Michigan. Units 1 and 2 were retired from operation on January 1, 2007. Units 3 and 4 were retired on October 1, 2009. In November of 2011, PIPP Units 5-6 switched from bituminous coal to subbituminous coal, yielding a fly ash meeting the ASTM C-618, Class C criteria. Units 5 -9 burn a low-sulfur, Powder River Basin subbituminous coal. Electrostatic precipitators and baghouses remove about 80,000 tons of fly ash, and 14,000 tons bottom ash is removed by a hydraulic conveying and dewatering system. Presque Isle Power Plant also has 10,000 tons of company owned vertical fly ash silo storage.

In 2004, a TOXECON unit was installed on the combined flue gas stream of Units 7, 8, and 9. "TOXECON is an integrated emission control system that achieves high levels of mercury removal, increases the collection efficiency of particulate matter (PM) and determines the viability of sorbent injection for SO_2 and NO_x control, while maximizing the use of coal combustion by-products" (17). The PIPP TOXECON unit uses activated carbon as a sorbent, and the by-product is about a 50/50 blend of ultrafine Class C fly ash and spent activated carbon sorbent. About 400 tons of this material is presently being landfilled each year.

We Energies is committed to developing and implementing full utilization of its CCPs. The company is working with several research groups, universities, regulators, consultants, and trade associations to develop environmentally friendly "green" products and applications for its CCPs. We Energies gas and electric utility service area is shown on Figure

2-4.

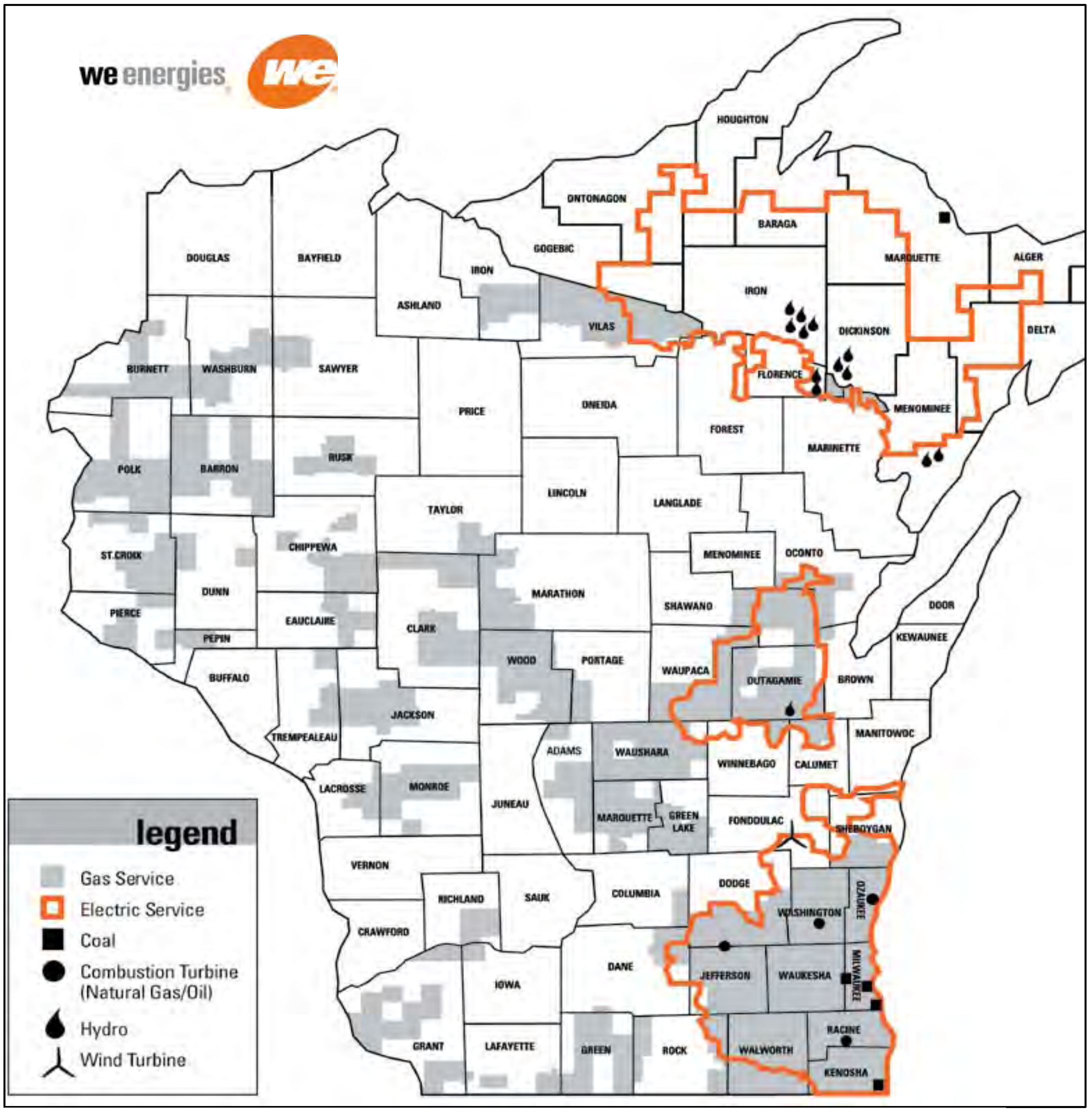


Figure 2-4: Wisconsin Energy Corporation Service Territories and Generation Facilities

Chapter 3

Properties of We Energies Coal Combustion Products

Fly ash, bottom ash, and flue gas desulfurization (FGD) produced at the coal-fueled power plants that are owned and operated by We Energies have been subjected to extensive tests for physical and chemical properties. The type of coal, percentage of incombustible matter in the coal, sulfur content, the pulverization process, furnace types and the efficiency of the combustion process determine the chemical composition of the coal combustion products (CCP).

Another factor affecting the quality of CCPs is whether the power plant is base loaded or frequently being brought in and out of service. A base loaded plant operates at consistent temperatures and combustion rates. Plants that are frequently changing load or coming in and out of service tend to produce more variability in coal ash characteristics. The use of low NO_x burners at power plants has sometimes resulted in an increase in loss on ignition and carbon content in the fly ash. Other NO_x reduction technologies such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) have sometimes added ammonia to fly ash with associated odors. Depending on the configuration of other air quality control systems for SO_x and Hg removal, the potential exists to also effect fly ash quality characteristics. We Energies has taken measures in early system design planning to minimize or eliminate the effects by applying these controls after the fly ash is collected.

Figure 3-1: Fly ash particles are spherical and average about 10 microns in diameter

We Energies purchases coal from several mines. Various factors affect the selection of coal sources, but quality and cost of coal are two very important considerations. The consistency of fly ash does not change significantly if the coal used in the plant is from a single geological formation or from a consistent blend of coals. But when coal sources change, the chemical and physical properties of the fly ash may change significantly if the type or chemistry of coal is changed. At times, coal from different sources may be blended to improve air emissions, to reduce generation costs, to increase the efficiency of combustion and/or to improve the quality of fly ash generated.

Physical, Chemical and Mechanical Properties of Fly Ash

Table 3-1 gives the chemical composition of fly ash from various We Energies power plants. The results shown are based on tests performed at We Energies state-certified lab and other outside certified testing facilities. We Energies fly ash marketers have on-site labs that test the fly ash generated from the power plant daily and more often if warranted. The quality and chemical composition of fly ash do not change very often because coal is usually purchased on long-term contracts. Fly ash from We Energies plants has actually been more consistent than many Portland cement sources.

Figures 3-2 and 3-3 show the fineness consistency and loss on ignition for Pleasant Prairie's fly ash. A customer may request samples for independent testing on a particular fly ash to independently determine its properties. As can be seen from Table 3-1, the chemical composition of fly ash differs from plant to plant and sometimes from unit to unit within a power plant.

Table 3-1: Chemical Composition of We Energies Fly Ash*

Source	ASTM C-618-08 Class F Class C	OCPP	OCXP	PIPP Units 5-6	PIPP Units 7-9	PPPP	VAPP
SiO_2, %	- -	36.71	48.25	43.91	38.23	37.45	48.27
Al_2O_3, %	- -	18.98	23.49	19.87	19.11	19.62	19.45
Fe_2O_3, %	- -	5.97	16.42	3.77	5.65	5.83	5.71
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	70.0 Min 50.0 Min	61.66	88.20	67.54	63.00	62.90	73.43
SO_3, %	5.0 Max 5.0 Max	1.50	0.45	0.35	2.65	2.42	0.28
CaO, %	- -	24.00	4.15	3.33	19.85	23.37	3.44
Moisture Content, %	3.0 Max 3.0 Max	0.03	0.12	0.15	0.02	0.02	0.07
LOI, %	6.0 Max ** 6.0 Max	0.64	1.87	24.09	0.82	0.54	17.89
Available Alkali as Na_2O, %	AASHTO M 295-06 1.5 Max	1.81	0.72	0.77	4.23	1.71	0.76

*Sampling data from 2009

**The use of Class F Pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available (ASTM C-618).

Fly ash is classified as Class F or Class C by ASTM C-618 based on its chemical and physical composition. We Energies contracts with marketers that distribute and test fly ash to ensure that customer supply, quality and consistency requirements are met.

The chemical composition of We Energies fly ash generated by burning sub-bituminous coal is different from that generated by burning bituminous coal. For example, burning 100% Wyoming Powder River Basin (PRB) sub-bituminous coal produces fly ash with calcium oxide content, typically in the range of 16 to 28%. However, burning 100% bituminous coal generates a fly ash with calcium oxide content in the range of 1 to 4%.

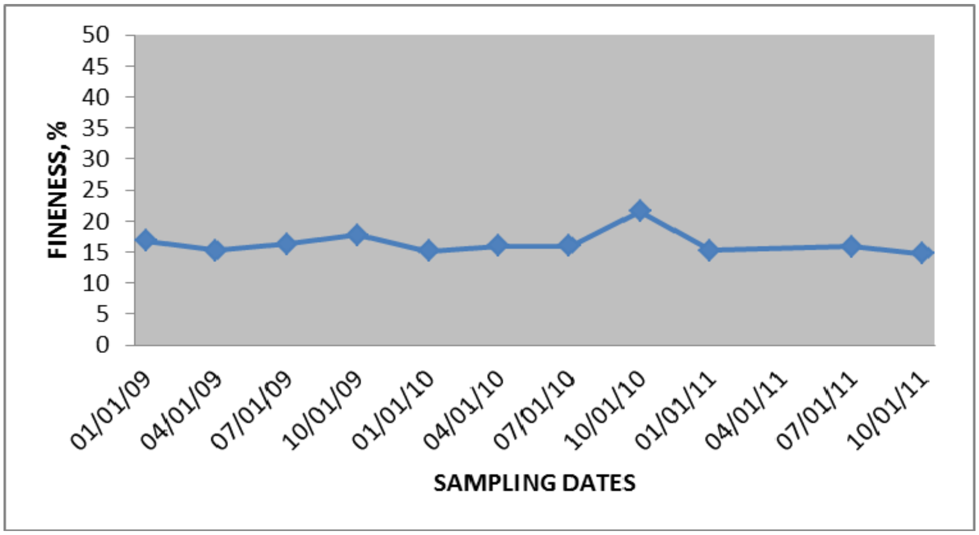


Figure 3-2: Fineness Consistency of PPPP Fly Ash

According to ASTM C-618, when the sum of SiO_2, Al_2O_3 and Fe_2O_3 is greater than 70%, the fly ash can be classified as Class F and when the sum is greater than 50% it can be classified as Class C fly ash. The fly ash must also meet the ASTM C-618 limits for SO_3, loss on ignition, fineness and other requirements.

Presque Isle Power Plant generated both Class C and Class F fly ash and had separate silos for each variety (see Table 3-1). By reviewing the chemical composition of fly ash from each plant, it is easy to determine if the fly ash is Class C or Class F and to select an ash that best meets end use requirements. In November of 2011, PIPP Units 5-6 switched from bituminous coal to subbituminous coal, and the fly ash now meets the ASTM C-618, Class C criteria.

By graphing individual parameter test results, it is possible to identify any significant changes. This is helpful in order to determine if a specific fly ash is suitable for a particular application or whether a blend of one or more materials is needed.

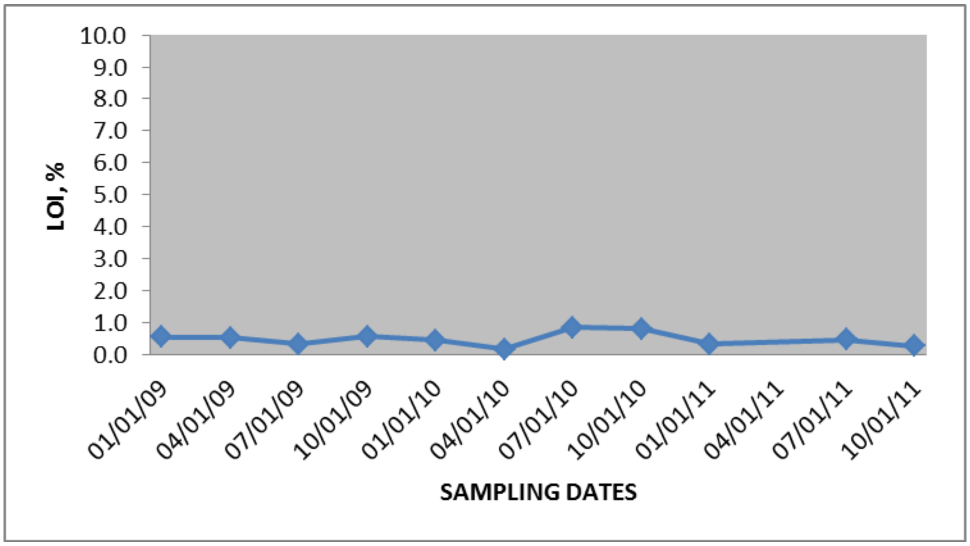


Figure 3-3: Loss on Ignition Consistency for PPPP Fly Ash

Table 3-2 shows the physical properties of fly ash at various We Energies power plants, along with the ASTM standard requirements.

Table 3-2: Fly Ash Physical Properties

SOURCE	ASTM C-618-08 Class F	ASTM C-618-08 Class C	OCPP Units 5-6	OCXP	PIPP Units 5-6	PIPP Units 7-9	PPPP	VAPP
Fineness:								
Retained on #325 Sieve, (%)	34 Max	34 Max	14.1	16.9	34.4	13.7	11.3	53.1
Strength Activity Index with Portland Cement, (%):								
% of Control @ 7 days	75 Min	75 Min	107.8	82.7	64.7	103.9	104.6	55.4
% of Control @ 28 days	75 Min	75 Min	110.9	84.1	72.5	106.8	107.8	65.5
Water Requirement:								
% of Control	105 Max	105 Max	93.0	95.9	115.7	95.0	93.8	115.7
Soundness:								
Autoclave Expansion (%)	0.8 Max	0.8 max	-0.01	-0.04	-0.03	-0.10	-0.01	-0.01
Drying Shrinkage:								
% Increase @ 28 days	0.03 Max	0.03 Max	0.01	0.01	0.01	0.00	0.01	0.01
Specific Gravity	-	-	2.72	2.43	2.16	2.67	2.55	2.13

Physical, Chemical and Mechanical Properties of Bottom Ash

Figure 3-4: Bottom ash

The coal combustion process also generates bottom ash, which is second in volume to the fly ash. Bottom ash is a dark gray, black, or brown granular, porous, predominantly sand size material. The characteristics of the bottom ash depend on the type of furnace used to burn the coal, the variety of coal, the transport system (wet or dry), and whether the bottom ash is ground prior to transport and storage. We Energies generates over 106,000 tons of bottom ash each year at its coal-fired power plants.

It is important that the physical, chemical and mechanical properties of bottom ash be studied before it can be beneficially utilized. The primary chemical constituents of We Energies bottom ash are shown in Table 3-3. The chemical characteristics of bottom ash are generally not as critical as for fly ash, which is often used in concrete, where cementitious properties and pozzolanic properties are important.

Table 3-3: Chemical Composition of We Energies Bottom Ash

Constituent	PPPP	MCPP	OCPP	OCXP	VAPP	PIPP
SiO_2	47.80	48.88	44.60	45.73	59.02	43.66
Al_2O_3	19.39	30.97	16.81	22.65	25.42	18.55
Fe_2O_3	6.36	7.20	6.37	23.48	5.86	5.99
CaO	16.94	4.84	21.58	3.56	3.77	19.01
MgO	4.29	1.28	5.46	0.81	1.45	4.76
SO_3	0.73	1.01	0.42	0.23	0.53	1.15
Na_2O	1.20	1.79	1.09	0.58	0.90	3.16
K_2O	0.68	0.96	0.33	1.53	1.39	0.46

In the case of bottom ash, physical and mechanical properties are critical. We Energies has been studying the properties of bottom ash that are important in construction applications for comparison to virgin materials currently dominating the market.

An additional consideration for bottom ash is its staining potential if used as an aggregate in concrete masonry products. Staining can occur if certain iron compounds such as pyrite are present. Pyrites can also present a potential for corrosion of buried metals. For these applications, it is important to identify if pyrites exist in sufficient quantity to present a problem (> 3.0 %).

Moisture-Density Relationship (ASTM D1557)

Bottom ash samples were tested to determine maximum dry density and optimum moisture content per the ASTM D-1557 test method. The test results are shown in Table 3-4.

Table 3-4: Physical Properties of Bottom Ash*

Bottom Ash Source	Max Dry Density, (lb/cu.ft)	Optimum Moisture Content, (%)	Hydraulic Conductivity, K(cm/sec)
PPPP	76.9	22.6	5.51×10^{-3}
MCPP	60.8	21.6	2.55×10^{-4}
OCPP	98.2	16.3	2.58×10^{-3}
OCXP	100.0	14.9	2.40×10^{-3}
VAPP	50.8	20.2	3.83×10^{-4}
PIPP, Unit 7-9	89.7	20.9	7.72×10^{-3}
SAND	110 – 115	7 – 17	$10^{-2} – 10^{-3}$

*Sampling data from 2011

We Energies bottom ashes are generally angular particles with a rough surface texture. The dry density of bottom ash is lower than sand or other granular materials typically used in backfilling.

The grain size distribution is shown in Table 3-5; Figures 3-5 through 3-10 show the grain size distribution curves for the various We Energies bottom ashes tested during 2011 following the U.S standards.

Engineering Properties of We Energies Bottom Ash

Unlike fly ash, the primary application of bottom ash is as an alternative for aggregates in applications such as sub-base and base courses under rigid and flexible pavements. It has also been used as a coarse aggregate for hot mix asphalt (HMA) and as an aggregate in masonry products. In these applications, the chemical properties are generally not a critical factor in utilizing bottom ash.

However, some engineering properties of the material are important and may need to be evaluated. These properties influence the performance of the material when exposed to freezing and thawing conditions and associated stress cycles.

Table 3-5: Bottom Ash - Grain Size Distribution (ASTM D-422)

Sieve Size	PPPP	MCPP	OCPP	OCXP	VAPP	PIPP Units 7-9
3/4”	100	100	97	99	98	93
1/2”	97	96	92	98	97	88
3/8”	95	93	87	96	95	83
#4	90	87	72	86	87	71
#8	83	77	58	68	76	59
#16	72	65	47	43	68	48
#30	57	53	37	31	63	37
#40	50	47	32	27	59	32
#50	42	41	27	25	49	27
#100	26	31	16	19	26	18
#200	13	22	7	13	12	11

The major test procedures and standards established by AASHTO and followed by many Transportation and highway departments, including the Wisconsin Department of Transportation (WisDOT) and Michigan Department of Transportation (MODOT), are listed in Table 3-6.

Table 3-6: AASHTO Test Procedures

Test Procedure	AASHTO Designation
Soundness (Magnesium Sulfate/Sodium Sulfate)	AASHTO T-104
Los Angeles Abrasion	AASHTO T-96
Grain Size	AASHTO T-27
Modified Proctor	AASHTO T-180
Atterberg Limits	AASHTO T-89 and T-90
Resistance to Freeze/Thaw (50 Cycles)	AASHTO T-103

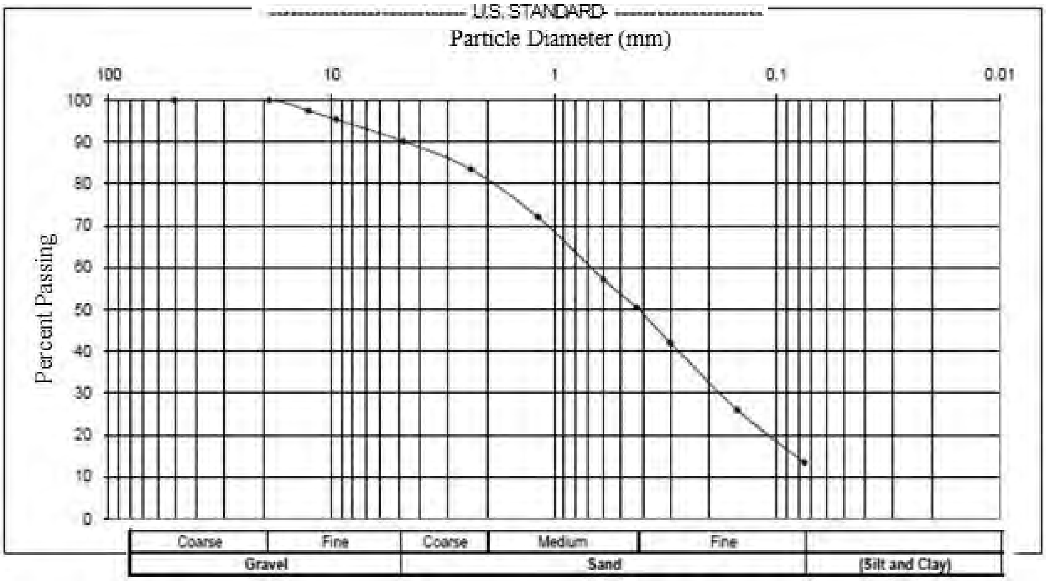


Figure 3-5: PPPP Bottom Ash Grain Size Distribution Curve (2011)

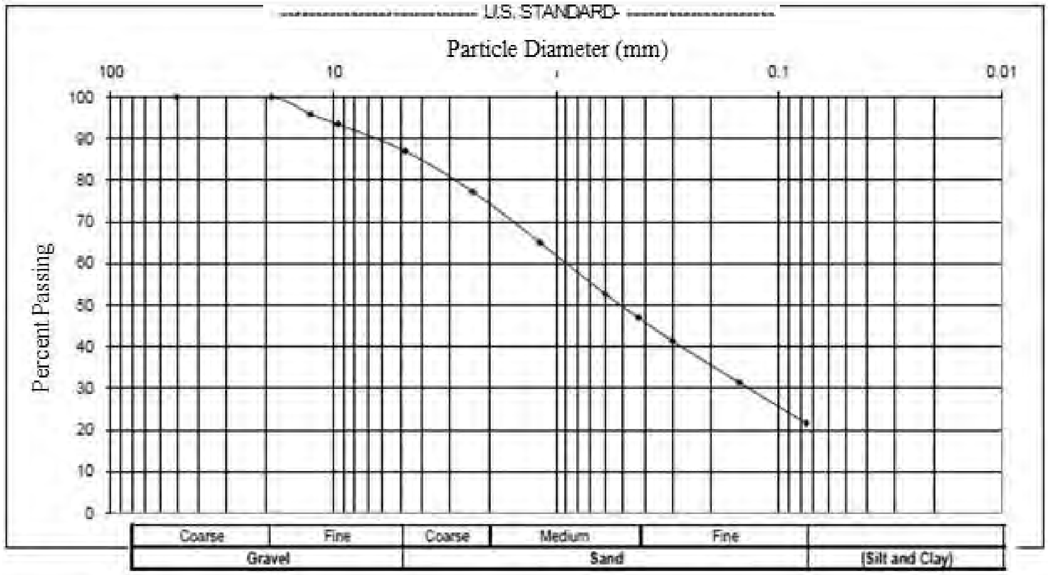


Figure 3-6: MCPP Bottom Ash Grain Size Distribution Curve (2011)

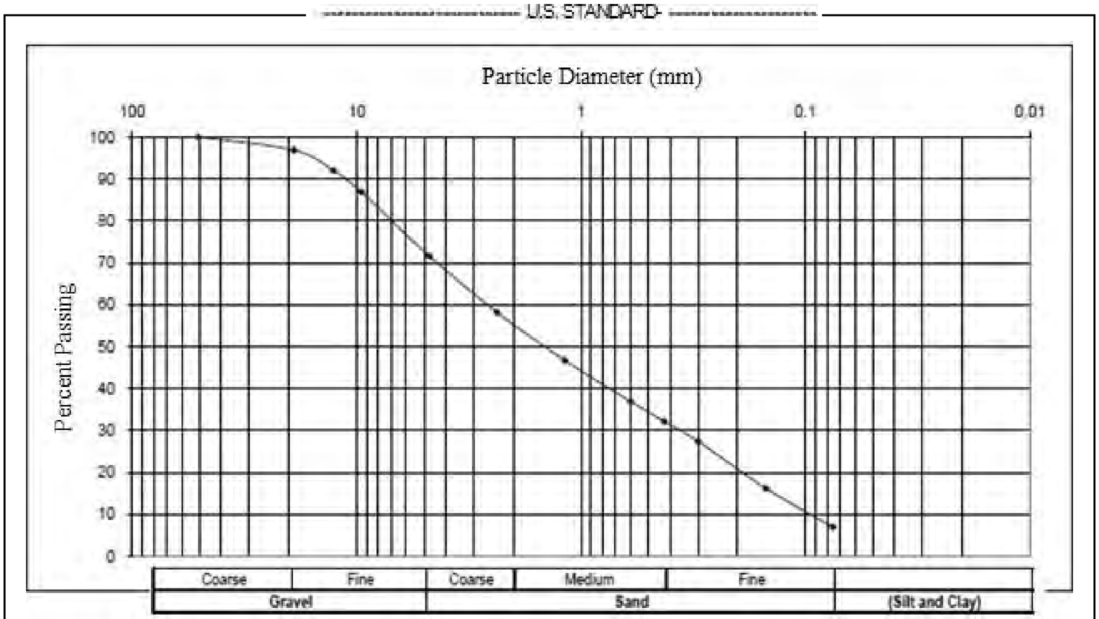


Figure 3-7: OCPP Bottom Ash Grain Size Distribution Curve (2011)

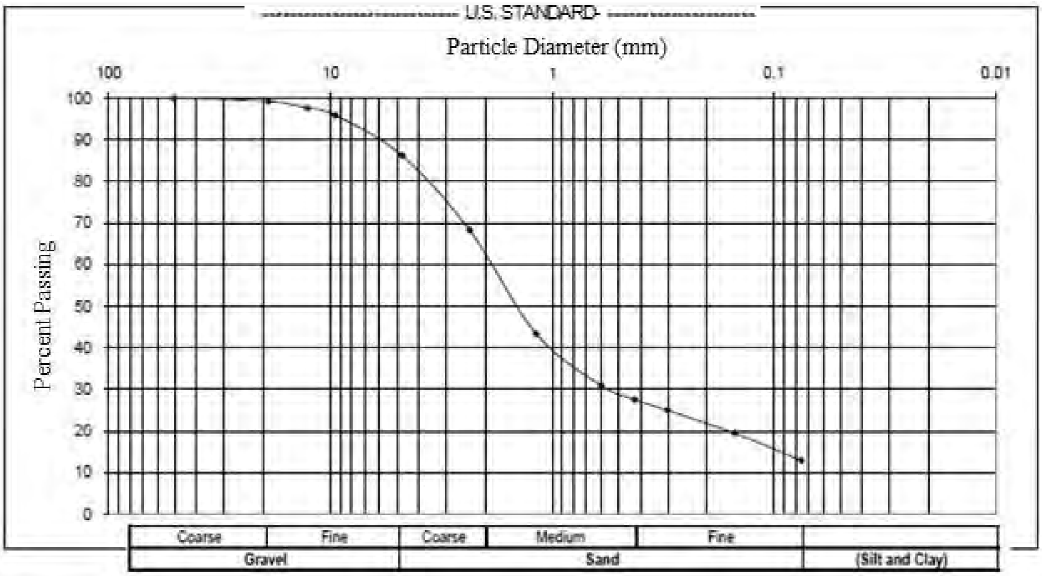


Figure 3-8: OCXP Bottom Ash Grain Size Distribution Curve (2011)

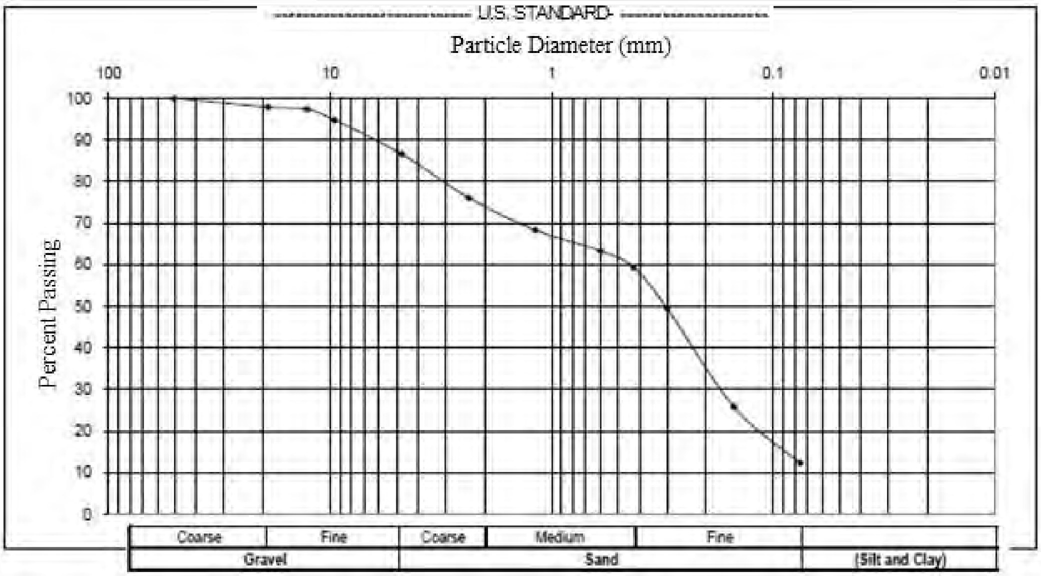


Figure 3-9: VAPP Bottom Ash Grain Size Distribution Curve (2011)

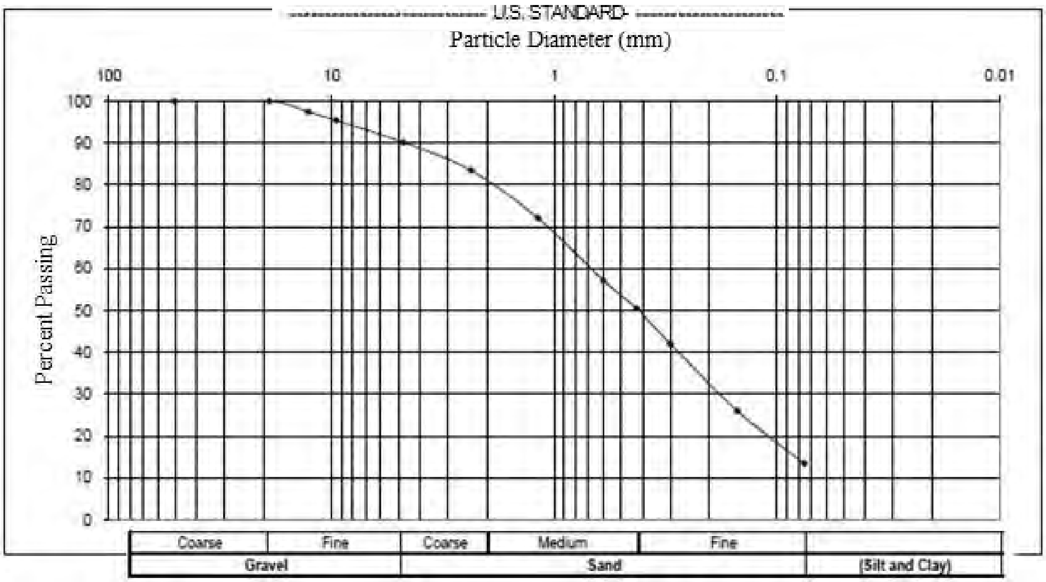


Figure 3-10: PIPP Bottom Ash Grain Size Distribution Curve (2011)

Results of Testing Bottom Ash to AASHTO Standards

In early 1994, 2004 and 2011, testing was performed on We Energies bottom ash to evaluate its use as a base course material, as granular fill for subbase and as a coarse aggregate for hot mix asphalt (HMA), following the procedures in the AASHTO Standards. The test results were then compared with the requirements in the WisDOT's standard specifications (19) and the MDOT's standard specifications for construction (20). The test results are tabulated in Tables 3-7 and 3-8.

Atterberg Limit tests were performed on Pleasant Prairie, Oak Creek Expansion and Presque Isle bottom ashes. The results show that all three materials tested are non-liquid and non-plastic. Section 301.2.3.5 of WisDOT Standard Specifications require that the base course aggregate not have a liquid limit of more than 25 and not have a plastic index of more than 6. WisDOT standard specifications do not identify a maximum liquid limit for hot mix asphalt coarse aggregate. Therefore, the bottom ash materials meet the WisDOT standard specification requirements for Atterberg Limits.

The Los Angeles Abrasion test results showed that the bottom ash samples tested were not as sound or durable as natural aggregate. However, the test results fall within the WisDOT limits of maximum 50% loss by abrasion for Mixtures E-0.3 and E-1.

WisDOT standard specifications require a minimum 58% fracture face for dense base course aggregate. The bottom ash also meets these specifications.

MDOT specifications limit a maximum loss of 50% for dense graded aggregates. Other grades of aggregates have a lower limit on abrasion loss. Hence, the samples tested meet only MDOT specifications for dense graded aggregates.

Pleasant Prairie and Oak Creek Expansion bottom ash meet the requirements of WisDOT section 460.2.2.3 of the Standard specifications for coarse aggregate for the HMA, Presque Isle bottom ash did not meet this requirement. However, Pleasant Prairie, Oak Creek Expansion and Presque Isle bottom ash did not meet the gradation requirements of WisDOT section 305.2.2.1 of the Standard Specifications for base course aggregate. The material requires blending with other aggregates and/or screening to meet requirements of WisDOT sections 305.2.2.1 and 460.2.2.3.

Pleasant Prairie, Oak Creek Expansion and Presque Isle bottom ash met the gradation requirements for Grade 2 granular fill specified by WisDOT although these materials need to be blended, washed or screened to meet the WisDOT specification for Grade 1 granular fill.

Table 3-7: Summary Of We Energies Bottom Ash Test Data and Comparison to WisDOT Specifications (19)

Analysis	Pleasant Prairie Bottom Ash	Oak Creek Expansion Bottom Ash	Presque Isle Unit 7-9 Bottom Ash	Reference Specifications
Soundness				
Result				
Fine Fraction	11.9	4.2	11.7	
Compliance				
Fine Fraction	Pass	Pass	Pass	WisDOT 301.2.3.5 & 460.2.7
Atterberg Limits				
Result	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	
Compliance	Pass	Pass	Pass	WisDOT 301.2.3.5
Los Angeles Abrasion				
Result				
100 revolutions (% loss)	26.9	27.5	23.4	
500 revolutions (% loss)	50.4	49.2	40.6	
Compliance				
100 revolutions (% loss)	Pass	Pass	Pass	WisDOT 301.2.3.5
	Fail	Fail	Fail	WisDOT 460.2.7
500 revolutions (% loss)	Pass	Pass	Pass	WisDOT 301.2.3.5
	Pass E-0.3 and E-1	Pass E-0.3 and E-1	Pass E-0.3 and E-1	WisDOT 460.2.7
Gradation				
Result	See Table 3-5	See Table 3-5	See Table 3-5	
Compliance				
As HMA Coarse Agg.	Pass	Pass	Fail (1)	WisDOT 460.2.2.3
As Base Coarse Agg.	Fail (1)	Fail (1)	Fail (1)	WisDOT 305.2.2.1
As Granular Backfill	Fail Grade 1 (2) Pass Grade 2	Fail Grade 1 (2) Pass Grade 2	Fail Grade 1 (2) Pass Grade 2	WisDOT 209.2.2
Freeze-Thaw Durability				
Result	18.3	8.5	11.7	
Compliance	Pass	Pass	Pass	WisDOT 301.2.4.5 & 460.2.2.3
Aggregate Angularity	(3)	(3)	(3)	CMM13.9

(1) - Requires blending with other aggregate to meet specifications.

(2) - Requires blending, washing or screening to reduce the amount of fines to meet specifications.

(3) - Bottom ash is angular in nature.

Table 3-8: Summary of We Energies Bottom Ash Test Data and Comparison to Michigan DOT Specifications (20)

Analysis	Pleasant Prairie Bottom Ash	Oak Creek Expansion Bottom Ash	Presque Isle Unit 7-9 Bottom Ash	Reference Specifications
Soundness				
Result				
Fine Fraction	11.9	4.2	11.7	
Compliance				
Fine Fraction	N/A (1)	N/A (1)	N/A (1)	AASHTO T-104
Atterberg Limits				
Result	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	Non-Liquid/ Non-Plastic	
Compliance	N/A (2)	N/A (2)	N/A (2)	AASHTO T-89 & T-90
Los Angeles Abrasion				
Result				
100 revolutions (% loss)	26.9	27.5	23.4	
500 revolutions (% loss)	50.4	49.2	40.6	
Compliance				
100 revolutions (% loss)	N/A	N/A	N/A	
500 revolutions (% loss)	(3)	(3)	(3)	MDOT 902
Gradation				
Result	See Table 3-5	See Table 3-5	See Table 3-5	
Compliance				
As HMA Coarse Agg.	Fail (4)	Fail (4)	Fail (4)	MDOT 902
As Base Coarse Agg.	Fail (4)	Fail (4)	Fail (4)	MDOT 902
As Granular Backfill	Fail (4)	Fail (4)	Fail (4)	MDOT 902
Freeze-Thaw Durability				
Result	18.3	8.5	11.7	
Compliance	Pass	Pass	Pass	AASHTO T-103

N/A = Not Available

(1)- MDOT does not have a specific requirement for soundness. Instead, MDOT relies on results of freeze-thaw durability.

(2)- MDOT does not have a specific requirement for Atterberg Limits.

(3)- Does not meet specifications for coarse aggregates or any of the open-graded aggregates. The materials meet the requirements for dense graded aggregates.

(4)- Material could be blended with another aggregate to help meet specifications.

Soundness test results for all three samples are well within the allowable limits per section 301.2.3.5 and section 460.2.7 of the WisDOT standard specifications with maximum % loss of 18% and 12%, respectively. MDOT specifies a maximum percent material loss by washing through the No. 200 sieve in lieu of the soundness test. Since MDOT relies on results of freeze-thaw durability for soundness requirements, the AASHTO T-103 limits to 20% for freeze-thaw durability.

Physical and Chemical Properties of We Energies Flue Gas Desulfurization (FGD) Gypsum

FGD Gypsum

Figure 3-11: We Energies FGD Gypsum

As part of We Energies environmental commitment to reduce emissions and minimize landfilling of coal combustion products, the company has installed FGD systems that produce a high purity gypsum by-product. The FGD gypsum is composed of tetrahedron crystals, ranging on average from 40-50 µm in particle size, appears light brown in color, with soil-like consistency, no odor, and low moisture content. It is chemically known as calcium sulfate dihydrate ($CaSO_4.2H_2O$). The typical characteristics and the chemical composition are shown on Table 3-9. We Energies generates over 166,000 tons of FGD gypsum each year cumulatively at Pleasant Prairie and the Oak Creek site power plants. The gypsum is used for wallboard manufacturing and agriculture.

Table 3-9: Typical Characteristics of We Energies FGD Gypsum*

Purity ($CaSO_4.2H_2O$)		> 95%
Impurities	$CaCO_3$	< 2%
	$MgCO_3$	< 1%
Calcium Content		> 20%
Sulfur Content		> 16%
Particle size distribution - % passing 200 mesh sieve		> 95%

* We Energies website: Agricultural Gypsum 2011

One important application of FGD gypsum is in agriculture. Due to local production, Wisconsin farmers have benefited economically by using FGD gypsum over mined natural gypsum. It provides soil and plant nutrients and also improves the soil's physical and chemical properties. It increases the soil permeability and water infiltration reducing erosion and lowering silt loadings in field runoff. The fine particle size of synthetic gypsum makes it soluble, releasing calcium (Ca^{2+}) and sulfate (SO_4^{2-}) ions. The Ca^{2+} provides structural support and enzyme signal activation, perception and transduction as an addition to the plant nutrients (21). By spreading gypsum to the soil, it doesn't alter the pH but rather neutralizes some acidity on a short-term basis. The neutralization occurs as the SO_4^{2-} displaces OH^- from the iron and aluminum hydrated oxides on soil surfaces.

The purity of FGD gypsum (> 95%) is an advantage over most natural rock gypsums (purity range of 80% to 96%) when used for wallboard for the purpose of lowering the weight of gypsum board. Table 3-10 presents the geotechnical properties and Figure 3-12 shows the grain size distribution curve for FGD gypsum produced at the Pleasant Prairie power plant.

Table 3-10: Geotechnical Properties of PPPP Gypsum*

Analysis	Results	Method
Maximum Dry density (lb/cu.ft)	77.6 @ 33% Optimum Moisture content	ASTM D-698
Hydraulic Conductivity (cm/sec)	0.003	ASTM D-5084
Shear Strength		ASTM D-4767
Internal Friction Angle (°)	42	
Cohesion	0	
Specific Gravity	2.38 @ 20°C	ASTM D-854
Angle of Repose (°)	44 at oven dried condition (0%wt) 46 at air dried condition (22%wt) 49 at natural moisture content (25%wt)	ASTM D-6393

*Sampling data from 2009

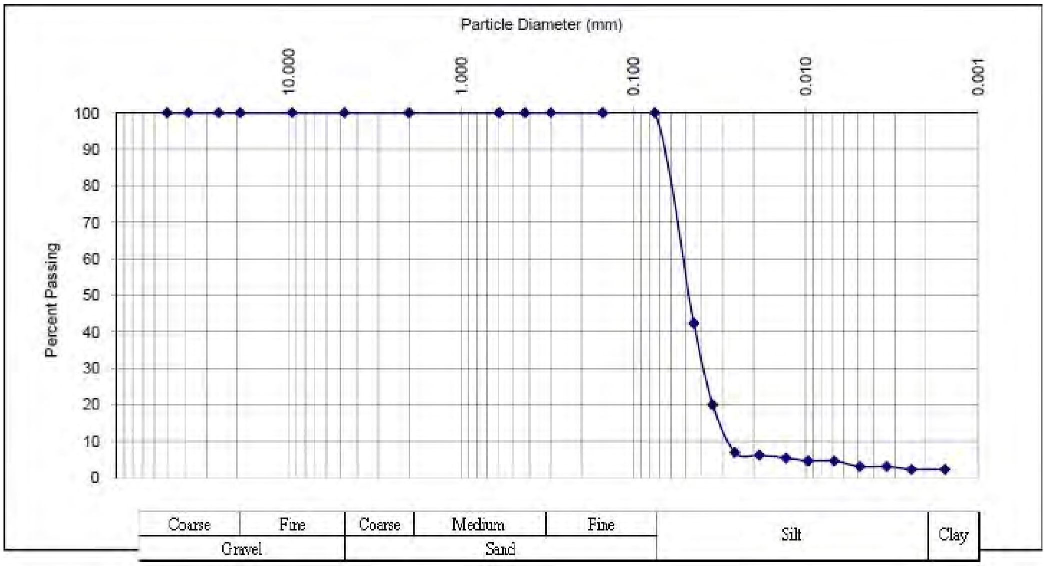


Figure 3-12: PPPP Gypsum Grain Size Distribution Curve (2009)

Overview of the Chemical Reaction from a Wet-Limestone Scrubber (22)

Flue-gas scrubbing is a stepped chemistry process (Figure 3-13), where the overall reaction is a classic example of aqueous acid-base chemistry applied on an industrial scale. The limestone slurry (composed primarily of calcium carbonate, $CaCO_3$) reacts with acidic sulfur dioxide, as represented in Equation 1.

$$\mathbf{CaCO_3 + 2H^{+} + SO_3^{-2} \rightarrow Ca^{+2} + SO_3^{-2} + H_2O + CO_2\uparrow \quad [1]}$$

In the absence of any other reactants, calcium and sulfite ions will precipitate as a hemihydrate, where water is actually included in the crystal lattice of the scrubber byproduct.

$$\mathbf{Ca^{+2} + SO_3^{-2} + \tfrac{1}{2}H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O\downarrow \quad [2]}$$

Many wet-limestone scrubbers operate at a solution pH of around 5.6 to 5.8. A very acidic scrubbing solution inhibits SO_2 transfer from gas to liquid; while excessive basic slurry ($pH > 6.0$) indicates an overfeed of limestone.

The oxygen in the flue gas greatly influences chemistry. Aqueous bisulfite and sulfite ions react with oxygen to produce sulfate ions (SO_4^{-2}).

$$\mathbf{2SO_3^{-2} + O_2 \rightarrow 2SO_4^{-2} \quad [3]}$$

Approximately the first 15 mole percent of sulfate ions co-precipitates with sulfite to form calcium sulfite-sulfate hemihydrate [$(0.85CaSO_3 \cdot 0.15CaSO_4) \cdot \tfrac{1}{2}H_2O$]. Any sulfate above the 15 percent mole ratio precipitates with calcium as gypsum.

$$\mathbf{Ca^{+2} + SO_4^{-2} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O\downarrow \quad [4]}$$

In summation, for every part of SO_2 removed from the flue gas, one part of calcium carbonate from the limestone must react with it. Hence, for every part of SO_2 removed, one part of gypsum by-product is generated.

$$\mathbf{SO_2 + CaCO_3 \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + CO_2 + O_2 \rightarrow CaSO_4 \cdot 2H_2O\ (gypsum)}$$

FGD Filter Cake

We Energies power plants also produce filtered solids out of waste water treatment during the process of removing sulfur dioxide using wet FGD systems, known as the FGD Filter Cake. The process is shown in Figure 3-14. The filter cake is a brown clay-like chunk with about 107% water content. The 2011 production of FGD Filter Cake was 1624 tons from PPPP and 3477 tons from OCXP compared to 2010, with an estimated production of 1540 tons from PPPP and 2204 tons from OCXP. Presently, the FGD filter cake is being stored for use as an internal landfill leveling layer.

In 2008, FGD filter cake from PPPP was tested from a stockpile and its geotechnical properties are shown on Table 3-11. Table 3-12 shows the chemical composition of FGD filter cake from samples collected in 2011 at OCXP and PPPP. NR538 PPPP FGD Filter Cake leachate test results are summarized in chapter 9 and was found to contain chloride, sulfate, boron, selenium, strontium and arsenic amongst other expected compounds. Thus, the filter cake material needs to be stabilized before it can be used for construction.

In the summer of 2009, a landfill access road (stretching approximately 425 feet long) was constructed to support heavy loaded multi-axle truck traffic at the Pleasant Prairie Power Plant. For a research based demonstration, the FGD filter cake was stabilized with the addition to PPPP Class C Fly ash for use in stabilizing a road base. The 12-inch base consisted of 80% recycled concrete, 20% FGD filter cake and 120 lbs/yd^2 of Class C fly ash. During the construction, rain complicated completion of the project because the handling and the compaction of the material became difficult due to an affinity for water. However construction was successfully completed and 2009 Falling Weight Deflectometer test results indicated that stabilization of the recycled crushed concrete with fly ash and filter cake likely increased the base course layer strength significantly. The road continues to provide good service and performance. Perhaps one day in the future, the minerals contained in the FGD filter cake can be evaluated further for additional applications.

Table 3-11: Geotechnical Properties of PPPP FGD Filter Cake

Analysis	SE Corner	Center	Average
Maximum Dry density (lb/cu.ft)	54.8	59.5	51.2
Optimum Moisture (%)	75.2	68.4	71.8
Consolidation			
Initial void ratio (e_o)	2.54	2.44	2.49
Compression Index (Cc)	0.78	0.75	0.77
Pre-consolidation pressure, Po (tons/sq.ft)	3.25	3.25	3.25
Coefficient of secondary compression, Cs	0.04	0.04	0.04
Specific Gravity (at 20ºC)	3.06	3.10	3.08
Atterberg Limits			
Liquid Limit (%)	129	116	123
Plasticity Index (%)	62	61	62

Table 3-12: Chemical Composition of We Energies FGD Filter Cake

Source	OCXP	PPPP
SiO_2, %	12.19	14.76
Al_2O_3, %	3.46	4.90
Fe_2O_3, %	10.00	7.28
CaO, %	22.94	13.16
MgO, %	3.67	12.97
Na_2O, %	0.12	0.24
K_2O, %	0.83	1.42
SO_3, %	18.90	16.59
Miscellaneous, %	1.43	1.53
L.O.I (at 95ºC), %	26.23	27.09
Total %	99.77	99.94

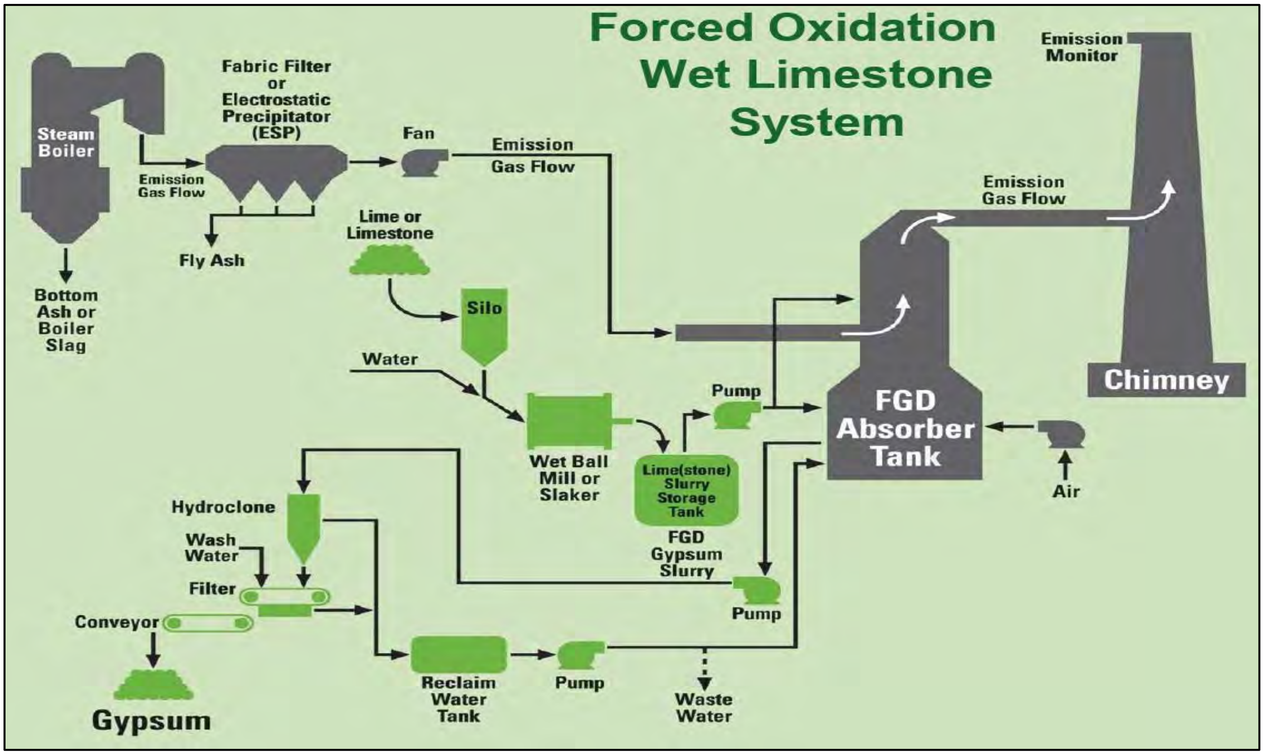


Figure 3-13: Schematic Diagram of a typical We Energies Wet FGD system.

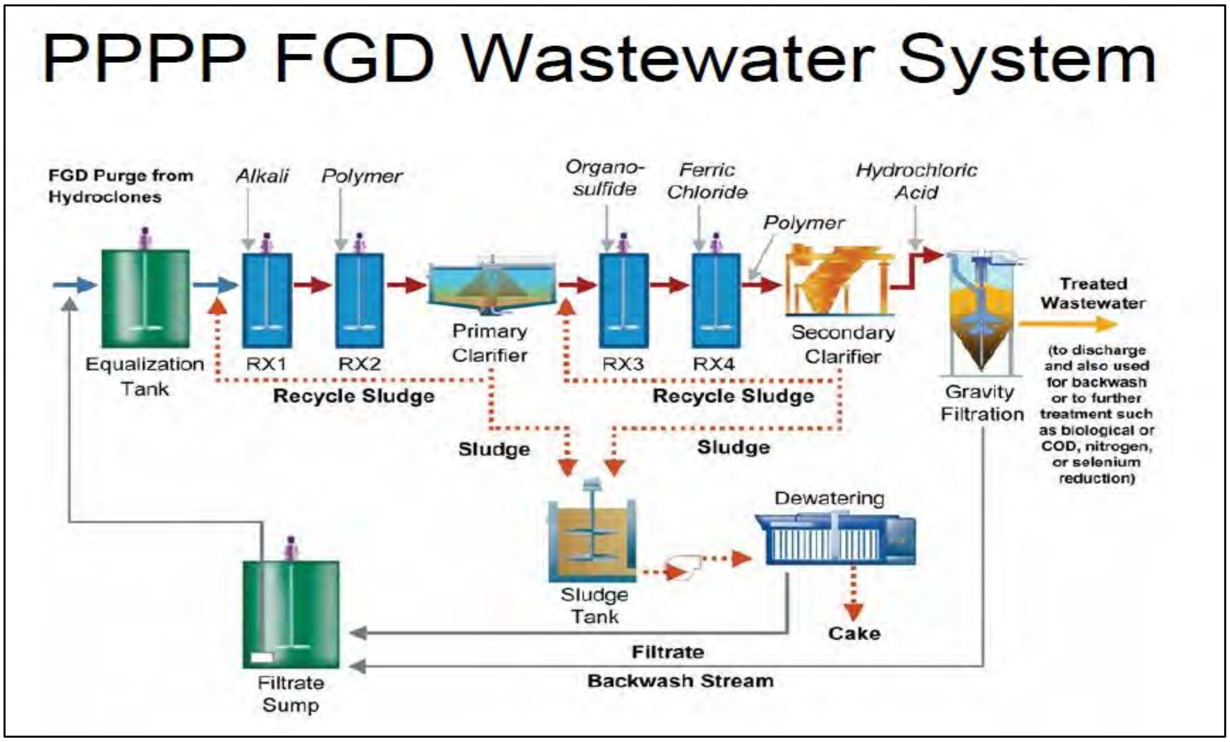


Figure 3-14: Schematic diagram of the production of FGD filter cake from the wet scrubber waste water treatment process.

Chapter 4

Concrete and Concrete Masonry Products Containing We Energies Fly Ash

Introduction

Coal combustion products have been used in the construction industry since the 1930's (8). Although the utilization of these products was limited to small-scale applications in the early days, the use of coal combustion products has gained increasing acceptance in the construction industry in the last few decades. The interest in coal combustion products significantly increased during the 1970's because of the rapid increase in energy costs and the corresponding increase in cement costs.

We Energies has been conducting extensive research to beneficially utilize fly ash, bottom ash and FGD gypsum generated at company-owned coal-fueled power plants for construction and agricultural applications. Many of these research efforts have been conducted in conjunction with universities, research centers and consultants, resulting in the development of cost effective and environmentally friendly products.

Today, We Energies fly ash, bottom ash and FGD gypsum are being widely used in the construction industry. Applications range from utilizing fly ash in the manufacture of concrete, concrete products, controlled low strength material (CLSM), liquid waste stabilization, roller-compacted no fines concrete, high-volume fly ash concrete, cold-in-place recycling of asphalt, lightweight aggregate, and soil stabilization. Of all these applications, the use of fly ash as an important ingredient in the production of concrete is by far the largest application.

Background on Hydration Reaction, Cementitious, And Pozzolanic Activity

To understand the behavior of fly ash in contact with water or in a concrete mixture, it is important to understand the reaction that takes place in freshly mixed concrete and the process by which it gains strength. The setting and hardening process of concrete, which occurs after the four basic components consisting of coarse aggregate, fine aggregate, cement and water are mixed together, is largely due to the reaction between the components cement and water. The other two components, coarse aggregate and fine aggregate, are more or less inert as far as setting and hardening is concerned.

The major components of cement that react with water to produce hydration reaction products are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF). The reactions can be summarized as shown below:

$2C_3S + 6H$	→	$C_3S_2H_3 + 3CH$
tricalcium silicate + water		C - S - H + calcium hydroxide
$2C_2S + 4H$	→	$C_3S_2H_3 + CH$
dicalcium silicate + water		C - S - H + calcium hydroxide
$C_3A + 3C\bar{S}H_2 + 26H$	→	$C_3A(C\bar{S})_3H_{32}$
tricalcium aluminate + gypsum + water		ettringite
$C_3A + C\bar{S}H_2 + 10H$	→	$C_3AC\bar{S}H_{12}$
		monosulphoaluminate hydrate

C_4AF forms hydration products similar to that of C_3A, where iron substitutes partially for alumina in the crystal structure of ettringite and monosulphoaluminate hydrate.

In the absence of sulfate, C_3A may form the following reaction products (8):

$$C_3A + 6H \rightarrow C_3AH_6$$
$$C_3A + CH + 18H \rightarrow C_4AH_{19}$$

Fly ash is pozzolanic. A pozzolan is defined as "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which, in finely divided or powdered form, and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds that possess cementitious properties" (23).

The major reaction that takes place is between the reactive silica of the pozzolan and calcium hydroxide producing calcium silicate hydrate. The alumina in the pozzolan may also react with calcium hydroxide and other components in the mixture to form similar products.

High-calcium fly ash is both cementitious and pozzolanic and has self-hardening properties in the presence of moisture. The reaction products include ettringite, monosulphoaluminate and C-S-H. These products are also formed when cement reacts with water and causes hardening in the cement-water mixture.

The rate of formation of C-S-H in the fly ash-water mixture is normally slower than that in a cement-water mixture. Because of this, at ages greater than 90 days, fly ash-cement-water continues to gain strength; while the cement-water pastes do not show as significant a gain in strength. However, this hydration behavior of C_3A and C_2S in fly ash is the same as that in cement. Low calcium fly ash has very little or no cementing properties alone, but will hydrate when alkalis and $Ca(OH)_2$ are added.

Concrete Containing We Energies Fly Ash

For centuries, concrete has been widely used for a variety of applications ranging from sidewalk slabs to bridges and tall buildings. Concrete used in the early days had low strength and the applications were limited, partly due to the strength of the concrete and partly due to the lack of understanding of design principles.

With the evolution of more sophisticated materials and engineering designs, many problems associated with strength were solved and high-strength concrete designs were developed. Today, engineers can select a concrete mixture with a specified strength for a particular application. In most cases, strength of concrete is not a limiting factor in project design.

Durability of concrete has been a challenge since the early days of concrete production. With applications increasing, the demand to find concrete that “performs” is increasing. Most durability problems associated with concrete get worse in adverse weather conditions. For example, in cold weather regions, concrete that is subjected to freezing and thawing tends to disintegrate faster if it is porous. Porosity is generally considered the most significant factor affecting the long-term performance of concrete.

Portland cement concrete is a mixture of coarse aggregates, fine aggregates, cement and water. The properties of concrete prepared by mixing these four components depends on the physical and chemical properties and the proportions in which they are mixed. The properties of concrete produced can be enhanced for specific applications by adding admixtures and/or additives.

The use of a particular admixture or additive has a definite purpose. For a particular application, it is important that the properties of the concrete be tailored to meet performance requirements.

Fly ash added in concrete as a supplementary cementing material achieves one or more of the following benefits:

- Reduces the cement content.
- Reduces heat of hydration.
- Improves workability of concrete.
- Attains higher levels of strength in concrete especially in the long term.
- Improves durability of concrete.
- Increases the “green” recycled material content of concrete.
- Attains a higher density.
- Lowers porosity and permeability.

The properties of fly ash, whether ASTM C-618, Class C or Class F, and the percentages in which they are used greatly affect the properties of concrete. Mixture proportioning and trial batches are critical to obtaining concrete with the desired fresh and hardened properties. Fly ash may be introduced in concrete as a blended cement containing fly ash or introduced as a separate component at the mixing stage.

Most of the We Energies fly ash is being used in concrete as a separate component at the concrete batching and mixing stage. This allows the flexibility of tailoring mixture proportions to obtain the required concrete properties for the particular application. Ready-mixed concrete producers have greater control with respect to the class and amount of fly ash in the concrete mixture to meet the specified performance requirements.

Fly ash has several other properties, in addition to its cementitious and pozzolanic properties, that are beneficial to the concrete industry (24). Low-calcium fly ash (ASTM C-618 Class F) has been used as a replacement for Portland cement in concrete used for the construction of mass gravity dams. The primary reason for this application has been the reduced heat of hydration of Class F fly ash concrete compared to Portland cement concrete. ASTM C-618 Class C fly ash concrete may also have a slightly lower heat of hydration when compared to Portland cement concrete. However, low calcium Class F fly ash concrete generates still lower heat of hydration, a desirable property in massive concrete construction, such as dams and large foundations.

Studies have also revealed that certain pozzolans increase the life expectancy of concrete structures. Dunstan reported that as the calcium oxide content of ash increases above a lower limit of 5% or as the ferric oxide content decreases, sulfate resistance decreases (25).

Dunstan proposed the use of a resistance factor (R), calculated as follows:

$R = (C-5)/F$
Where C = percentage of CaO
Where F = percentage of Fe_2O_3

Dunstan summarized his work in terms of the selection of fly ash for sulfate-resistant concrete as follows (25):

R limits [a]	Sulfate Resistance [b]
< 0.75	Greatly improved
0.75 – 1.5	Moderately improved
1.5 – 3.0	No significant change
> 3.0	Reduced

[a] At 25% cement replacement

[b] Relative to ASTM Type II cement at a water/cementitious materials ratio of 0.45

The influence of pozzolans on the sulfate resistance of concrete is not completely understood today. However, based on the studies at the U.S. Army Corps of Engineers, Mather reported that a pozzolan of high fineness, high-silica content and high amorphousness is most effective against expansion due to sulfate attack.

Alkali-aggregate reactions (AAR) also cause expansion and damage in concretes produced with reactive aggregates and available alkalis from the paste. However, a variety of natural and artificial pozzolans and mineral admixtures, including fly ash, can be effective in reducing the damage caused by AAR. Researchers have reported that the effectiveness of fly ash in reducing expansion due to AAR is limited to reactions involving siliceous aggregate. The reactive silica in power plant fly ash combines with the cement alkalis more readily than the silica in aggregate. The resulting calcium-alkali-silica “gel” is nonexpansive, unlike the water-absorbing expansive gels produced by alkali-aggregate reactions. In addition, adding fly ash to concrete increases ASR resistance and improves the concrete’s ultimate strength and durability while lowering costs.

The following factors are important in determining the effectiveness of using fly ash to control AAR.

- The concentration of soluble alkali in the system.
- The amount of reactive silica in the aggregate.
- The quantity of fly ash used.
- The class of fly ash.

According to Electric Power Research Institute (EPRI) studies (26), both Class C and Class F fly ash can be effective at mitigating ASR in concrete when used as substitutes for Portland cement. The major difference between the two ash types is that a greater portion of cement must be replaced with Class C ash to provide the same effect as using Class F ash in a mix design with a smaller ash-to-cement ratio. According to EPRI studies, replacing Portland cement with Class C ash at volumetric rates of 30-50% is effective in controlling ASR. The greater the proportion of Class C fly ash used in a mix, the greater the ASR control benefit.

The concentration of soluble (available) alkali and not the total alkali content is critical for the reaction. Studies have shown that if the acid soluble alkali-content is in excess of 5.73 lb/cu yd, then it can cause cracking, provided that reactive aggregates are present. (This is approximately equivalent to 4.21 lb/cu yd as water-soluble alkali.) For high-calcium Class C fly ash, the amount of alkali in the ash affects the effectiveness of expansion reduction. Another study by EPRI (27) indicated that for high-calcium (22.5% CaO) moderate-alkali (2.30% Na_2O_{eq}) fly ash, the amount of fly ash required to control expansion due to ASR varies significantly from one aggregate to another. In the case of the extremely reactive aggregate, between 50%-60% of fly ash would be required to reduce expansion under the 0.10% level. For less reactive aggregate, a lower fly ash replacement level is required. Even high-calcium (21.0% CaO) high-alkali (5.83% Na_2O_{eq}) fly ash contributed in reducing ASR expansion; however, an expansion higher than 0.10% level occurred. Therefore, it is necessary to test the amount of alkali in the fly ash prior to incorporating it in the concrete to control ASR.

The following aggregates and their mineralogical constituents are known to react with alkalis:

- Silica materials - opal, chalcedony, tridymite and cristobalite
- Zeolites, especially heulandite
- Glassy to cryptocrystalline rhyolites, dacites, andesites and their tuffs
- Certain phyllites

Low-calcium (ASTM C-618, Class F) fly ash is most effective in reducing expansion caused by alkali-silica reactions where the fly ash is used at a replacement level of approximately 20% to 30%. Once the replacement threshold has been reached, the reduction in expansive reaction for a given cement alkali level is dramatic. Additionally, the greater the proportion of cement replaced with Class F fly ash, the greater the ASR reduction. In some cases where silica fume, a very fine material that is high in reactive SiO_2, is used in concrete for high strength, adding Class F or Class C fly ash to create a “ternary blend” can significantly reduce ASR susceptibility without diminishing concrete performance. The actual reaction mechanism for the alkali-aggregate reaction and the effect of fly ash is not fully understood today and will require more research to find a satisfactory explanation.

Soundness of aggregates or the freedom from expansive cracking is one of the most important factors affecting the durability of concrete. At early ages, unloaded concrete cracks because of two reasons: thermal contraction and drying shrinkage. When concrete hardens under ambient temperature and humidity, it experiences both thermal and drying shrinkage strains.

The level of shrinkage strain depends on several factors, including temperature, humidity, mixture proportions, type of aggregates, etc. Shrinkage strain in hardened concrete induces elastic tensile stress. Cracks appear in concrete when the induced tensile stress exceeds the tensile strength of the concrete. Creep may reduce the induced tensile stress to a certain extent, but the resultant stress can be large enough for cracking concrete.

Using sufficient steel reinforcement has traditionally controlled cracking. However, using reinforcement does not solve this problem completely. By using reinforcement, fewer large cracks may be reduced to numerous invisible and immeasurable micro-cracks (28). Transverse cracks seen in bridge decks are typical examples. Cracking in concrete is the first step to deterioration, as it results in the migration of harmful ions into the interior of concrete and to the reinforcement.

Several preventive and mitigating measures can be used to minimize the degradation of concrete due to corrosion of reinforcing steel. The use of fly ash as a partial replacement for cement is a cost-effective solution (inclusion of fly ash in a mixture provides the same workability at a lower water content and lower cement content both of which reduces the concrete shrinkage). In several states across the country, the Department of Transportation (DOT) has made it mandatory to include fly ash as an ingredient. The heat of hydration is substantially reduced when fly ash is used in concrete as a partial replacement to cement.

Durability of concrete is very critical in most DOT applications, especially in regions subject to cold weather conditions. In such cases, the incorporation of fly ash in concrete is advantageous, even though the setting and hardening process may be slightly slower than ordinary Portland cement concrete.

Fly ash has been used in concrete for several decades. Research work on short-term and long-term behavior of concrete containing fly ash has been conducted by several research groups. However, the properties of fly ash vary with the specific coal burned as well as the process of coal preparation, firing and collection.

Hence, We Energies has conducted research on the actual fly ash generated at its coal-fueled plants. This research has been conducted with the aid of universities and research institutions in conjunction with concrete producers to develop mix designs that can be readily used for construction. Several parameters, both short-term and long-term, have been studied, and their performances evaluated to identify the suitability of the particular mixture design for a specific field application. One important point is the spherical shape of fly ash with its lubricating effect for pumping and providing the same workability with a lower water to cementitious materials ratio. Also, fly ash is usually finer than Portland cement and thus produces a denser concrete with lower permeability.

Compressive Strength of Concrete Containing We Energies ASTM C-618, Class C Fly Ash (Phase I Study)

Concrete is used in several applications requiring different levels of strength. Most applications require concrete with a compressive strength in the range of 3,000 to 5,000 psi. Based on the type of application, engineers select a mixture design with a specified 28-day compressive strength. Other durability factors such as porosity or freeze-thaw resistance also influence the selection of a concrete mixture.

With the introduction of fly ash concrete, the long-term (56 day or 1 year) properties of concrete have shown dramatic improvement. Since long-term properties of concrete are vital, most construction professionals are interested in understanding the performance of fly ash and the resulting concrete made using fly ash.

The influence of We Energies fly ash on the quality of concrete has been studied for several years. Fly ash is used as a partial replacement for cement at various replacement levels. In order to understand the properties of We Energies fly ash and the short-term and long-term performance of concrete containing We Energies fly ash, a great amount of research work has been conducted.

The following data is from a research project conducted at the Center for By-Products Utilization at the University of Wisconsin-Milwaukee for We Energies (29). This work was done with the objective of developing mixture proportions for structural grade concrete containing large volumes of fly ash. ASTM C-618, Class C fly ash from We Energies Pleasant Prairie Power Plant was used in this research project.

Preliminary mixture proportions were developed for producing concrete on a 1.25 to 1 fly ash to cement weight basis replacement ratio. The replacement levels varied from 0% to 60% in 10% increments. Water to cementitious materials ratios (w/c) of 0.45, 0.55 and 0.65 were used in this project to develop concrete with strength levels of 3,000 psi; 4,000 psi and 5,000 psi. It is interesting to observe that at fly ash utilization levels rising above 50%, Portland cement becomes the admixture or supplementary cementitious material.

Actual concrete production was performed at two local ready mixed concrete plants utilizing different cement and aggregate sources. Three quarter inch maximum size aggregates were used in the mixtures and the slump was maintained at 4”± 1”. Entrained air was maintained in the range of 5-6% ± 1%. The concrete mixtures were prepared at ready mixed concrete plants using accepted industry practices. Six-inch diameter by 12” long cylinder specimens were prepared for compressive strength tests. The compressive strength tests were performed at various ages in accordance with standard ASTM test methods. The chemical and physical properties of PPPP fly ash used in these tests are shown in Table 4-1.

Tables 4-2 to 4-4 show the mixtures designed for concrete in the various strength levels and various percentages of cement replacement with fly ash. The compressive strength results are shown in Tables 4-5 to 4-7.

Table 4-1: Chemical and Physical Test Data Pleasant Prairie Power Plant (PPPP) Fly Ash

Chemical Composition	Average (%)	ASTM C-618
Silicon Oxide (SiO_2)	40.89	---
Aluminum Oxide (Al_2O_3)	16.13	---
Iron Oxide (Fe_2O_3)	6.01	---
Total ($SiO_2+Al_2O_3+Fe_2O_3$)	63.03	50.0 min
Sulfur Trioxide (SO_3)	2.98	5.0 max
Calcium Oxide (CaO)	25.30	---
Magnesium Oxide (MgO)	4.56	5.0 max
Loss on ignition	0.45	6.0 max
Available alkalies as Na_2O	1.19	1.5 max
Fineness % retained on #325 wet sieve	18.83	34.0 max
Pozzolanic activity index with cement 28 days with lime 7 days	92.43 1805	75.0 min 800 min
Water requirement % of the control	91	105 max
Soundness Autoclave expansion (%)	0.15	0.8 max
Specific gravity	2.58	---

Discussion of Test Results - 3,000 psi Concrete

Compressive strength test results for the six different 3000 psi concrete mixtures are shown in Table 4-2. The specified strength for these mixtures is 3,000 psi. These test results show that with an increase in cement replacement levels with fly ash, the early age compressive strength decreases.

The decrease is not significant for concrete with 20% and 30% replacement levels. At the 7-day age, cement replacement with up to a 40% replacement level produces concrete with compressive strength comparable to that of the control mix. At the 28-day age, all mixtures showed strength levels higher than the design compressive strength of 3,000 psi. However, concrete containing 40% replacement of cement with fly ash had the highest strength.

Table 4-2: PPPP Class C Fly Ash Concrete Mix and Test Data - 3000 psi (21 MPa) Specified Strength

Mix No.	P4 - 1	P4 - 2	P4 - 3	P4 - 4	P4 - 5	P4 - 6
Specified design strength, psi	3000	3000	3000	3000	3000	3000
Cement, lbs	425	341	300	255	210	171
Fly ash, lbs	0	100	150	208	260	310
Water, lbs	281	273	272	262	258	249
Sand, SSD, lbs	1610	1610	1610	1610	1610	1610
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4 ¼	4¼	4¼	3½	3¾	4¾
Air content, %	1.2	1.0	1.0	1.2	1.1	0.8
Air temperature, °F	84	82	82	79	78	68
Concrete temperature, °F	82	82	82	82	82	80
Concrete density, pcf	153.4	154.1	154.6	154.8	154.5	154.7

Table 4-3: PPPP Fly Ash Concrete Mix and Test Data 4000 psi (28 MPa) Specified Strength

Mix No.	P4 - 7	P4 - 8	P4 - 9	P4 - 10	P4 - 11	P4 - 12
Specified design strength, psi	4000	4000	4000	4000	4000	4000
Cement, lbs	517	414	364	310	259	209
Fly ash, lbs	0	125	190	251	310	375
Water, lbs	297	284	273	274	272	242
Sand, SSD, lbs	1530	1530	1530	1530	1530	1530
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4¾	3¾	4	4½	4	4
Air content, %	1.4	1.1	1.1	0.8	1.2	1.1
Air temperature, °F	90	92	93	88	78	68
Concrete temperature, °F	83	83	84	82	82	83
Concrete density, pcf	154.2	154.3	154.2	154.4	154.6	153.4

As the age of concrete increased, the compressive strength of all concrete mixtures containing fly ash increased at a level higher than that of the control mix. Concrete with 40% replacement of cement with fly ash continued to show the highest strength level, but all fly ash concrete mixtures showed strength levels higher than that of the control mix at the 56- and 91-day ages.

Discussion of Test Results - 4,000 psi Concrete

Mixes P4-7 through P4-12 were designed for a compressive strength of 4,000 psi. At an age of 3 days, 20% fly ash concrete showed the highest strength.

At the 7-day age, concrete with up to 50% cement replacement showed compressive strength levels comparable to that of the control mix P4-7. Mixes P4-8 and P4-9 with 20% and 30% replacements showed strengths higher than the control mixture at the 7-day age.

At the 28-day age, all mixtures showed strengths higher than the design strength of 4,000 psi. Also, all mixtures containing fly ash showed higher levels of strength compared to the control mix. Mix P4-10 with 40% replacement of cement showed the maximum strength.

This trend continued at later ages with P4-11, the 50% replacement of cement with fly ash, showing the highest strength of 7,387 psi at the 91-day age.

Table 4-4: PPPP Class C Fly Ash Concrete Mix and Test Data 5000 psi (34 MPa) Specified Strength

Mix No.	P4 - 13	P4 - 14	P4 - 15	P4 - 16	P4 - 17	P4 - 18
Specified design strength, psi	5000	5000	5000	5000	5000	5000
Cement, lbs	611	490	428	367	305	245
Fly ash, lbs	0	145	220	295	382	411
Water, lbs	290	291	289	270	278	268
Sand, SSD, lbs	1450	1450	1450	1450	1450	1450
3/4" aggregates SSD, lbs	1810	1810	1810	1810	1810	1810
Slump, inch	4¾	4½	4½	4½	4½	4
Air content, %	1.1	1.1	1.0	1.0	1.5	1.3
Air temperature, °F	66	62	68	65	62	58
Concrete temperature, °F	70	63	72	69	70	70
Concrete density, pcf	155.7	155.3	155.3	155.2	155.3	155.0

Discussion of Test Results: 5,000 psi Concrete

Mixes P4-13 to P4-18 were designed with a 28-day compressive strength of 5,000 psi. At the 3-day age, concrete with 20% cement replacement showed compressive strength higher than that of the control mix P4-13.

However, concrete with up to 40% cement replacement showed compressive strength in the acceptable range. At the 7-day age, concrete with up to 40% cement replacement showed strength comparable to the control mix. At the

28-day age, all mixes showed strengths higher than the design strength of 5,000 psi. Also, all fly ash concrete mixes showed strengths higher than the control mix, with the 40% cement replacement concrete showing the highest strength.

At the 56- and 91-day ages, the trend continued with the 50% cement replacement concrete showing the highest strength. Even the 60% replacement concrete showed 38% higher strength compared to the control mix at the 91-day age.

Conclusions: 3000 psi; 4000 psi and 5000 psi Concrete

In conclusion, these tests establish that good quality structural concrete can be made with high cement replacements by fly ash. Even 50% and 60% replacements showed higher strengths than the control mixture at 56- and 91-day ages. But this level of cement replacement with fly ash generally will not be made for structural grade concrete for flexural members, such as beams where rapid form stripping is required.

However, these higher replacements may be used for mass concrete where temperature control is needed and early age strength levels are not needed. At the 40% cement replacement level, the strength levels at early ages are within acceptable limits and can be used for structural grade concrete.

Therefore, it can be concluded that fly ash from Pleasant Prairie Power Plant can be used in the manufacture of structural grade concrete with cement replacement levels of up to 40%, on a 1.25 to 1 fly ash to cement weight basis replacement ratio.

The following figures and tables show strength versus age and give the test data.

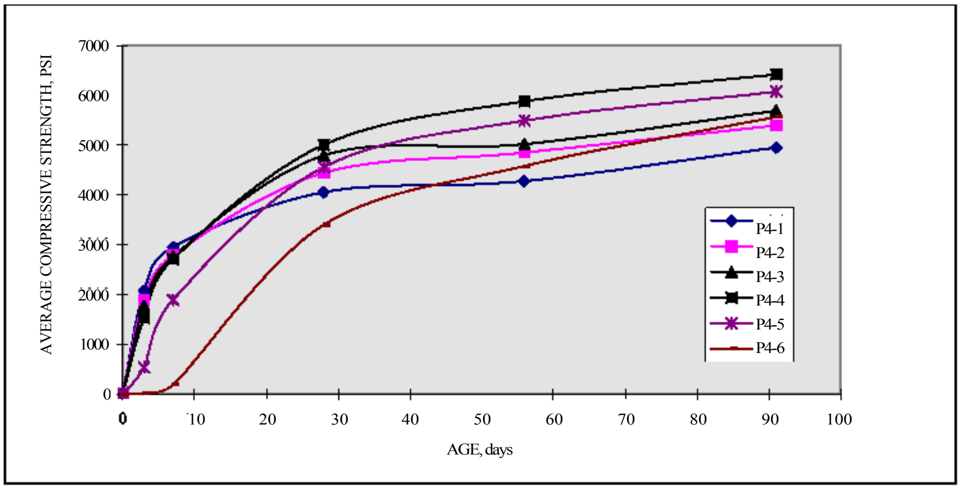


Figure 4–1: Compressive Strength vs. Age Comparison – Mix Nos. P4-1 through P4-6

Other important observations from this study are the following:

1. Replacement of cement with fly ash in concrete increases workability of the mixture.
2. The water demand decreases with the increase in fly ash content. For a given workability, the water to cementitious materials ratio decreases with increases in fly ash content.
3. Pleasant Prairie Power Plant fly ash can be used for the manufacture of structural grade concrete.

Table 4-5: PPPP Class C Fly Ash Concrete Strength Test Data - 3000 psi (21 MPa) Specified Strength

Mix No.	P4-1		P4-2		P4-3		P4-4		P4-5		P4-6	
Specified strength, psi	3000		3000		3000		3000		3000		3000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg
1*	1715	1662	1567	1543	1378	1374	1295	1315	572	576	516	524
1*	1695		1541		1386		1297		577		530	
1*	1576		1521		1358		1353		578		527	
3	2020	2072	1938	1886	1758	1764	1545	1534	572	537	30	26
3	2120		1898		1725		1599		526		24	
3	2076		1822		1810		1459		514		25	
7	2995	2950	2770	2790	2820	2755	2688	2707	1936	1892	202	187
7	3065		2784		2775		2712		1810		176	
7	2789		2817		2670		2723		1931		182	
28	3986	4055	4105	4440	4605	4789	5051	5004	4545	4556	3203	3396
28	4131		4476		4821		5038		4587		3427	
28	4048		4738		4941		4923		4538		3558	
56	4363	4276	4804	4850	4947	5019	5909	5881	5445	5492	4626	4576
56	4350		5011		4877		5811		5457		4811	
56	4115		4735		5234		5923		5575		4290	
91	4960	4953	5160	5393	5850	5687	6400	6417	6080	6073	5630	5567
91	4970		5730		5380		6490		6040		5550	
91	4930		5290		5830		6360		6100		5520	

* After Accelerated Curing, Using Boiling Water Method

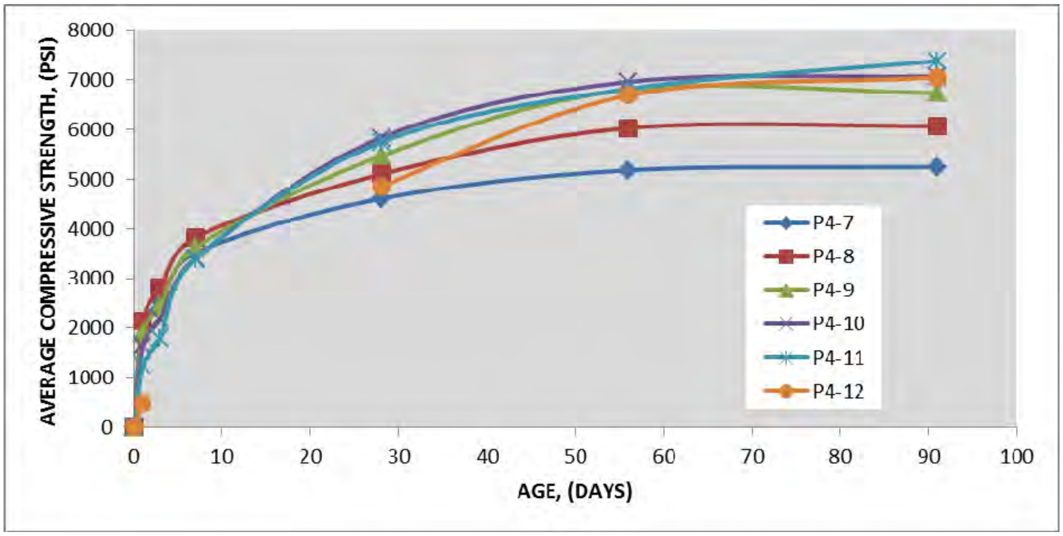


Figure 4–2: Compressive Strength vs. Age Comparison – Mix Nos. P4-7 through P4-12

Table 4-6: PPPP Class C Fly Ash Concrete Strength Test Data - 4000 psi (28 MPa) Specified Strength

Mix No.	P4-7		P4-8		P4-9		P4-10		P4-11		P4-12	
Specified strength, psi	4000		4000		4000		4000		4000		4000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg	Actual	Avg
1*	2068	2055	2163	2148	1868	1893	1658	1647	1233	1240	514	490
1*	2041		2134		1887		1648		1220		472	
1*	2057		2148		1924		1636		1267		484	
3	2476	2548	2786	2808	2393	2436	2218	2181	1767	1793	40**	41**
3	2579		2789		2509		2194		1805		39**	
3	2590		2849		2407		2131		1807		43**	
7	3597	3521	3815	3828	3520	3625	3423	3411	3461	3395	70**	79**
7	3476		3899		3689		3524		3327		78**	
7	3490		3769		3667		3286		3398		88**	
28	4779	4612	5189	5102	5110	5471	5995	5840	5746	5749	4895	4858
28	4706		5140		5685		5628		5719		5030	
28	4350		4976		5618		5897		5782		4648	
56	5262	5183	5964	6034	6628	6811	7139	6967	6912	6825	6787	6694
56	5172		5926		6751		6621		6737		6659	
56	5114		6211		7054		7142		6827		6635	
91	5382	5249	5871	6075	6613	6742	6560	7075	7348	7387	7372	7057
91	5284		6172		6672		7310		7557		6731	
91	5080		6182		6942		7354		7257		7068	

* After Accelerated Curing, Using Boiling Water Method
** Cylinders were green when tested.

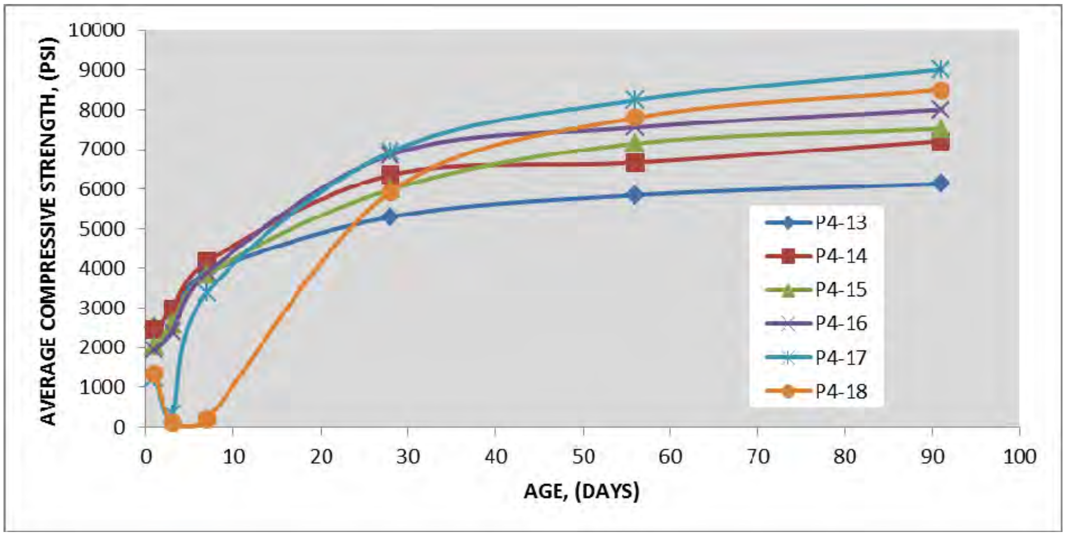


Figure 4-3: Compressive Strength vs. Age Comparison – Mix Nos. P4-13 through P4-18

Table 4-7: PPPP Class C Fly Ash Concrete Strength Test Data - 5000 psi (34 MPa) Specified Strength

Mix No.	P4-13		P4-14		P4-15		P4-16		P4-17		P4-18	
Specified strength, psi	5000		5000		5000		5000		5000		5000	
Percent fly ash	0		20		30		40		50		60	
Compressive Strength, psi												
Test Age. days	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg	Act.	Avg
1*	2579	2519	2438	2448	2089	2044	1938	1942	1210	1230	1315	1336
1*	2498		2441		2041		1965		1234		1360	
1*	2481		2465		2003		1924		1246		1332	
3	2839	2904	3115	2987	2570	2591	2390	2390	287**	324**	111**	116**
3	2930		2936		2570		2379		369**		117	
3	2944		2909		2632		2401		285**		120**	
7	3811	3902	4130	4168	3762	3854	3913	3892	3430	3392	203**	205**
7	4028		4220		3935		3811		3409		206**	
7	3868		4154		3864		3952		3338		203**	
28	5002	5300	6412	6353	5839	5993	6851	6864	6919	6935	5795	5931
28	5484		6381		6102		6786		7045		6079	
28	5413		6266		6038		6954		6842		5919	
56	5803	5848	6653	6667	7240	7148	7565	7452	8174	8237	7803	7795
56	5856		6624		7031		7350		8079		7834	
56	5885		6723		7173		7442		8457		7749	
91	5900	6134	7025	7209	7179	7519	8086	8004	9012	9012	8504	8493
91	6315		7400		7835		8133		9016		8274	
91	6188		7201		7542		7792		9007		8701	

* After Accelerated Curing, Using Boiling Water Method
**Cylinders were green when tested.

Water Demand

Figures 4-4, 4-5 and 4-6 show the relationship between the amount of water and the percentage of fly ash replacement for the same workability corresponding to 3,000 psi, 4,000 psi and 5,000 psi nominal compressive strength concrete mixtures shown in Tables 4-2 through 4-4. For a given workability (slump 4" ± 1"), it can be seen that as the percentage of fly ash increases in the mixture, the water demand decreases (30).

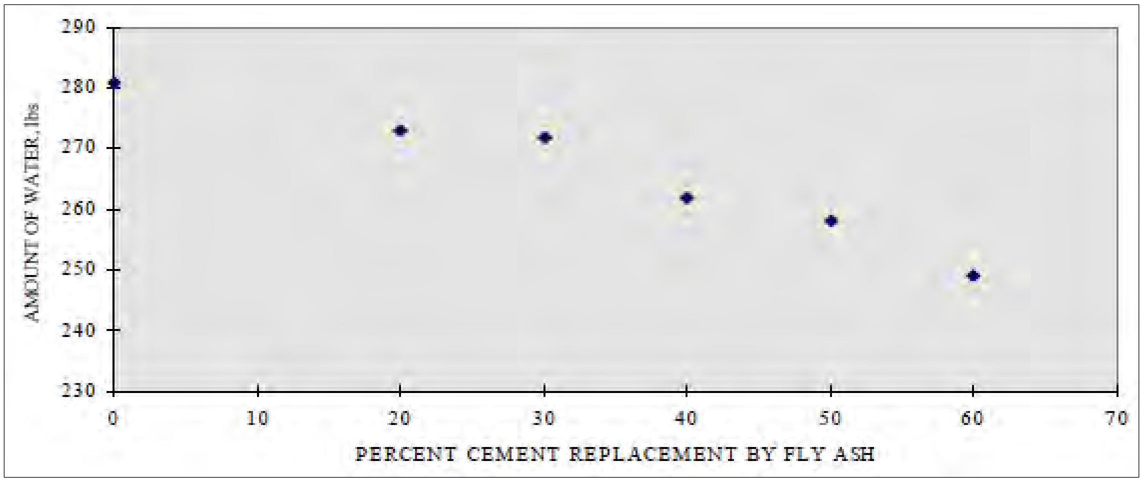


Figure 4-4: Relationship Between Water Demand and Cement Replacement by Fly Ash (3000 psi Concrete with the Same Workability)

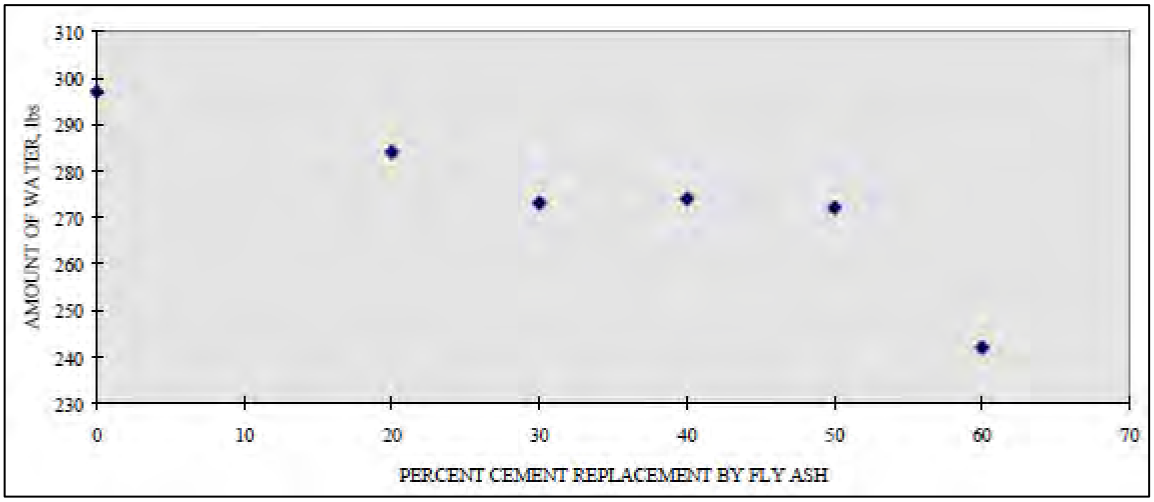


Figure 4-5: Relationship Between Water Demand and Cement Replacement by Fly Ash (4000 psi Concrete with the Same Workability)

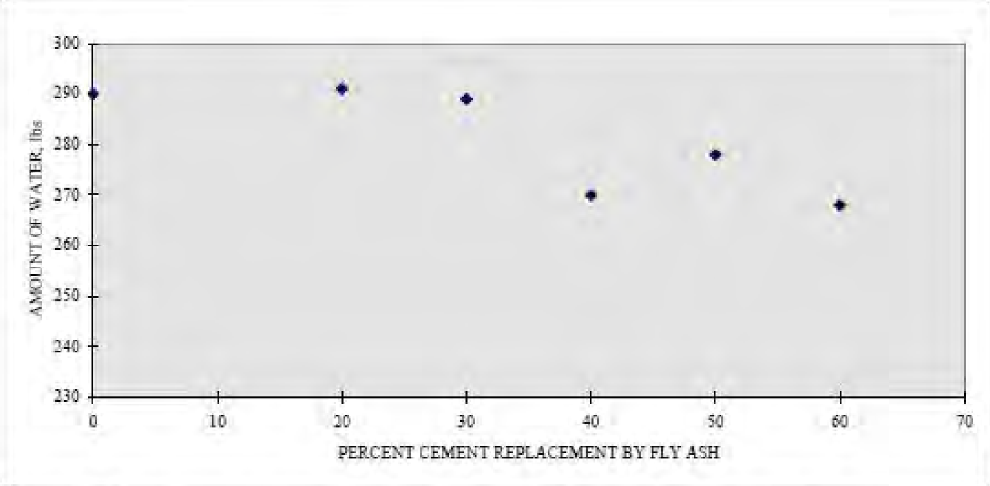


Figure 4–6: Relationship Between Water Demand and Cement Replacement by Fly Ash (5000 psi Concrete with the same Workability)

Figure 4-7 shows the relation between the water to cementitious material ratio and the percentage of cement replacement by fly ash for 3,000 psi; 4,000 psi and 5,000 psi concrete. The figure shows that as the percentage of cement replacement with fly ash increases the water to cementitious material ratio decreases. These results confirm that fly ash concrete requires less water when compared to a similar concrete mix without fly ash for a given slump. Less water equates to denser, less permeable concrete with higher durability.

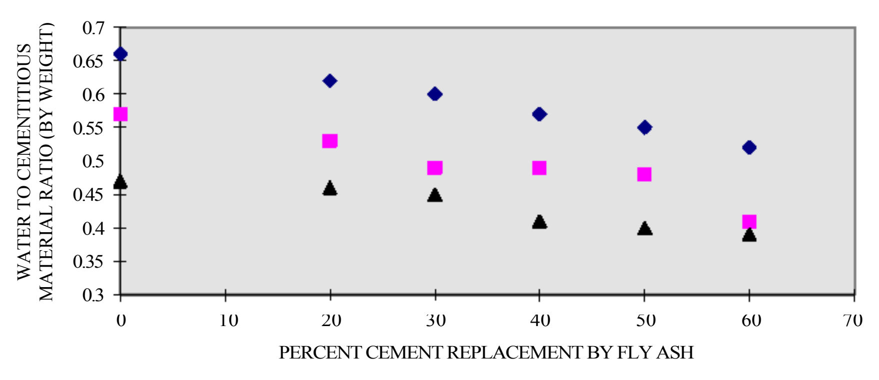


Figure 4–7: Relationship Between Water to Cementitious Ratio and Cement Replacement by Fly Ash (3000, 4000 and 5000 psi Concrete with the same Workability)

Workability

Slump is one measure of workability. Throughout the project, slump was measured and noted. Earlier researchers have reported that workability increases with the increase in fly ash content. This research confirms this same observation. Though the water to cementitious material ratio was reduced as the fly ash content increased, the same workability was obtained.

Time of Set, Modulus of Elasticity, Drying Shrinkage and Poisson's Ratio for We Energies ASTM C-618 Class C Fly Ash Concrete (Phase II Study)

As an extension of the project to determine the compressive strength of ASTM C-618, Class C fly ash concrete, it was decided to study the effects of Class C fly ash on time of set, modulus of elasticity, drying shrinkage and Poisson's ratio. Mixture proportions were developed for producing concrete on a 1.25 to 1 fly ash replacement for cement basis. The replacements were in the amounts of 35, 45 and 55%, on a weight basis. Basic w/c ratios of 0.45, 0.55 and 0.65 were proportioned for no fly ash concrete. Table 4-8 shows the mixture proportions with the actual w/c ratios for these fly ash concrete mixtures.

Time of Set

In order to determine the time of set, another set of mixtures were prepared. Table 4-8 shows the mixture proportions. P4-43, P4-24 and P4-25 are mixture designs with a 28-day compressive strength of 3,000 psi. Mixtures P4-44, P4-26 and P4-27 are designed for a 28-day compressive strength of 4,000 psi, and P4-45, P4-28 and P4-29 are designed for a 28-day compressive strength of 5,000 psi. Table 4-9 shows the initial and final setting time for fly ash concrete with cement replacement levels up to 55%. For 3,000 psi concrete, the initial set time increased about an hour for every 10% increase in fly ash.

However, the actual initial setting time of 8 hours ± one hour is essentially the same for the 35, 45 and 55% cement replacement levels. The final set time is seen to increase about 90 minutes for every 10% increase in fly ash content, when compared to the 35% fly ash mix. But the actual final setting time of 8½ to 11½ hours would not have any serious effect on a typical construction project.

Table 4-8: PPPP ASTM C-618 Class C Fly Ash Concrete Mix Data

NON-AIR-ENTRAINED CONCRETE

Mix No.	Total Cementitious Material, lbs/cy	Cement, lbs/cy	Fly Ash, lbs/cy	Water, lbs/cy	w/c *	Slump, in **	Air, %***
P4-43	457	278	179	267	0.584	3.3	1.0
P4-24	471	236	235	267	0.567	3.3	1.4
P4-25	478	193	285	255	0.533	6.3	0.7
P4-44	557	337	220	273	0.490	6.2	0.8
P4-26	574	285	289	266	0.463	3.7	1.3
P4-27	580	235	345	264	0.455	5.8	0.8
P4-45	656	398	258	266	0.405	4.0	0.8
P4-28	700	350	350	275	0.393	3.8	1.0
P4-29	675	275	400	266	0.394	5.0	0.7

AIR-ENTRAINED CONCRETE

Mix No.	Total Cementitious Material, lbs/cy	Cement, lbs/cy	Fly Ash, lbs/cy	Water, lbs/cy	Daravair, ml/cy	w/c *	Slump, in **	Air, %***
P4-46	537	316	221	254	193	0.473	3.2	6.0
P4-47	546	269	277	249	175	0.456	5.0	4.9
P4-38	555	222	333	240	194	0.432	3.6	5.6
P4-48	605	360	245	273	230	0.451	4.2	6.5
P4-39	616	305	311	265	216	0.430	4.7	5.6
P4-40	625	248	377	251	231	0.402	4.5	5.1
P4-49	751	464	287	295	248	0.393	4.5	6.1
P4-41	779	392	387	284	241	0.365	4.8	5.2
P4-42	797	320	477	264	255	0.331	3.8	4.6

* Based on total cementitious material

** Measured in accordance with ASTM Designation: C 143-78 Standard Test Method for Slump of Portland Cement Concrete

*** Measured in accordance with ASTM Designation: C 231-82 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

Table 4-9: Time of Setting*

NON-AIR-ENTRAINED CONCRETE				
Mix No.	Nominal 28-day Compressive Strength, psi	Nominal Percentage of Fly Ash	Time of Setting, HR:MIN	
			Initial	Final
P4-43	3,000	35	6:55	8:30
P4-24	3,000	45	7:45	9:55
P4-25	3,000	55	8:45	11:20
P4-44	4,000	35	7:35	9:25
P4-26	4,000	45	7:30	9:50
P4-27	4,000	55	7:55	10:25
P4-45	5,000	35	6:30	8:15
P4-28	5,000	45	7:15	9:25
P4-29	5,000	55	7:00	9:15

AIR-ENTRAINED CONCRETE				
Mix No.	Nominal 28-day Compressive Strength, psi	Nominal Percentage of Fly Ash	Time of Setting, HR:MIN	
			Initial	Final
P4-46	3,000	35	6:40	8:40
P4-47	3,000	45	8:15	10:25
P4-38	3,000	55	7:15	9:45
P4-48	4,000	35	7:30	9:45
P4-39	4,000	45	6:40	9:10
P4-40	4,000	55	6:55	9:30
P4-49	5,000	35	6:45	8:20
P4-41	5,000	45	7:30	9:40
P4-42	5,000	55	5:40	7:10

* Determined in accordance with ASTM Designation: C-403-85 Time of Setting of Concrete Mixtures by Penetration Resistance

The final setting time for 4000 psi and 5000 psi concrete showed a much less increase in time with increase in the fly ash content. The 5000 psi concrete with 55% fly ash content actually showed a decrease by 10 minutes for final setting time compared to 5000 psi concrete with 45% fly ash content.

The initial and final setting time for air-entrained concrete is also shown on Table 4-9. It can be seen from the results that the initial and final setting time for air-entrained fly ash concrete is not significantly different as the fly ash replacement is increased to levels of 55% for the 3,000; 4,000; and 5,000 psi concrete.

The final setting time for 5000 psi air-entrained concrete is actually less than that of 3000 psi and 4000 psi air-entrained concrete. The 3000 psi air-entrained concrete showed the maximum increase in setting time, when fly ash content is increased from 35% to 45%. But for the same strength concrete with 55% fly ash content, the setting time was lower than that of the mixture containing 45% fly ash. Hence, it is reasonable to believe that initial and final setting time is not significantly different for normal strength concrete with up to 55% replacement of cement with this source of Class C fly ash.

Modulus of Elasticity, Poisson's Ratio and Compressive Strength

Static modulus of elasticity, Poisson's ratio and compressive strength were determined for six different types of concrete. All six of the mixtures contained 45% replacement of cement with fly ash on a 1 to 1.25 ratio by weight. Mixtures P4-24, P4-26, and P4-28 were non-air-entrained concrete and mixes P4-47, P4-39, and P4-41 were air-entrained concrete mixtures. P4- 24, P4-26, and P4-28 were designed for 3,000 psi; 4,000 psi; and 5,000 psi compressive strength, respectively. Also, P4-47, P4-39 and P4-41 were designed for 3,000 psi; 4,000 psi; and 5,000 psi compressive strengths respectively.

Table 4-10: ASTM C-469 Test Results at 28 Days *
(Non-Air-Entrained Concrete)

Mix No.	Modulus of Elasticity psi x 10^6	Poisson's Ratio	Compressive Strength, psi
P4-24- A	**	**	6590
B	4.70	0.18	6380
C	4.75	0.18	6430
D	4.84	0.19	6730
Average	**4.76**	**0.18**	**6530**
P4-26- A	**	**	6290***
B	4.98	0.19	7530
C	5.11	0.19	7600
D	5.05	0.18	7680
Average	**5.05**	**0.19**	**7600**
P4-28- A	**	**	8850
B	4.97	0.18	8900
C	4.85	0.19	8880
D	4.86	0.19	9130
Average	**4.89**	**0.19**	**8940**

* Tested in accordance with ASTM Designation: C-469-83 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

** Determined to establish level of loading for modulus of elasticity determination.

*** Bad shear break-omitted from average.

Table 4-11: ASTM C-469 Test Results at 28 Days * (Air-Entrained Concrete)

Mix No.	Modulus of Elasticity psi x 10 ^{6}	Poisson's Ratio	Compressive Strength, psi
P4-47- A	**	**	6210
B	4.19	0.17	6420
C	4.25	0.16	6520
D	4.23	0.16	6160
Average	**4.23**	**0.16**	**6160**
P4-39- A	**	**	6100
B	4.17	0.17	6240
C	4.15	0.16	6110
D	4.15	0.16	6110
Average	**4.17**	**0.17**	**6150**
P4-41- A	**	**	7180
B	4.37	0.21	7090
C	4.43	0.17	7370
D	4.37	0.18	7350
Average	**4.39**	**0.19**	**7250**

*Tested in accordance with ASTM Designation: C-469-83 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

**Determined to establish level of loading for modulus of elasticity determination.

As can be seen from Tables 4-10 and 4-11, the compressive strengths obtained were much higher than the design strength. In accordance with the ACI 318 Building Code, the static modulus of elasticity is equal to 57,000 √f'c. The values of modulus of elasticity shown in Table 4-10 for non-air-entrained and Table 4-11 for air-entrained fly ash concrete follow nearly the same well-established relationship between compressive strength and the static modulus of elasticity. A detailed discussion of the results can be obtained in reference 31.

The static Poisson's ratios obtained for these mixtures (both non-air-entrained and air-entrained) fall within the accepted limits for concrete of 0.15 to 0.20, with higher strength concrete showing a higher value.

Length Change: Drying Shrinkage in Air and Expansion in Water

The test results for both air-entrained and non-air-entrained concrete with 45% replacement of cement with fly ash are shown on Table 4-12. The data from all of these mixtures fell between 0.014 and 0.046 for non-air-entrained mixtures and between 0.02 and 0.044 for the air-entrained mixtures.

The test results for expansion in water fell between 0.002 and 0.01 for non-air-entrained concrete and between 0.003 and 0.015 for air-entrained concrete.

Table 4-12: Length Change*

NON-AIR-ENTRAINED CONCRETE

Mix No.	Expansion in Water, % 28 days	Shrinkage in Air (73°F, 50% RH), %			
		4 days	7 days	14 days	28 days
P4-24 A	0.009	0.015	0.026	0.031	0.039
B	0.009	0.015	0.023	0.031	0.036
C	0.010	0.014	0.024	0.029	0.037
Average	0.009	0.015	0.024	0.030	0.037
P4-26 A	0.003	0.023	0.033	0.038	0.046
B	0.007	0.018	0.030	0.035	0.041
C	0.002	0.021	0.030	0.032	0.039
Average	0.004	0.021	0.031	0.035	0.042
P4-28 A	0.006	**	0.030	0.036	0.043
B	0.009	**	0.027	0.035	0.040
C	0.009	**	0.028	0.034	0.042
Average	0.008		0.028	0.035	0.042

AIR-ENTRAINED CONCRETE

Mix No.	Expansion in Water, % 28 days	Shrinkage in Air (73°F, 50% RH), %			
		4 days	7 days	14 days	28 days
P4-47 A	0.004	0.022	0.030	0.039	0.045
B	0.003	0.023	0.030	0.040	0.045
C	0.006	0.019	0.027	0.040	0.041
Average	0.004	0.021	0.029	0.038	0.044
P4-39 A	0.0200	0.005	0.014	0.023	0.027
B	0.020	0.003	0.013	0.021	0.028
C	0.017	0.007	0.014	0.023	0.026
Average	0.019	0.005	0.014	0.022	0.027
P4-41 A	0.016	0.006	0.014	0.022	0.028
B	0.019	0.009	0.018	0.026	0.032
C	0.015	0.002	0.012	0.018	0.024
Average	0.017	0.006	0.015	0.022	0.028

* Measured in accordance with ASTM Designation: C-157-80 Standard Test Method for Length Change of Hardened Cement Mortar and Concrete.

** Not measured.

Freezing and Thawing Durability

Freezing and thawing tests were performed on two 4,000 psi, 28-day compressive strength concrete mixtures with 45% fly ash replacement for cement. Mix P4-26 was non-air-entrained, and mix P4-39 was air-entrained. Tables 4-13 and 4-14 give the freeze-thaw test results for non-air-entrained concrete and air-entrained concrete, respectively. ASTM Test Designation C666-84, Procedure A, was followed. Non-air-entrained concrete failed after a low number of cycles of rapid freezing and thawing as expected. However, air-entrained concrete didn't indicate failure even after 300 cycles of freezing and thawing.

These test results demonstrate that properly air-entrained fly ash concrete with 45% of cement replacement with this source of Class C fly ash exhibits a high durability against freezing and thawing.

Table 4-13: Freeze-Thaw Tests* - Non-Air-Entrained Concrete

Mix No.	Percent Expansion at 25 Freeze-Thaw Cycles	Percent Expansion at 44 Freeze-Thaw Cycles
P4-26 A	0.189	0.293
B	0.180	0.258
C	0.130	0.189
Average	0.166	0.247
Mix No.	Percent Weight Change at	
	25 Freeze-Thaw Cycles	44 Freeze-Thaw Cycles
P4-26 A	+0.2	+0.4
B	+0.2	+0.3
C	+0.1	+0.2
Average	+0.2	+0.3
Mix No.	Relative Dynamic Modulus of Elasticity at	
	25 Freeze-Thaw Cycles, %	44 Freeze-Thaw Cycles, %
P4-26 A	61	45
B	71	58
C	78	45
Average	70	49
Mix No.	Durability Factor	
P4-26 A	5	
B	9	
C	10	
Average	8	

* Tested in accordance with ASTM Designation C-666-84 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A).

Table 4-14: Freeze-Thaw Tests* (Air-Entrained Concrete)

	Percent Expansion at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	0.004	0.011	0.022	0.030	0.041	0.057	0.062	0.078
B	0.004	0.012	0.021	0.024	0.028	0.041	0.047	0.053
C	0.008	0.011	0.024	0.036	0.050	0.059	0.065	0.075
Average	0.005	0.011	0.022	0.030	0.040	0.052	0.058	0.068

	Percent Weight Loss at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	0.0	0.2	0.8	1.3	1.9	2.6	3.0	3.4
B	0.0	0.6	0.6	0.9	1.4	1.8	2.2	2.6
C	0.0	0.1	0.2	0.6	1.2	1.7	2.3	3.0
Average	0.0	0.3	0.5	0.9	1.5	2.0	2.5	3.0

	Relative Dynamic Modulus of Elasticity at Freeze-Thaw Cycle Indicated							
Mix No.	40	75	106	141	195	238	267	300
P4-39 A	99	98	98	97	95	90	86	83
B	99	99	99	98	98	98	95	92
C	99	99	99	98	98	98	97	96
Average	99	99	99	98	97	95	93	90

Mix No.	Durability Factor
P4-39 A	83
B	92
C	96
Average	90

* Tested in accordance with ASTM Designation C-666-84 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Procedure A).

Phase II Test Result Conclusions

The following are the major results of this study:

1. For both air-entrained and non-air-entrained concrete, the initial and final setting time is not significantly different for normal strength concrete with up to 55% replacement of cement with fly ash.
2. For non-air-entrained and air-entrained fly ash concrete, with fly ash replacement of up to 45% and compressive strength in the range of 3,000 to 5,000 psi, the static modulus of elasticity is in conformance with established relationships to compressive strength.
3. Poisson's ratio of these fly ash concretes is within the accepted limits for concrete.
4. Properly air-entrained high-volume fly ash concrete exhibits good resistance to freezing and thawing.

Abrasion Resistance of Concrete Containing We Energies ASTM C-618, Class C Fly Ash

Abrasion is a common form of wear observed in pavements due to friction forces applied by moving vehicles. Abrasion wear can also occur due to rubbing, scraping, skidding or sliding of other objects on the pavement/concrete surface.

Resistance of concrete surfaces to abrasion is influenced by several factors including concrete strength, aggregate properties, surface finishing and type of toppings. Previous studies have reported that the abrasion resistance of a concrete surface is primarily dependent on the compressive strength of concrete.

Typically, higher compressive strength concrete has better resistance to abrasion provided that the concrete has properly cured hard surface material consisting of aggregate and paste having low porosity and high strength which all contribute to the abrasive resistance of concrete.

Abrasion Test Sample Preparation

ASTM C-618, Class C fly ash from Pleasant Prairie Power Plant of We Energies was used in this study. Fine and coarse aggregate used in this project met ASTM C-33 gradation requirements.

The Portland cement was Lafarge Type 1, meeting requirements of ASTM C-150. Commercially available Catexol AE 260, air-entraining agent and a Daracem^{TM} 100 superplastisizer were also used.

Mixture proportions are shown on Table 4-15. Of the 11 mixtures produced, three were control mixtures and the other eight mixtures contained ASTM C-618, Class C fly ash. Mixture proportions containing fly ash replacement for cement on a 1.25 to 1 basis in the range of 15% to 75% by weight were established. The water to cementitious materials ratio was maintained at 0.35 ± 0.02 and air content was kept at 6% ± 1% for the primary mixtures. The mixtures that didn't meet the above requirements were classified as secondary mixtures and these were not used for detailed analysis of test results.

Slab specimens for abrasion resistance were prepared according to ASTM C-31 procedures. Fresh concrete properties are reported in Table 4-15. Compressive strength test results are shown in Table 4-16.

Abrasion resistance tests were performed at 28 and 91 days after moist curing of the slab specimens. Abrasion tests were conducted on the specimens using ASTM C-944 test methods. The ASTM C-944 test produced a depth of abrasion of about one mm (0.04”) after about 60 minutes of exposure to the abrasive force. This method was too slow. An accelerated method was developed as an alternative. Details of the method can be obtained from reference 32.

Table 4-15: Mixture Proportions Using Pleasant Prairie Power Plant - Class C Fly Ash, 6000 PSI (41.8 MPa) Specified Strength*

Mix. No.	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Specified design strength (psi)	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
Cement (lb/yd^3)	675	671	661	568	445	378	305	177	556	305	180
Fly Ash (lb/yd^3)	0	0	0	125	239	313	378	514	123	383	519
Water (lb/yd^3)	208	210	237	240	245	259	249	257	225	230	258
Water-to-cementitious ratio	0.31	0.32	0.36	0.35	0.36	0.37	0.36	0.37	0.33	0.33	0.37
Sand, SSD (lb/yd^3)	1212	1205	1207	1208	1158	1175	1153	1112	1190	1111	1084
1 in. aggregates, SSD (lb/yd^3)	2134	2113	2083	2092	2036	1998	1914	1861	2059	1933	1878
Slump (in.)	1	1¾	4¾	2½	6¼	4¾	2¼	3	5¾	4½	4¾
Air content (%)	2.6	2.4	6.3	4.1	5.1	6.4	8.5	3.7	6.7	7	6.4
HRWR[1] (liq oz/ yd^3)	71.0	70.0	74.6	75	73	71.0	68.0	67.6	73.5	68.8	67.0
AEA[2] (liq oz/ yd^3)	7.2	9.0	7.0	7.8	9.0	13.3	21.0	23.4	10.8	22.9	35.7
Air Temperature (°F)	68	68	70	70	70	70	78	79	--	--	--
Concrete Temperature (°F)	69	68	73	73	73	78	78	79	70	78	77
Fresh Concrete Density (lb/ft^3)	156.0	156.0	148.6	152.7	149.4	147.3	140.3	145.8	149.8	145.9	147.6
Hardened Concrete density, SSD (lb/ft^3)	156.9	156.8	154.2	156.8	151.8	150.8	142.4	143.5	152.3	146.2	145.2

Notes:

[1] High Range Water Reducer (HRWR);

[2] Air-Entraining Agent

* Subdesignation P indicates primary mixes for this research project and S indicates secondary (duplicate) mixes. Main conclusions are shown with the data from the primary mixes only.

Abrasion Test Results and Discussion

The compressive strengths were measured at ages 1, 3, 7, 28 and 91 days, and are shown in Table 4-16. At early ages, fly ash concrete exhibited lower compressive strength compared to the control mix. At the 28-day age, 30% fly ash concrete showed peak compressive strength.

Beyond 30% cement replacement, the compressive strength decreased with an increase in fly ash content. The compressive strength of concrete also decreased with increasing air content. This is expected and has been reported by earlier researchers.

Abrasion tests were performed at ages of 28 and 91 days. Abrasion measurement using the modified method is a relative indicator of abrasion and is reported in Tables 4-17 and 4-18. Abrasion wear decreased with an increase in specimen age and resulting increased strength.

Concrete mixtures of up to 30% cement replacement by fly ash had abrasion resistance similar to that for concrete produced without fly ash. Beyond 30% cement replacement, abrasion resistance decreased. It can also be said that with the decrease in compressive strength, abrasion resistance decreased (abrasion wear increased).

The above work leads to the following key conclusions:

1. Concrete containing up to 30% cement replacement by fly ash exhibited similar or better compressive strength when compared to concrete produced without fly ash, at ages of three days and beyond (See Figure 4-8).
2. Compressive strength is the key factor affecting abrasion resistance. Stronger concrete mixtures exhibited higher resistance to abrasion (See Figure 4-9).
3. Effect of air content on abrasion resistance of concrete was insignificant within the tested range.

Table 4-16: Compressive Strength Test Data

Mix No.	C-1 (S)		C-2 (S)		C-3 (P)		P4-1 (S)		P4-2 (P)		P4-3 (P)		P4-4 (S)		P4-5 (S)		P4-6 (P)		P4-7 (P)		P4-8 (P)	
Specified Strength, psi	6000		6000		6000		6000		6000		6000		6000		6000		6000		6000		6000	
Percent fly ash	0		0		0		15		30		40		50		70		15		50		70	
	Compressive Strength, PSI																					
Test Age, Days	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg	Act	Avg
1 1 1	5380 5130 5095	5200	5150 515 5450	5240	3870 3965 4030	3955	4050 3970 4030	4015	1875 1910 1560	1780	1110 1175 1090	1125	385 300 335	400	- - -	*	2480 2370 2420	2425	- - -	*	- - -	*
3 3 3	6330 6580 6410	6440	5955 5980 5935	5955	4530 4860 4355	4925	5090 4925 5290	5100	3855 4075 4210	4045	2610 2720 2590	2640	1415 1505 1485	1490	- 60 50	55	4300 4270 4155	4240	1495 1550 1920	1655	- - -	*
7 7 7	6935 6950 6770	6885	6540 6750 6755	6680	5180 4905 5100	5160	6245 6270 6120	6210	5315 5340 5210	5290	3560 3450 3580	3530	2245 2240 2150	2240	65 60 70	65	5070 5250 5255	5195	2540 2410 2545	2465	85* 130** 90**	100**
28 28 28	7915 7620 7605	7715	7760 7985 7875	7870	6405 6065 6375	6280	6885 7105 7665	7220	7050 6605 6965	6875	5290 5545 4760	5200	3265 3125 3110	3170	2305 2265 2530	2365	6875 6820 6550	6750	4630 4440 4775	4615	3015 2785 1800	2535
91 91 91	9215 9140 9340	9230	870 8940 8755	8800	7000 6965 6770	6910	8145 8290 8220	8220	7920 8225 8074	8075	5555 6020 6585	6055	4295 4305 4125	4240	3880 4415 4440	4245	8655 7525 7455	7880	5785 5550 5970	5765	5360 5040 3885	4760

+ S = Secondary mixes, P = Primary mixes   *These readings could not be recorded because the specimens were soft. **Tested at 11 days.

Table 4-17: Abrasion Resistance Test Results at 28-Day Age

Mix No.*	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (P)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Percent, Fly Ash	0	0	0	15	30	40	50	70	15	50	70
Time (m)	Depth of Wear, mm										
5	0.11	0.10	0.23	0.14	0.14	0.18	0.34	0.44	0.18	0.23	0.30
10	0.26	0.26	0.46	0.36	0.34	0.49	0.57	1.00	0.32	0.63	0.68
15	0.64	0.41	0.69	0.52	0.50	0.78	0.90	1.38	0.54	0.92	1.29
20	1.04	0.63	0.82	0.70	0.66	1.00	1.09	1.71	0.64	1.11	1.40
25	1.17	0.75	1.01	0.92	0.85	1.27	1.38	1.90	0.90	1.27	1.89
30	1.45	0.88	1.11	1.08	1.02	1.58	1.63	2.34	1.03	1.49	2.00
35	1.65	1.04	1.28	1.24	1.18	1.77	1.86	2.63	1.18	1.58	2.35
40	1.88	1.21	1.39	1.39	1.33	2.01	2.04	2.94	1.33	2.16	2.81
45	1.99	1.33	1.57	1.62	1.50	2.18	2.22	--	1.49	2.34	3.04
50	2.17	1.50	1.75	1.78	1.74	2.28	2.44	--	1.65	2.56	--
55	2.28	1.67	1.89	1.96	1.88	2.45	2.62	--	1.80	2.72	--
60	2.42	1.85	2.06	2.16	2.05	2.56	2.76	3.68	1.95	2.85	3.55

* P = Primary mixes, S = Secondary mixes

Table 4-18: Abrasion Resistance Test Results at 91-Day Age

Mix No. *	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Percent, Fly Ash	0	0	0	15	30	40	50	70	15	50	70
Time (m)	Depth of Wear, mm										
10	0.23	0.23	0.29	0.26	0.17	0.29	0.46	0.48	0.27	0.57	0.61
15	0.43	0.45	0.49	0.41	0.35	0.54	0.74	0.74	0.53	0.88	0.96
20	0.55	0.62	0.75	0.62	0.53	0.78	0.96	0.90	0.64	1.10	1.25
25	0.72	0.75	0.96	0.79	0.76	1.01	1.18	1.15	0.82	1.50	1.51
30	0.74	0.90	1.10	0.94	0.90	1.18	1.37	1.39	0.99	1.65	1.68
35	1.13	1.03	1.24	1.11	1.04	1.29	1.55	1.64	1.10	1.77	1.89
40	1.27	1.12	1.39	1.27	1.18	1.50	1.74	1.85	1.26	2.01	2.03
45	1.37	1.27	1.46	1.44	1.31	1.71	1.92	2.04	1.39	2.16	2.16
50	1.50	1.41	1.58	1.53	1.48	1.85	2.04	2.24	1.50	2.27	2.32
55	1.64	1.50	1.68	1.65	1.64	1.97	2.21	2.38	1.59	2.33	2.47
60	1.80	1.63	1.77	1.75	1.70	2.08	2.34	2.54	1.71	2.41	2.59

* P = Primary mixes, S = Secondary mixes

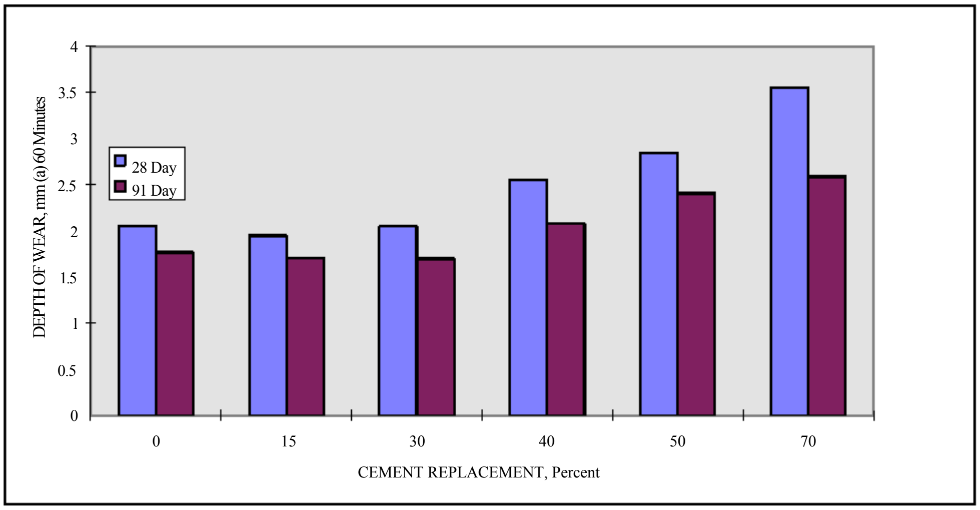


Figure 4–8: Abrasion Resistance vs. Cement Replacement with Class C Fly Ash

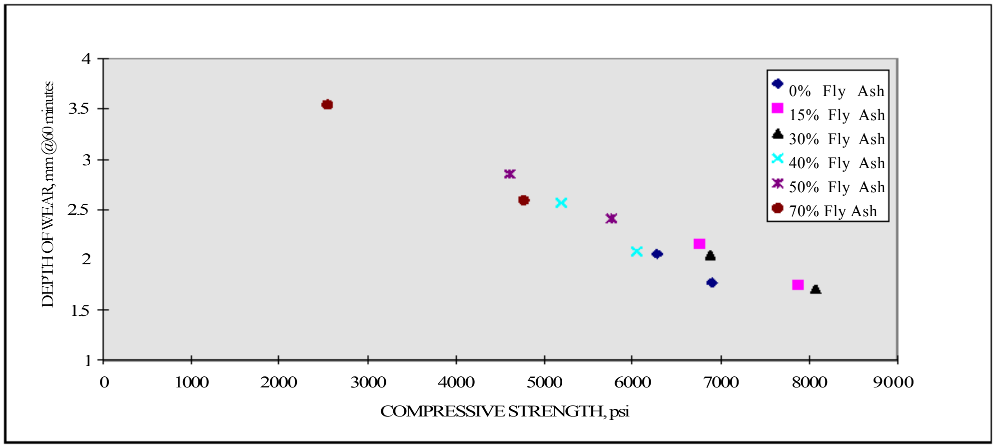


Figure 4–9: Abrasion Resistance vs. Compressive Strength of Concretes Containing Different Percentages of Fly Ash

Chloride Ion Permeability of High Strength We Energies Fly Ash Concrete Containing Low Cement Factor

Permeability of concrete is a very important factor affecting its durability. A decrease in permeability of concrete increases the resistance to the ingress of aggressive agents, which in turn, would lead to improved concrete durability.

The following discussion is based on a study conducted at the Center for By-Products Utilization at the University of Wisconsin in Milwaukee for We Energies. Several concrete mixes were designed with and without fly ash. The control mixture was designed for a 28-day compressive strength of 5800 psi without any fly ash. However, other mixtures were designed with various percentages of fly ash as a partial replacement of cement. ASTM C-618, Class C fly ash from Pleasant Prairie Power Plant was used in these tests.

Table 4-19 shows the mixture proportions for the various mixtures, including fresh concrete properties. For this study, the water-to-cementitious materials ratio and air content for the primary mixtures were maintained at about 0.35 ± 0.02 and 6% ± 1%, respectively. The mixtures that did not meet these target parameters were called secondary mixes. The primary mixtures were used to make major conclusions, while the secondary mixes were used to study the effect of air content on concrete strength and permeability (33).

The concrete mixing procedure was performed according to ASTM C-192 procedures, and specimens were also cast in accordance with ASTM C-192 “Making and Curing Concrete Test Specimens in the Laboratory” procedures.

Compressive Strength Test Results

Compressive strength tests were measured per ASTM C-39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” procedures. Air and water permeability was measured in accordance with the Figg Method. Chloride ion permeability was measured according to ASTM C-1202 “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Permeability”.

Compressive strength results are shown in Table 4-20 and on Figures 4-10 and 4-11. Fly ash with up to 35% cement replacement and replaced on a 1.25 fly ash per 1.00 cement weight ratio, showed results similar to the reference concrete at a 3-day age. Beyond 30% cement replacement, the mixtures exhibited lower compressive strength when compared to the reference mixture. At the 28-day age the concrete showed strength levels comparable to the control mixture.

Table 4-19: Mixture Proportions Using ASTM Class C Fly Ash 5800 PSI Specified Strength

Parameter	Mixture No. *										
	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
Cement (lb/cu. yd)	671	669	632	553	437	371	293	180	539	302	185
Fly ash (lb/cu. yd)	0	0	0	121	234	307	364	523	120	381	533
Water (lb/cu. yd)	207	211	228	234	224	253	238	258	217	229	261
[W (C + FA)]	0.31	0.31	0.36	0.35	0.33	0.37	0.36	0.37	0.33	0.34	0.36
Sand, SSD (lb/cu. yd)	1205	1200	1150	1171	1141	1111	1052	1074	1168	1104	1023
25 mm aggregates, SSD (lb/cu/yd)	2122	2130	1992	2034	1975	1943	1852	1901	1989	1920	1930
Slump (inches)	1.0	1.8	4.7	2.6	6.3	4.7	2.2	3.0	5.7	4.5	4.7
Air content (%)	2.6	2.4	6.3	4.1	5.2	6.4	8.5	3.7	6.7	7	6.4
Superplasticizer, (US fl oz/ cu. yd)	69.9	69.9	75.1	69.9	72.5	69.9	67.3	67.3	72.5	69.9	67.3
Air entraining agent (US fl oz/ cu. yd)	7.3	8.5	7.0	7.8	9.1	13.3	21.0	23.4	10.9	22.9	35.7
Air temperature (°F)	68	68	70	70	70	70	79	79	-	-	-
Concrete temperature (°F)	68	68	73	73	73	79	79	79	70	79	77
Fresh concrete density (lb/cu. yd)	4210	4210	4010	4120	4040	3980	3790	3940	4040	3940	3990
Hardened concrete density, SSD (lb/cu. yd)	4240	4230	4160	4230	4100	4070	3840	3880	4110	3950	3920

*Subdesignation (P) indicates primary mixtures and (S) indicates secondary (duplicate) mixtures. Main conclusions are drawn based on the data obtained from primary mixtures. Secondary mixtures are used for analysis of effect of air content variations.

Table 4-20: Compressive Strength Test Results

Test Age (days)	Mixture No. *										
	C-1 (S)	C-2 (S)	C-3 (P)	P4-1 (S)	P4-2 (P)	P4-3 (P)	P4-4 (S)	P4-5 (S)	P4-6 (P)	P4-7 (P)	P4-8 (P)
	(a) Fly Ash (percent) -- % of Total Cementitious Materials FA/(Cement + FA)										
	0	0	0	18	18	35	45	55	55	74	74
	(b) Compressive Strength (PSI) – Average of Three Test Observations										
1	5210	5240	3960	4020	2420	1780	1130	410	-	-	-
3	6440	5960	4580	5100	4230	4050	2640	1490	1650	60	-
7	6890	6690	5160	6200	5190	5290	3520	2230	2460	60	100
28	7710	7870	6280	7220	6740	6870	5200	3170	4610	2360	2540
91	9220	8800	6900	8220	7870	8080	6050	4230	5770	4250	4760
365	11480	11340	8480	10190	9090	10250	7240	4840	5650	5290	5920

*P and S refer to primary and secondary mixtures, respectively.

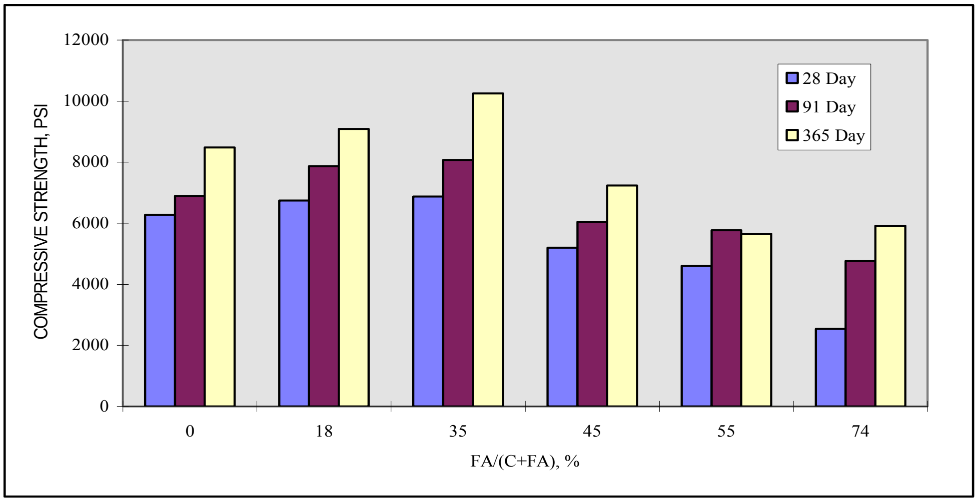


Figure 4–10: Compressive Strength of Concrete made with and without Fly Ash for Primary Mixtures

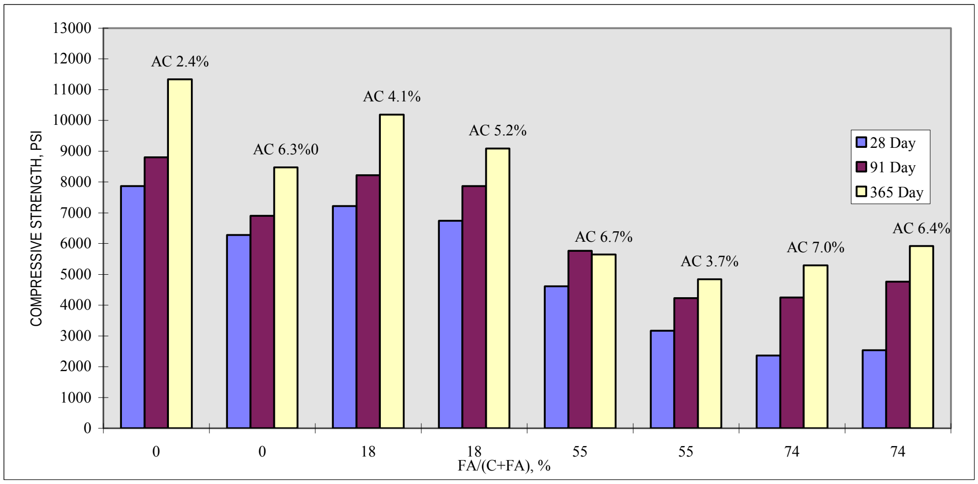


Figure 4–11: Compressive Strength of Concrete made with and without Fly Ash having Different Percentage of Air Content

Permeability Test Results

Concrete air and water permeabilities were measured at an age of 14, 28 and 91 days. Also, the chloride ion permeability was determined at 2 months, 3 months and 1 year. Air, water and chloride permeability values decreased with age, as expected, due to the improvement in concrete microstructure.

Air permeability test results are given in Table 4-21 and shown on Figures 4-12 and 4-13. At the 14-day age, concrete without fly ash and 18% fly ash concrete were rated "good" and mixtures with higher fly ash contents were rated "fair." At the 28-day age, the reference mixture and mixtures with up to 45% fly ash were rated "good." At the 91 day age, 55% fly ash mixtures showed the maximum resistance to air permeability. Figure 4-13 shows the effect of air content on the concrete's resistance to air permeability. No specific relationship is seen between air permeability and air content for concretes with and without fly ash.

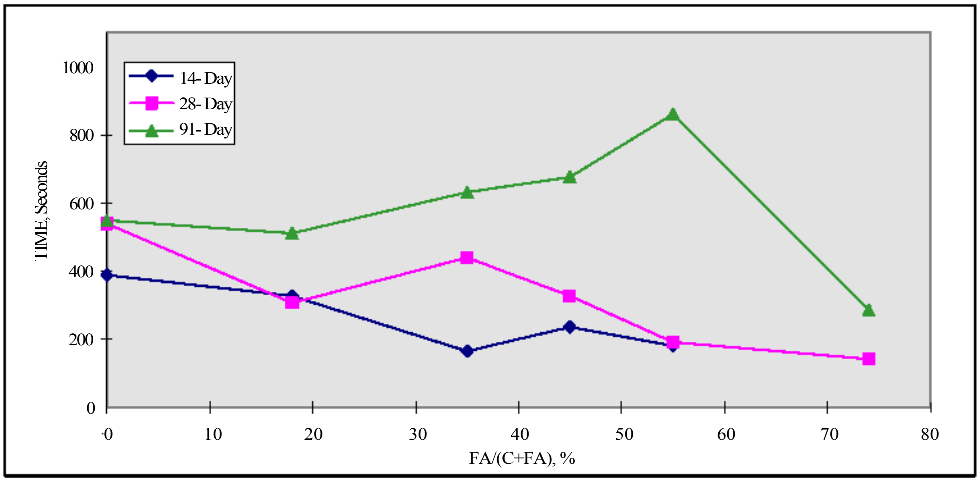


Figure 4–12: Air Permeability (Time) vs. Fly Ash Content for Primary Mixtures

Table 4-21: Air Permeability Test Results

Mixture No. *	Fly Ash ** (%)	Average Time*** (Seconds)		
		14-day	28-day	91-day
C-1 (S)	0	543	465	830
C-2(S)	0	352	433	532
C-3(P)	0	389	539	549
P4-1(S)	18	295	558	528
P4-6(P)	18	327	307	511
P4-2(P)	35	165	440	632
P4-3(P)	45	236	328	676
P4-4(S)	55	241	173	585
P4-7(P)	55	181	192	861
P4-5(S)	74	---	170	235
P4-8(P)	74	---	142	286

The following classification for the air permeability of concrete is used (Cather et al. 1984)

Time in Seconds for Pressure Change	Interpretation
<30	Poor
30 - 100	Moderate
100 - 300	Fair
300 - 1,000	Good
> 1,000	Excellent

* P = Primary; S= Secondary

** As a percentage of total cementitious materials, FA/(Cement + FA).

***Test data are average of five test observations.

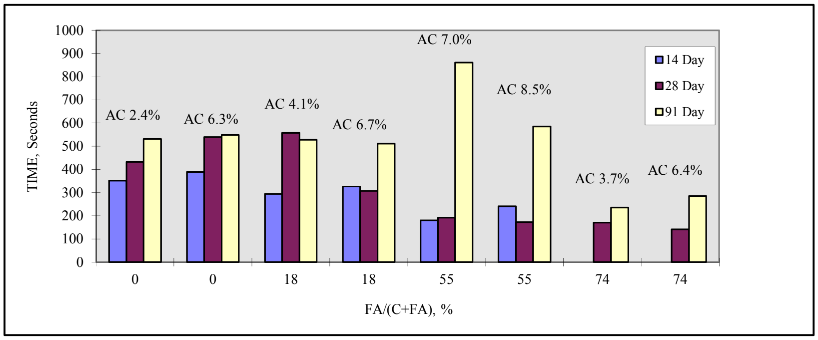


Figure 4–13: Air Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Water permeability decreased as the age of concrete specimens increased, as shown on Figures 4-14 and 4-15 and on Table 4-22. At the 14-day age, concrete resistance to water permeability was improved for mixes with up to 35% fly ash when compared to the reference mixture without fly ash. The 18% to 45% fly ash mixtures were rated as "good."

At 91 days, concrete mixtures with fly ash to total cementitious materials ratio of 35% to 55% were rated as "excellent." All other mixtures were only rated "good." In these mixtures, due to pozzolanic action, the grain structure showed substantial improvement. Water permeability showed no major variations when compared to variations in air content for all concrete with and without fly ash.

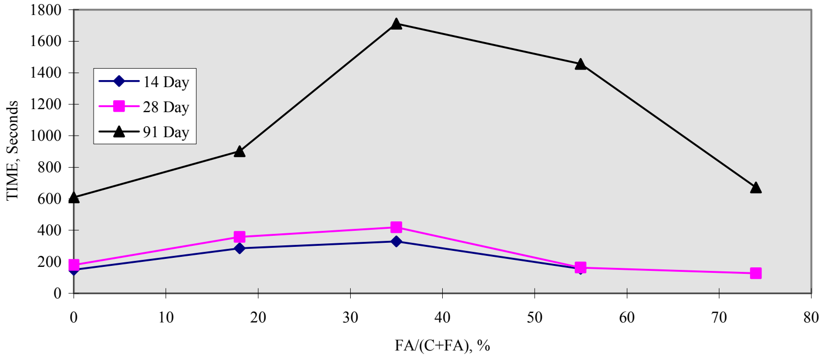


Figure 4–14: Water Permeability (Time) vs. Fly Ash Content for Primary Mixtures

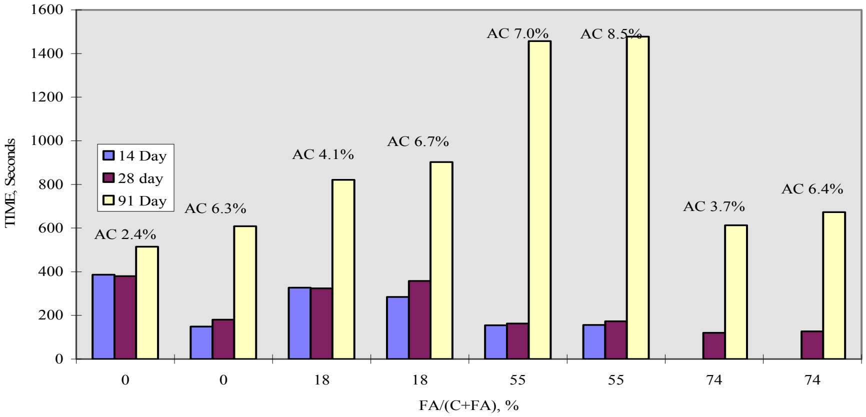


Figure 4–15: Water Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Table 4-22: Water Permeability Test Results

Mixture No. *	Fly Ash** (%)	Average Time *** (Seconds)		
		14-day	**28-day**	**91-day**
C-1 (S)	0	294	392	614
C-2(S)	0	386	372	515
C-3(P)	0	149	180	609
P4-1(S)	18	327	324	821
P4-6(P)	18	285	358d	902
P4-2(P)	35	330	418	1,713
P4-3(P)	45	201	241	1,365
P4-4(S)	55	156	173	1,477
P4-7(P)	55	155	163[a]	1,457
P4-5(S)	74	--	120	613
P4-8(P)	74	--	127[a]	673

Time in Seconds for Absorption[b]	Protective Quality[b]
<40	Poor
40 - 100	Moderate
100 - 200	Fair
200 - 1000	Good
> 1,000	Excellent

* P = Primary; S = Secondary

** As a percentage of total cementitious materials, FA/(Cement + FA)

*** Test data are average of five test observations

[a] Test was performed at 40 days

[b] Classification based on Arup Research & Development

The chloride ion permeability of the concrete mixtures is shown in Table 4-23 and Figures 4-16 and 4-17. At the age of 2 months, the high-volume fly ash mixtures showed lower chloride ion permeability when compared to the reference mixture without fly ash, except for the 74% fly ash to total cementitious materials ratio concrete. The permeability in this case was in the range of 2,000 to 4,000 coulombs (rated “moderate”) per ASTM C-1202 criteria. With additional time, the resistance to chloride ion permeability of these mixtures showed substantial improvement.

At the age of one year, all the fly ash concrete mixtures attained a “very low” (100 to 1,000 coulombs) level of chloride ion permeability in accordance with ASTM C-1202 criteria where the reference mixtures exhibited a “low” (1,000 to 2,000 coulombs) level of chloride permeability.

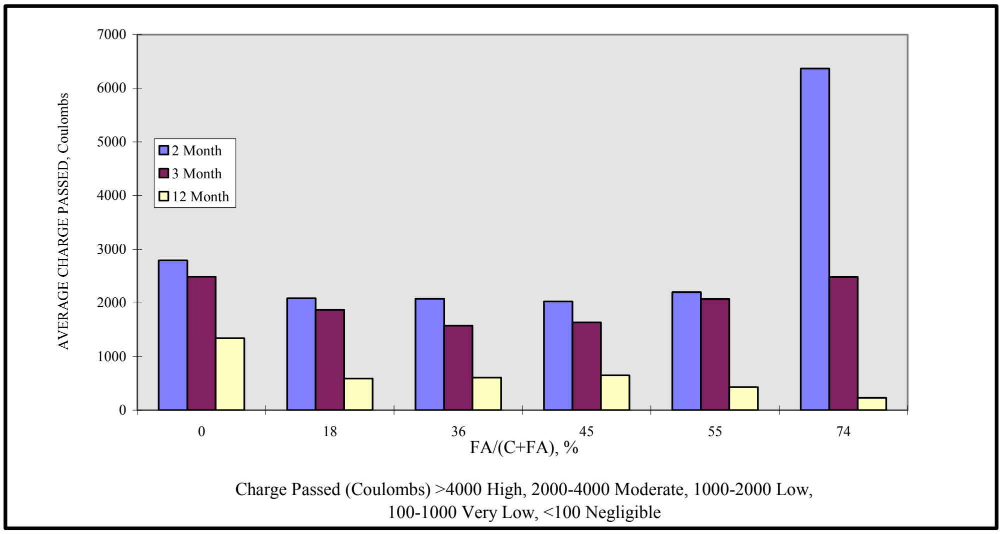


Figure 4–16: Chloride Permeability vs. Fly Ash Content for Primary Mixtures

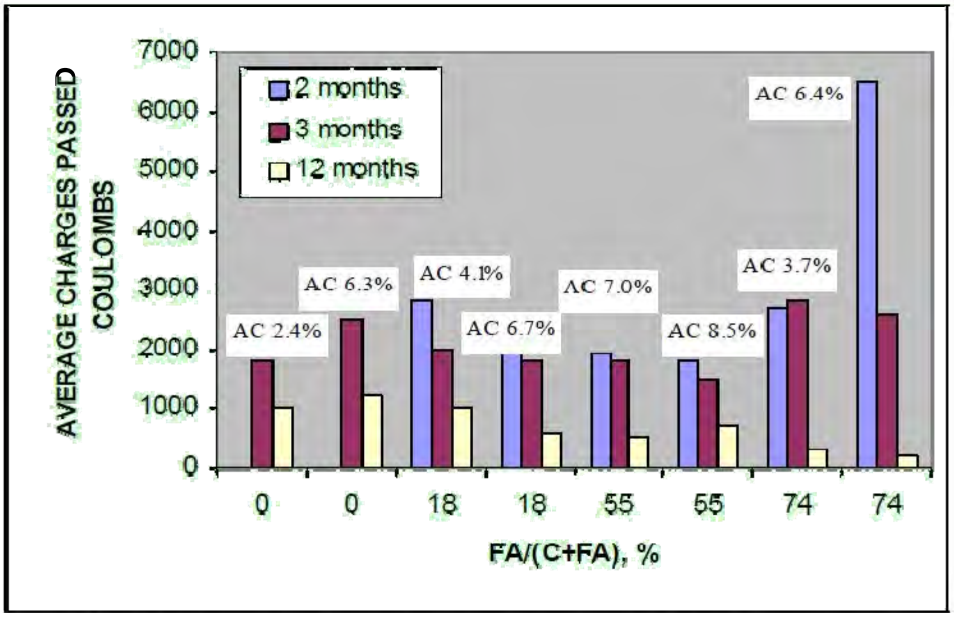


Figure 4-17: Chloride Ion Permeability of Concrete with and without Fly Ash having Different Percentages of Air Content

Table 4-23: Chloride Ion Permeability Test Results

Mixture No. *	Fly Ash** (%)	Average Charge Passed*** (Coulombs)		
		2-month	3-month	1-year
C-1 (S)	0	--	2,128	1,170
C-2(S)	0	--	1,729	1,085
C-3(P)	0	2,792	2,488	1,340
P4-1(S)	18	2,782	1,907	985
P4-6(P)	18	2,084	1,873	590
P4-2(P)	36	2,077	1,576	605
P4-3(P)	45	2,026	1,638	650
P4-4(S)	55	2,041	1,620	650
P4-7(P)	55	2,200	2,075	430
P4-5(S)	74	2,561	2,750	405
P4-8(P)	74	6,370	2,482	230

Charge Passed (Coulombs) [a]	Chloride Permeability[a]
>4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
<100	Negligible

* P = Primary; S= Secondary

* As a percentage of total cementitious materials, FA/(Cement + FA).

*** Test data are average of five test observations. [a] Based on ASTM C-1202

The chloride ion permeability showed no major variation with change in air content. It can be concluded from this work that:

1. The optimum ASTM C-618, Class C fly ash from We Energies PPPP content is in the range of 35% to 55% with respect to compressive strength, air permeability, water permeability and chloride permeability.
2. Air-entrained high strength concretes can be produced with up to a 35% fly ash to total cementitious material ratio with good resistance to air, water and chloride ion permeability.
3. Concrete mixtures with up to 55% fly ash to total cementitious material ratio showed “good” resistance to air permeability.
4. Concrete mixtures with 35% to 55% fly ash to total cementitious material ratio exhibited excellent resistance to water permeability at 91-day age.
5. The resistance to chloride ion permeability increased as the concrete aged. At the age of one year, all the fly ash mixtures showed very low chloride ion permeability.

6. Air content had little effect on air, water and chloride ion permeability of concrete, within the test limits.

High-Volume Fly Ash Concrete - Pilot Project

Figure 4–18: Sussex Corporate Center boulevard entrance paved with high-volume fly ash concrete

Several pilot projects were completed as part of the research work to demonstrate and better understand the actual performance of We Energies coal combustion products. All the pilot projects were very successful, and have been in service for several years. The following are examples of such projects.

Sussex Corporate Center Pilot

Pavements at the Sussex Corporate Center, Village of Sussex, Wisconsin, were constructed using high-volume fly ash concrete in 1995. Concrete pavements do not require major maintenance for 30 to 50 years, while asphalt pavements typically last only 10-15 years, after which they are generally milled and surfaced or replaced.

Tax Incremental Financing (TIF) was used as a means of encouraging investment on this project. If asphalt pavement is constructed using TIF and it needs replacement in 10 or 15 years, that work will not be funded by most TIF districts. Since the decision to construct concrete pavement using TIF funds was made, there was no reason to worry about finding alternate financing for future pavement maintenance (34).

The Sussex Corporate Center is a 221-acre business park development for small light-industrial business offices and includes approximately 20 commercial parcels. High-volume fly ash concrete was used for paving approximately 4,220 linear feet of dual 28-foot lane divided concrete boulevard and 4,210 linear feet of 36-foot wide concrete pavements placed for the corporate center roadways. 9-inch thick concrete pavements were placed over a 6-inch crushed limestone base course.

Concrete Pavement Mixture

The concrete mixture was designed for a minimum of 4,000 psi compressive strength at 28 days. ASTM C-618, Class C fly ash from Pleasant Prairie Power Plant was used on the project. Table 4-24 gives the mixture design for the concrete pavement.

Table 4-24: Sussex Corporate Center Concrete Mixture Proportions

Material Description	Quantity Per Cubic
Cement Type 1	360 lbs.
Class C Fly Ash	214 lbs.
Sand	1,410 lbs.
Stone (#1 and #2)	1,800 lbs.
Water (total)	± 21 gal.
Air Entrainment	20 oz.
Water Reducer	As needed for workability

The fly ash used met the standards of ASTM C-618 and the cement met ASTM C-150 Type 1 standards. Table 4-25 is a comparison between the Wisconsin Department of Transportation pavement specification and this paving mixture containing 40% fly ash.

Table 4-25: Cement vs. Cement Plus Fly Ash Cost Comparison

Description	Cement/Cy (lbs)	Cement cost/Cy @ $85/ton	Fly Ash/Cy (lbs)	Fly Ash Cost/Cy at $26/ton	Cost of Cementitious Material	Savings/Cy with 40% HVFA Concrete
WI State Spec Pavement	480	$20.40	110	$1.43	$21.83	$3.41
40% HVFA Spec Pavement	360	$15.30	240	$3.12	$18.82	

Figure 4-19 : Aerial view of the Village of Sussex Corporate Center that was paved with high-volume fly ash concrete.

The Sussex Corporate Center saved $34,000 on this project, which was approximately 5.5% of the pavement cost by using high-volume fly ash concrete. Since the success of this initial project, the village of Sussex has paved additional roads and sidewalks with this same mixture.

Figure 4-20 : Maple Avenue roadway and sidewalk located in the village of Sussex and paved with high-volume fly ash concrete.

Pavement Construction with High-Volume We Energies Class C and Class F Fly Ash Concrete

An existing crushed stone road providing access to an ash landfill was paved using fly ash concrete. Five different concrete mixtures, 20% and 50% ASTM C-618, Class C fly ash, and 40, 50, and 60% off-spec ASTM C-618, Class F fly ash were used to pave a 6,600 foot (2,012 m) long roadway carrying heavy truck traffic. A 20-foot wide, 8-inch thick concrete pavement with ¼-inch per-foot slope from the centerline to the edge of the roadway was placed over the existing crushed stone base. The pavement was designed to comply with the State of Wisconsin Standard Specification for Road and Bridge construction with the exception of using four experimental high-volume fly ash concrete mixtures. A concrete mix with a minimum 28-day compressive strength of 3,500 psi was specified. The air content of fresh concrete was specified to be 5 to 7% by volume (35). The road was opened to traffic within 10 days of paving completion. It has been providing good service after several Wisconsin winters.

Figure 4-21: Another view of Maple Avenue located in the village of Sussex paved with high-volume fly ash concrete.

Figure 4-22: Finishing touch to We Energies' high-volume fly ash concrete demonstration project at Pleasant Prairie Power Plant.

Figure 4-23: High-volume fly ash demonstration road paving at Pleasant Prairie Power Plant. Note the difference between the darker slate colored class F fly ash concrete and lighter tan colored high-volume class C fly ash concrete.

The following observations were made by the contractor during the construction.

- Air entrainment and slump were more difficult to control for the off-spec ASTM C-618 Class F fly ash concrete than ASTM C-618 Class C fly ash concrete.
- ASTM C-618 Class F fly ash concrete was more “sticky” and took a longer time to reach strength at which saw cuts could be made.
- Twenty percent and 50% Class C fly ash concrete showed two shades of tan, earth-tone colors, and 40% Class F concrete had a medium gray slate-tone color when wet.

Off-spec ASTM C-618 Class F fly ash obtained from Oak Creek Power Plant and ASTM C-618 Class C fly ash obtained from Pleasant Prairie Power Plant were used on this project. ASTM C-150, Type I Portland cement was also used. The mixture proportions are shown on Tables 4-26 to 4-27.

Concrete specimens were also made for the following tests:

1. Compressive strength
2. Splitting tensile strength
3. Flexural strength
4. Freezing and thawing resistance
5. Drying shrinkage
6. Deicing salt scaling resistance
7. Chloride ion permeability
8. Abrasion resistance

Table 4-26: Concrete Mixture and Site Test Data for 3500 psi Specified Design Strength Concrete at 28-Day Age

Mixture No.	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3	S3-4
Cement (lbs.) *	364	365	364	296	294	296	479	480	479	477
Fly ash (lbs.) *	244	245	243	296	296	296	113	110	109	110
Water (lbs.) *	164	165	165	155	161	152	172	180	148	183
Sand (lbs.) *	1,544	1,538	1,544	1,158	1,294	1,298	1,370	1,366	1,376	1,366
Coarse aggregates (lbs.) *	1,848	1,842	1,840	1,710	1,888	1,898	1,932	1,926	1,932	1,930
Slump (inches)	4	1¾	1¾	2¾	2¾	3	2	1¼	1¾	3
Air Content (%)	6.2	5.2	5.0	5.4	5.0	5.5	5.9	5.2	6.0	6.0
Air Temp (°F)	90	98	98	96	76	78	76	76	76	75
Concrete Temp (°F)	85	92	91	92	86	86	84	84	84	82
Concrete Density (pcf)	144.2	141.9	146.2	145.6	147.0	147.8	146.5	147.7	144.6	136.4

* Mixture proportions data provided by the ready mixed concrete supplier.

Mixture S1: 40% Class F Fly Ash (120 liq. oz superplasticizer and 15 liq. oz air entraining agent)

Mixture S2: 50% Class C Fly Ash (12 liq. oz air entraining agent)

Mixture S3: 20% Class C Fly Ash (7 liq. oz air entraining agent)

Table 4-27: Concrete Mixture and Site Test Data for 3500 psi Specified Design Strength Concrete at 28-Day Age

Mixture No.	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P2-1	P2-2	P2-3
Cement (lbs.)*	367	366	367	366	368	367	295	267	293
Fly ash (lbs.) *	245	243	244	244	244	245	293	263	296
Water (lbs.) *	165	167	162	164	166	164	177	158	158
Sand (lbs.) *	1,546	1,546	1,544	1,552	1,548	1,546	1,299	1,169	1,300
Coarse aggregates (lbs.) *	1,842	1,846	1,838	1,844	1,844	1,852	1,898	1,712	1,896
Slump (inches)	9	5¼	3¼	1½	1¾	2	3	3	3½
Air Content (%)	8.5	6.5	6.2	5.6	5.9	5.9	6.0	6.0	6.2
Air Temp (°F)	84	92	96	100	102	103	98	96	73
Concrete Temp (°F)	83	84	86	85	86	86	86	88	84
Concrete Density	141.5	141.0	143.4	141.5	142.4	142.8	143.4	134.5	135.5

*Mixture proportions data provided by the ready mixed concrete supplier

Mixture P1: 40% Class F Fly Ash (120 liq. oz. superplasticizer and 15 liq. oz. air entraining agent)

Mixture P2: 50% Class C Fly Ash (12 liq. oz. air entraining agent)

Tables 4-28 to 4-40 show the results of the above tests. It can be concluded from this paving project that:

1. Paving grade air-entrained concrete can be produced with 40% of Portland cement replaced with off-spec ASTM C-618, Class F fly ash plus a superplasticizer, when the water-to-cementitious materials ratio is maintained around or below 0.36.
2. The 50% ASTM C-618, Class C fly ash concrete mixture is suitable for pavement construction.
3. All concrete mixtures gained strength with age. Cores taken from the pavement showed higher compressive strengths than lab-cured concrete cylinders.
4. High-volume fly ash concrete mixtures showed higher freezing and thawing resistance than the WDOT reference mix with 20% ASTM C-618, Class C fly ash.
5. High-volume fly ash concrete exhibited lower drying shrinkage when compared to the reference mixture.

6. The high-volume Class C fly ash mixture (50% replacement) showed lower resistance to de-icing salt scaling when compared to the other two mixtures in the laboratory. This has not been observed in the field.
7. All mixtures showed good resistance to chloride ion penetration. High-volume off-spec ASTM C-618 Class F fly ash concrete performed better than the other two mixtures, for resistance to chloride ion penetration.
8. The 20% ASTM C-618 Class C fly ash mixture showed better resistance to abrasion than the other two mixes.

Table 4-28: Average Compressive Strength Test Results from the Construction Site - Prepared Concrete Cylinders for Specified Design Strength 3500 psi at 28-Day Age

Test Age, Days	Mixture Numbers									
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3	S3-4
1	1,230	--	--	--	--	1,020	--	1,720	--	--
3	1,770	2,580	1,700	1,920	1,750	1,900	2,690	2,650	2,870	--
7	2,450	--	--	--	--	2,900	--	3,620	--	3,560
28	3,430	5,160	4,460	4,260	4,390	3,900	4,020	4,450	4,860	4,530
56	4,530	5,850	5,260	4,960	5,140	5,270	5,860	6,060	5,890	--
91	4,720	--	--	--	--	5,300	--	6,170	--	--
182	5,310	--	--	--	--	6,020	--	6,320	--	--
365	5,430	7,420	4,810	5,810	5,680	6,400	6,909	6,690	7,060	--

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-29: Average Compressive Strength Test Results From Ready Mix Plant Cylinders for Specified Design Strength 3500 psi at 28-Day Age

Test Age, Days	Mixture Numbers								
	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P2-1	P2-2	P2-3
7	2,550	3,010	3,040	2,790	2,490	3,120	2,250	2,180	2,570
28	3,740	4,640	4,510	2,980	3,720	4,380	3,680	3,640	3,200

Mix P1: 40% Class F Fly Ash
Mix P2: 50% Class C Fly Ash

Table 4-30: Core Strength Test Data
ASTM C-42 (Compressive Strength)

Core Number	Average Length (in)			Average Diameter (D)	Cross Sectional Area (in^2)	L/D * Ratio	Max. Loads (lbs.)	1- Year Compressive Strength (psi)	
	As Received	After Cutting	After Capping, L					Actual	Average
200 A	8.10	7.38	7.54	3.77	11.16	2.00	71,000	6360	6900
200 B	8.00	7.26	7.47	3.77	11.16	1.98	70,000	6270	
200 C	7.44	7.38	7.51	3.77	11.16	2.00	90,000	8070	
1500 A	7.85	7.25	7.50	3.77	11.16	1.99	76,000	6810	6660
1500 B	8.10	7.30	7.51	3.77	11.16	1.99	75,000	6720	
1500 C	8.69	7.32	7.53	3.77	11.16	2.00	72,000	6450	
3500 A	7.69	7.27	7.49	3.77	11.16	1.99	72,000	6450	6560
3500 B	7.56	7.20	7.44	3.77	11.16	1.97	75,500	6770	
3500 C	7.66	7.13	7.33	3.77	11.16	1.94	72,000	6450	

Core Number	Type of Fracture	Defects in Specimen or Cap	Nominal Age (yr)	Core Moisture Condition as Tested	Nominal Size of Aggregates
200 A	Cone	None	1	Wet	1”
200 B	Cone & Shear	None	1	Wet	1”
200 C	Cone	None	1	Wet	1”
1500 A	Cone	None	1	Wet	1”
1500 B	Cone	None	1	Wet	1”
1500 C	Cone	None	1	Wet	1”
3500 A	Cone & Split	None	1	Wet	1”
3500 B	Cone & Split	None	1	Wet	1”
3500 C	Cone	None	1	Wet	1”

*All cores drilled and tested along direction of placement
200 A, B, C Mix S3: 20% Class C Fly Ash
1500 A, B, C Mix S2: 50% Class C Fly Ash
3500 A, B, C Mix S1: 40% Class F Fly Ash.

Table 4-31: Average Tensile Strength Test Results (psi)

Test Age, Days	Mix Numbers								
	S1-1	S1-2	S1-3	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3
3	230	250	235	250	230	255	300	340	340
7	280	320	260	330	325	360	340	400	410
28	400	400	340	420	370	400	430	440	490
56	510	520	440	530	400	440	440	530	540

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-32: Average Flexural Strength Test Results (psi)

Test Age, Days	S1-1	S2-3	S3-2
3	340	310	490
7	420	370	520
28	580	600	670
56	640	700	700
182	870	780	760

Mix S1: 40% Class F Fly Ash
Mix S2: 50% Class C Fly Ash
Mix S3: 20% Class C Fly Ash

Table 4-33: Summary of Test Results on Concrete Prisms after Repeated Cycles of Freezing and Thawing*

Specimen No	Source of Fly Ash	Percent Replacement	No. of Freeze-thaw Cycles Completed	Resonant Frequency	Weight	Pulse Velocity	Relative Dynamic Modulus of Elasticity (%)	Durability Factor (%)
2.20.1	P-4	20	300	-13.9	-0.58	-6.65	74.2	74
2.20.2			300	-9.1	-0.12	-5.63	82.7	83
2.20.3			300	-21.9	-0.63	-6.47	61.0	61
F-25	P-4	50	300	-3.4	-0.14	-1.89	93.3	93
F-26			300	-7.2	+0.17	-2.46	86.1	86
F-27			300	-4.4	+0.24	-2.31	91.4	91
F-1	OCPP	40	300	-0.3	-0.42	-1.38	99.3	99
F-2			300	-2.8	-0.44	-3.86	94.4	94
F-3			300	-2.7	-0.41	-2.64	94.6	95

*Freezing and thawing cycles were carried out in accordance to ASTM C-666, Procedure A.
The number of cycles completed at the termination of the test was 300.

Table 4-34: Changes in Fundamental Longitudinal Resonant Frequency of Test Prisms During Freeze-Thaw Cycling per ASTM C666 Procedure A

Source of Fly Ash	Percent Replacement	Size of Specimen, (in.)	Fundamental Longitudinal Resonant Frequency N, (cps)						
			Reference Moist-Cured Prisms			Freeze – Thaw Test Prisms			
			Initial	At end of Freeze-Thaw Cycle Time	Percent Change	N*	N**	N***	Percent Change
P - 4	20	3 x 4 x 12¼	6504 6546 5679	6764 6820 6838	4.0 4.2 3.9	6526 6547 6492	6180 [150] 6103 [150] 6140 [150]	5620 [300] 5954 [300] 5070 [300]	-13.9 -9.1 -21.9
P - 4	50	3 x 4 x 12¼	6431 6340 6400	6778 6645 6722	5.4 4.8 5.0	6412 6350 6379	6178 [150] 6030 [150] 6092 [150]	6194 [300] 5891 [300] 6101 [300]	-3.4 -7.2 -4.4
OCPP	40	3 x 3 x 11¼	7162 7150 7142	7493 7480 7443	4.6 4.6 4.2	6912 6975 6971	6673 [150] 6805 [150] 6770 [150]	6890 [300] 6780 [300] 6780 [300]	-0.3 -2.8 -2.7
			Weight W, (Kg)						
			Initial	At end of Freeze-Thaw Cycle Time	Percent Change	W*	W**	W***	Percent Change
P - 4	20	3 x 4 x 12¼	5.280 5.786 5.807	5.843 5.810 5.832	0.40 0.41 0.41	5.834 5.770 5.827	5.873 [150] 5.763 [150] 5.785 [150]	5.800 [300] 5.763 [300] 5.790 [300]	-0.58 -0.12 -0.63
P - 4	50	3 x 4 x 12¼	5.733 5.647 5.677	5.762 5.675 5.706	0.51 0.50 0.51	5.789 5.763 5.738	5.797 [150] 5.784 [150] 5.759 [150]	5.781 [300] 5.773 [300] 5.752 [300]	-0.14 0.17 0.24
OCPP	40	3 x 3 x 11¼	3.842 3.826 3.780	3.853 3.837 3.793	0.29 0.29 0.34	3.843 3.850 3.874	3.846 [150] 3.856 [150] 3.878 [150]	3.827 [300] 3.833 [300] 3.858 [300]	-0.42 -0.44 -0.41

Table 4-35: Changes in Ultrasonic Pulse Velocity of Test Prisms During Freeze-Thaw Cycling Per ASTM C666 Procedure A

				Ultrasonic Pulse Velocity V, ($^{m}/_{s}$)						
				Reference Moist-Cured Prisms			Freeze-Thaw Test Prisms			
Specimen No.	Source of Fly Ash	Percent Replacement	Size of Specimen, (in.)	Initial	At end of Freeze-Thaw Cycles Time	Percent Change	V*	V**	V***	Percent Change
2.20.4	P-4	20	3 x 4 x 12¼	4876	4762	1.84				
2.20.5				4718	4784	1.40				
2.20.6				4769	4821	1.09				
F-28	P-4	50	3 x 4 x 12¼	4620	4718	2.12				
F-29				4592	4718	2.74				
F-30				4559	4676	2.57				
F17	OCPP	40	3 x 3 x 11¼	4726	4830	2.20				
F21				4582	4734	3.32				
F22				4627	4774	3.18				
2.20.1	P-4	20	3 x 4 x 12¼				4704	4473 [150]	4391 [300]	-6.65
2.20.2							4726	4539 [150]	4460 [300]	-5.63
2.20.3							4655	4480 [150]	4354 [300]	-6.47
F-25	P-4	50	3 x 4 x 12¼				4599	4473 [150]	4512 [300]	-1.89
F-26							4586	4403 [150]	4473 [300]	-2.46
F-27							4552	4391 [150]	4447 [300]	-2.31
F-1	OCPP	40	3 x 3 x 11¼				4481	4453 [150]	4419 [300]	-1.38
F-2							4582	4298 [150]	4405 [300]	-3.86
F-3							4510	4432 [150]	4391 [300]	-2.64

*Average resonant frequency of prisms after moist curing at the commencement of the freeze-thaw cycling.

**Number in brackets represents the number of freeze-thaw cycles completed at the time of testing.

***Termination of freeze-thaw test.

Table 4-36: Flexural Strength of Reference Moist Cured and Freeze-Thaw Test Specimens

Source of Fly Ash	Percent Replacement	Size of Specimen, in.	Flexural Strength			
			Reference Moist Cured Prisms		Freeze Thaw Test Prisms	
			psi	MPa	psi	MPa
P-4	20	3 x 4 x 12¼	1149 1180 1280	7.8 8.1 8.8	550 100 60	3.8 0.7 0.4
P-4	50	3 x 4 x 12¼	1010 930 930	6.9 6.4 6.4	390 450 480	2.7 3.1 3.3
OCPP	40	3 x 3 x 11¼	1330 1080 1080	9.1 7.4 7.4	680 710 830	4.7 4.9 5.7

Table 4-37: Shrinkage-Expansion and Moisture Change up to 112 Days for Drying Shrinkage Prisms and Prisms Stored in Water

Curing Conditions	Source of Fly Ash	Percent Replacement	Shrinkage/Expansion Strain, 10^{-6} (After 91-day age)					Weight Change, % of Initial Weight
			7d	**14d**	**28d**	**56d**	**112d**	**112d**
Air-dried at 23°C 50% RH after 91 days in water	P-4 P-4 OCPP	20 50 40	98 107 53	187 213 116	356 338 196	462 444 284	524 516 356	2.76 3.02 2.38
Continuous Water Storage	P-4 P-4 OCPP	20 50 40	+18 9 +17	9 27 +27	9 53 +17	+18 36 +36	+27 +9 +44	+0.17 +0.28 +0.08

Notes:

Prior to air-drying, the specimens were stored in lime-saturated water for 91 days.

Strains were measured on 3 x 4 x 11¼ inch specimens. Positive values indicate expansion.

Testing is to continue up to 448 days, after the 91-day age.

Table 4-38: Results of De-Icing Salt Scaling Tests on High-Volume Fly Ash Concrete Specimens

No. of Cycles	Test Specimens											
	PPPP, 20% Replacement		PPPP, 20% Replacement		PPPP, 50% Replacement		PPPP, 50% Replacement		OCPP, 40% Replacement		OCPP, 40% Replacement	
	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft2	Visual Rating	Scaled Residue lb/ft^2
11	0+		O+	0.015	2+	0.035	2	0.030	1-	0.017	1	0.030
22	0+	0.039	0+	0.030	3	0.158	3	0.170	2-	0.053	1	0.053
32	1	0.051	1-	0.045	4-	0.234	3+	0.265	2+	0.071	2	0.062
42	1+	0.076	1-	0.081	4	0.342	4-	0.374	2+	0.099	2	0.090
50	2	0.104	1-	0.107	*	*	4-	1.474	2+	0.135	2+	0.116

Notes:

Specimens were subjected to the de-icing salt scaling tests after 3 weeks of moist curing followed by 3 weeks of air cure in the laboratory atmosphere.

A 3% by weight NaCl solution was used as the deicing salt solution.

Visual ratings shown were made according to the Standard ASTM C-672.

* The specimens failed by the fracture of the dike on the scaling surface.

Visual Rating Per ASTM C-672.

0 = no scaling

1 = very slight scaling (1/8 in. depth), max. no coarse aggregate visible)

2 = slight to moderate scaling

3 = moderate scaling (some coarse aggregate visible)

4 = moderate to severe scaling

5 = severe scaling (coarse aggregate visible over entire surface)

Table 4-39: Results for Chloride Ion Permeability from Cores

Core Designation	Test Slice Location	Maximum Current During Test (Amperes)	Actual Total Charge Passed (Coulombs)	Average Total Charge Passed (Coulombs)	Overall Average Total Charge Passed (Coulombs)	AASHTO Chloride Permeability Equivalent **
600-A	Top Middle Bottom	0.054 0.044 0.041	1132 943 840			
600-B	Top Middle Bottom	0.037 0.035 0.045	772 761 900	Top: 1056 Middle: 798 Bottom: 900	918	Very Low
600-C	Top Middle Bottom	0.064 0.033 0.045	1263 690 961			
1900-A	Top Middle Bottom	0.018 0.019 0.023	365 353 481			
1900-B	Top Middle Bottom	0.018 0.018 0.020	351 363 401	Top: 376 Middle: 372 Bottom: 424	391	Very Low
1900-C	Top Middle Bottom	0.022 0.020 0.020	412 400 391			
3100-A	Top Middle Bottom	0.010 0.009 0.011	181 202 212			
3100-B	Top Middle Bottom	0.010 0.009 0.010	200 180 210	Top: 181 Middle: 184 Bottom: 198	188	Very Low
3100-C	Top Middle Bottom	0.008 0.008 0.009	162 170 172			

Notes:

* Per AASHTO T-277

** > 4,000 = High

2,000 - 4,000 = Moderate

1,000 - 2,000 = Low

100 - 1,000 + Very Low

<100 = Negligible

Cores 600A, B, C are from mixture S3: 20% ASTM C618, Class C Fly Ash Concrete

Cores 1900 A, B, C are from mixture S2: 50% ASTM C618, Class C Fly Ash Concrete

Cores 3100 A, B, C are from mixture S1: 40% ASTM C618 Class F Fly Ash Concrete

Table 4-40: Abrasion Resistance of High-Volume Fly Ash Concrete Specimens

Time of Abrasion, (Sec.)	Depth of Wear, (mm)		
	PPPP, 20%	PPPP, 50%	OCPP, 40%
50	0.559	0.581	0.853
100	0.798	0.961	1.318
150	0.961	1.085	1.482
200	1.055	1.237	1.640
250	1.167	1.192	1.680
300	1.273	1.245	1.891
350	1.293	1.318	2.100
400	1.395	1.379	2.211
450	1.452	1.592	2.532
500	1.493	1.680	2.816
550	1.534	1.809	2.950
600	1.562	1.699	3.318
650	1.681	1.850	
700	1.711	1.772	
750	1.753	1.810	
800	1.769	1.879	
850	1.788	1.876	
900	1.811	2.022	
950	1.838	2.296	
1000	1.911	2.416	
1050	1.924	2.403	
1100	1.923	2.624	
1150	1.968	2.535	
1200	2.001	2.527	

Notes:

The specimens used were 12 x 12 x 4 in. slabs.

The specimens were subjected to abrasion testing following eight months of moist curing. The abrasion testing was done according to ASTM C-779, Procedure C.

Long Term Performance of High Volume Fly Ash Concrete Pavement

To evaluate the long-term strength properties and durability of HVFA concrete systems, a study was conducted by the University of Wisconsin – Milwaukee, Center for By-Products Utilization (36). All concrete mixtures developed in this investigation were used in construction of various pavement sections from 1984 to 1991. Core specimens and beams were extracted from in-place pavements for measurement of compressive strength (ASTM C-39), resistance to chloride-ion penetration (ASTM C-1202), and hardened concrete density (ASTM C-642).

Density of Concrete Mixtures

The fresh density values of the concrete mixtures varied within a narrow range for all mixtures. The fresh concrete values were a similar order of magnitude as that of hardened concrete density values for the mixtures. Thus, both the fresh and hardened density values were not significantly influenced by the variations in fly ash content, type, or age within the tested range.

Compressive Strength

The compressive strength of the concrete mixtures increased with age. The rate of increase depended upon the level of cement replacement, class of fly ash, and age. In general concrete strength decreased with increasing fly ash concentration at the very early ages for both classes of fly ash. Generally the early-age strength of Class F fly ash concrete mixtures were lower compared to Class C fly ash concrete mixtures. However, the long-term strength gain by the high volume Class F fly ash concrete system was better than comparable Class C fly ash concrete, as shown in Figure 4-24. This is probably due to the fact that Class F fly ash made a greater contribution of pozzolanic C-S-H compared to Class C fly ash. This in turn resulted in a greater improvement in the microstructure of the concrete made with Class F fly ash compared to Class C fly ash, especially in the transition zone. Therefore, the use of this Class F fly ash is the most desirable from the long-term perspective for the manufacture of high-performance concrete (HPC) because HPCs are required to possess both long-term high-strength properties and durability. However, Class C fly ash also continued to gain strength over time and is also expected to perform well.

Resistance to Chloride-Ion Penetration

All concrete mixtures tested in this investigation showed excellent resistance to chloride-ion penetration. The general performance trend with respect to resistance to chloride-ion penetration followed a similar trend as indicated by the compressive strength. The highest resistance to chloride-ion penetration for the mixtures containing high volumes of Class F fly ash was due to the same reasons as described for the compressive strength data (i.e., improved microstructure of concrete).

Summary

Based on the data recorded in this investigation, the following general conclusions may be drawn:

(1) Concrete density was not greatly influenced by either the class or the amount of fly ash or the age within the tested range.

(2) The rate of early-age strength gain of the Class C fly ash concrete mixtures was higher compared to the Class F fly ash concrete mixtures. This was primarily attributed to greater reactivity of Class C fly ash compared to Class F fly ash.

(3) Long-term pozzolanic strength contribution of Class F fly ash was greater compared to Class C fly ash. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were higher than that for Class C fly ash concrete mixtures.

(4) Concrete containing Class F fly ash exhibited higher long-term resistance to chloride-ion penetration compared to Class C fly ash concrete. The best long-term performance was recorded for both the 50% and 60% Class F fly ash concrete mixtures as they were found to be relatively impermeable to chloride-ions in accordance with ASTM C-1202. All fly ash concrete mixtures irrespective of the type and amount of fly ash, showed excellent performance with respect to chloride-ion penetration resistance.

(5) Based on the results obtained in this investigation, it is desirable to use significant amounts of Class F fly ash in the manufacture of low-cost HPC concrete systems for improved long-term performance. However, Class C fly ash also continued to gain significant strength over time as well.

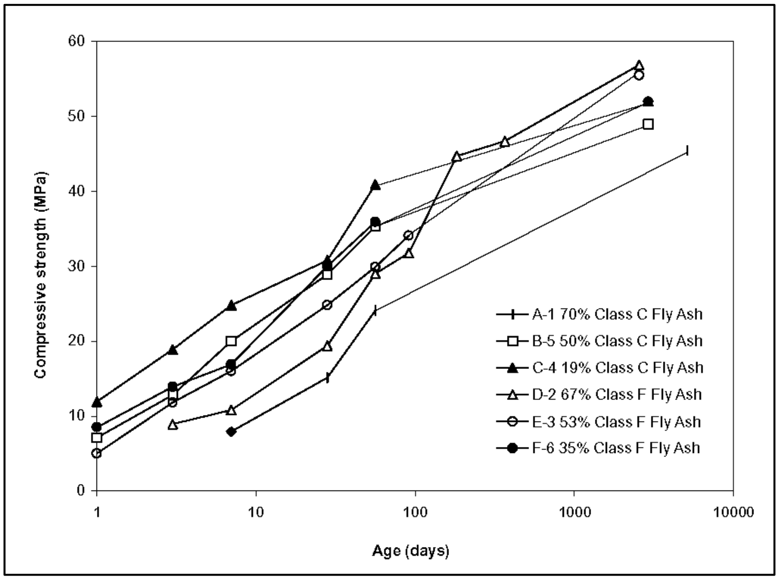


Figure 4–24: Compressive Strength vs. Age

Roller Compacted No-Fines Concrete Containing We Energies Fly Ash for Road Base Course

Many problems associated with pavement failure are due to the pressure of water under rigid surface pavements. When high pressure from heavy traffic is applied on pavements in the presence of water, pumping occurs. Pumping causes erosion of the pavement base, as fines along with water are pumped out. The continued effect of pumping is a loss of support, leading to pavement failure. An open-graded permeable base is used to avoid such problems. The open-graded permeable base pavement system consists of a permeable base, separator layer and edge drainage. Permeable bases can be treated or untreated with cementitious binders.

A demonstration project was designed to use an off-spec ASTM C-618, Class F fly ash in the open-graded concrete base course and an ASTM C-618 Class C fly ash in the concrete pavement for an internal road at the Port Washington Power Plant located in Port Washington, Wisconsin.

The roadway cross section (see Figures 4-25 and 4-26) consisted of an initial layer of filter fabric installed to prevent fines from the subgrade moving up and blocking drainage in the base course, topped by a 6” thick layer of open-graded concrete base course and a 10 in. thick, high-volume fly ash concrete pavement. This pavement was designed in compliance with Wisconsin DOT standards, with the exception of using high-volume fly ash in the open-graded base, and concrete pavement. Underdrains, manholes and storm sewer piping were also installed as part of this project, to ensure proper functioning of the pavement system (37).

The properties of fly ash and cement used in this project are shown on Table 4-41. The ASTM C-618, Class F fly ash used on the project is off-specification with a very high LOI.

The mixture proportions for the open-graded base course were composed of 160 lb/cu yd cement, 125 lb/cu yd fly ash, 81 lb/cu yd water, 2600 lb/cu yd ¾ in. coarse aggregate and no fine aggregate.

The mixture proportions for high-volume fly ash concrete pavement included 300 lb/cu yd cement, 300 lb/cu yd Class C fly ash, 221 lb/cu yd water, 1200 lb/cu yd sand, 966 lb/cu yd ¾” aggregate and 966 lb/cu yd 1-1/2” coarse aggregate. The water to cementitious materials ratio was maintained at about 0.37.

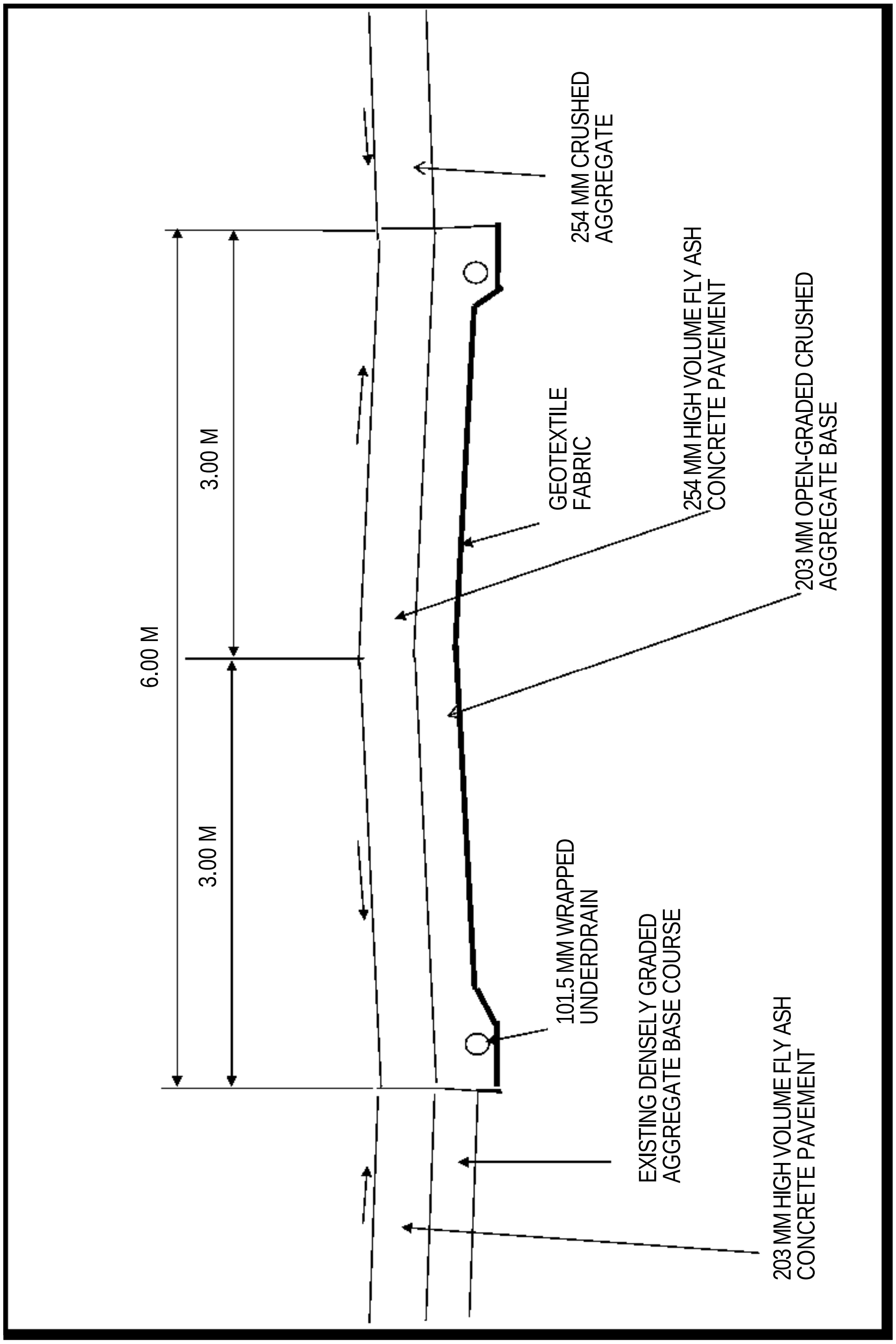


Figure 4-25: Pavement Cross Section

Notes:

1. Pavement slope varies to maintain drainage. Typical slope 20.8 mm per meter.
2. Expansion joints with dowel bars provided at intersection with existing pavement
3. Transverse joints at approximately 6 meter intervals
4. Transverse joints were saw cut to a minimum depth of 762 mm.

Table 4-41: Properties of Cement and Fly Ashes Used

Chemical Composition (%)	Cement Type I	ASTM C-150 Type I	Class F Fly Ash	Class C Fly Ash	ASTM C-618 Class F	ASTM C-618 Class C
Silicon dioxide, SiO_2	20.0	--	36.5	35.4	--	--
Aluminum oxide, Al_2O_3	4.3	--	16.0	23.3	--	--
Ferric oxide, Fe_2O_3	2.5	--	7.0	5.6	--	--
Total, $SiO_2 + Al_2O_3 + Fe_2O_3$	26.8	--	61.5	64.3	70.0 min	50.0 min
Sulfur trioxide, SO_3	2.3	3.0 max	1.5	2.4	5.0 max	5.0 max
Calcium oxide, CaO	64.0	--	2.1	26.7	--	--
Magnesium oxide, MgO	2.0	6.0 max	--	--	5.0 max	5.0 max
Available alkali, Na_2O	0.3	--	0.7	0.9	1.5 max	1.5 max
Moisture content	--	--	1.2	0.13	3.0 max	3.0 max
Loss on ignition	2.0	3.0 max	31.3	0.6	6.0 max	6.0 max
Physical Properties of Cement						
Air content (%)	9.5	12 max			--	
Fineness (m^2/kg)	351	280 min			--	
Autoclave expansion (%)	-0.02	0.8 max			--	
Specific gravity	3.16				--	
Compressive strength (psi) 1-day 3-day 7-day 28-day	1990 3500 4230 5420	-- 174 min 2760 min --			- - - - -	- - - - -
Vicat time of initial set (min)	145	45 min 375 max			--	--
Physical Properties of Fly Ashes						
Fineness retained on No. 325 sieve (%)	--	--	25.5	19.4	34 max	34 max
Pozzolanic activity index with cement (% of control) 7-day 28-day	-- --	-- --	64 73	92.4 99.4	75 min 75 min	75 min 75 min
Water requirement (% of control)	--	--	112	93.0	105 max	105 max
Autoclave expansion (%)	--	--	-0.02	-0.02	0.8 max	0.8 max
Specific gravity	--	--	2.02	2.60	--	--

Field testing was performed during the placement of base course and the concrete pavement. Slump measurements were taken on both the base course mixture and concrete mixture. Also, air content (ASTM C-231) and temperature (ASTM C-1064) measurements were recorded for the concrete mixture.

Compressive strength was also measured on cylinders made from selected batches of base course and paving slab concrete mixtures, in accordance with ASTM procedures.

Figure 4-26: Open-graded cementitious base course material being placed over filter fabric at Port Washington Power Plant's high-volume fly ash concrete pavement demonstration project.

Results and Discussion

- Base Course Material: The compressive strength data is shown in Table 4-42. The permeable base was designed to have a compressive strength in the range of 490 to 990 psi. However, the mixture provided 670 psi at 28-day age and 810 psi at 56-day age.
- Fly Ash Concrete Pavement: Since there already was significant data on high-volume fly ash concrete, only compressive strength of the pavement concrete mixtures was measured. Based on earlier work, it was assumed that a mixture meeting air content and strength requirements would satisfy other durability requirements.

Table 4-43 gives the compressive strength results for the pavement concrete mixtures. The mixture showed a compressive strength of 4870 psi at the 28-day age, which was 20% higher than the design strength of 4000 psi. The pavement was inspected visually to determine its performance over the past several years. No obvious pavement distress was seen during the inspections.

Table 4-42: Open-Graded Base Course Test Results

Test	No. of Tests	Average
Slump (in.)	91	7
Compressive Strength (psi)		
3-day	59	290
7-day	59	421
28-day	59	667
56-day	59	812

Table 4-43: High-Volume Fly Ash Concrete Test Results
Specified Strength: 4000 psi at 28-Day Age

Test	No. of Tests	Average
Slump (in.)	174	1/8
Air Content (%)	170	6.0
Concrete Temperature (°F)	174	57
Compressive Strength (psi)		
3-day	62	2170
7-day	62	3320
28-day	62	4870
56-day	62	5550

Sample specifications are included in Appendix 12.1 for current We Energies cast-in-place concrete.

Bricks, Blocks, and Paving Stones Produced with We Energies Fly Ash

Coal combustion product applications have shown a substantial increase in the past decade. However, only a limited amount of fly ash and bottom ash are actually used in the production of masonry units, such as bricks, blocks, and paving stones. Since only limited research was done on room-cured and steam-cured ash bricks and blocks, We Energies funded research on a project to investigate the properties of bricks and blocks containing We Energies fly ash at the Center for By-Products Utilization of the University of Wisconsin-Milwaukee.

Testing Program

The testing program consisted of the following stages:

1. Developing mixture proportions for room temperature cured bricks and blocks utilizing ASTM C-618 Class C fly ash.
2. Extended testing using different types of (ASTM Class C and Class F) fly ash from different sources, and using bottom ash as a replacement for natural aggregates.
3. Studying the effect of different curing systems.
4. Producing small size blocks using selected mix recipes and testing their properties.

Stage 1 Testing

Fly ash from power plants other than We Energies was also used in this work. However, the data presented here is only information relevant to We Energies products. In the first stage testing, only ASTM C-618, Class C fly ash from Dairyland Power Corporation was used. The intent of this work was to develop a suitable and economic brick and block mixture utilizing coal ash.

From the Stage 1 studies, it was concluded that:

1. The dry-cast vibration method is better for obtaining higher compressive strength masonry units.
2. Sufficient strength develops (greater than 2000 psi) when the specimens are cured in a fog room for 28 days. No firing or steam curing is required for this.
3. Most masonry products require only a compressive strength of 2000 psi to 3000 psi. Hence, it is appropriate to raise the aggregate to cementitious ratio and introduce the bottom ash as partial replacement of aggregates in the mixtures.

Stage 2 Testing

Two types of fly ash from We Energies were used in this testing, ASTM C-618 Class C (F-2) and an off-spec ASTM C-618 Class F (F-4) fly ash. The chemical properties of fly ash used in this project are given in Table 4-44.

Table 4-44: Chemical Properties of We Energies Fly Ash

Compositions Material	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	K_2O	Na_2O	TiO_2	LOI
F-2	32.91	19.36	28.85	4.83	5.38	0.34	1.95	1.58	0.64
F-4	48.21	26.26	2.66	1.14	10.61	1.08	2.26	1.21	7.89

Specimens were made by making semi-dry and wet mixtures and casting them directly into the steel mold for vibrating on a vibration table (38). The molded specimens were cured for one day in the fog room, then removed from molds and placed back in the fog room until the time of test.

Nine 2 inch cubes were made for compressive strength and bulk density tests for each mixture. Three cubes were tested at each test age. Compressive strength tests were performed in accordance with ASTM C-192 "Standard Practice for Making and Curing Specimens in the Laboratory". Bulk density tests were performed in accordance with the ASTM C-642 "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete" procedures. Mixture proportions are shown in Table 4-45.

Table 4-45: Mix Proportions for Concrete Masonry Units

Mix. No.	Cement (%)	Fly Ash (%)	Aggregate/ Cementitious Material	ASTM C-618 Fly Ash
17	0	100	4.5/1	Class C (F-2)
18	20	80	4.5/1	Class C (F-2)
19	40	60	4.5/1	Class C (F-2)
20	60	40	4.5/1	Class C (F-2)
25	20	80	4.5/1	Class F (F-4)*
26	40	60	4.5/1	Class F (F-4)*
27	60	40	4.5/1	Class F (F-4)*
28	80	20	4.5/1	Class F (F-4)*

* LOI = 7.89

The aggregate used throughout this work was ⅜" size natural pea gravel as coarse aggregate and natural sand as fine aggregate. The aggregate in the mixture consisted of 50% fine and 50% coarse aggregate.

Test Results

Table 4-46 shows the compressive strength and bulk density test results. The specimens made with ASTM C-618 Class C fly ash gave higher compressive strengths than those with ASTM Class F fly ash for the same fly ash content.

ASTM C-618, Class C fly ash generally has a slightly higher specific gravity than Class F fly ash. Hence, Class C fly ash mixtures show a slightly higher bulk density.

Table 4-46: Compressive Strength and Bulk Density

Mix No.	Compressive Strength (psi)			Bulk Density (lb/cu.ft.)
	3-day	7-day	28-day	
17	1650	2320	3340	156.4
18	220	260	2110	155.3
19	1420	2350	4540	152.3
20	2580	4250	6500	155.8
25	340	530	1320	150.1
26	1310	1760	3420	153.3
27	2740	3880	5790	152.8
28	3700	5150	6670	155.0

Stage 3 Testing

After reviewing the work done in Stages 1 and 2, and evaluating the commercial block manufacturing process, modifications were made to the mixture design. Commercial manufacturers use a higher aggregate-to-cement ratio in the mixture than used in the laboratory.

Six blocks measuring approximately 4 x 2.5 x 1.8125 inches with two rectangular 1.25 x 1.25 inch open cells were manufactured. The blocks have a gross area of 10 sq. inches and a net area of 6.25 sq. inches (62.5% of gross area). This size is a proportionately reduced size of block manufactured in the local area for testing purposes.

The mixture design is shown in Table 4-47. Dry material components were first blended with water and then the mixture was tamped into a block mold in three layers. Each layer was compacted by a vibrating pressed bar, then removed from the mold, and stored in the curing tank for steam curing or stored in a fog room.

The blocks were tested for compressive strength and bulk density, water absorption and dimensional stability. All tests were carried out in accordance with ASTM C-140. Table 4-48 shows the compressive strength and bulk density test results and water absorption test results.

Table 4-47: Mix Design for Blocks

Mix No.	Water (%)*	W/ (C+FA)	Cementitious (%) **		Aggregate (%) ***		Type of Fly Ash
			Cement	Fly Ash	Sand	Pea Gravel	
1	5.0	0.42	100	0	67	33	None
3	5.2	0.36	40	60	67	33	Class C (F-2)
5	6.3	0.44	40	60	67	33	Class F (F-4)

* Percentage of the total mixture weight

** Percentage of materials by weight of total cementitious (cement + fly ash)

*** Percentage of materials by weight total aggregates (sand + pea gravel)

Table 4-48: Compressive Strength, Bulk Density, and Water Absorption of Blocks

Mix No.	Compressive Strength (psi)		Bulk Density (lb./cu. ft.)		Water Absorption %	
	Individual	Average	Individual	Average	Individual	Average
1	470 480 530	490	154.3 156.0 153.9	154.7	8.0 8.7 7.6	8.1
3	484 448 454	460	151.3 145.9 147.9	148.4	8.0 7.7 8.9	8.2
5	365 408 394	390	152.1 145.1 148.1	148.4	8.3 9.7 9.0	9.0

Note: Tests were performed after 7 days curing (24-hour steam curing plus 6 days fog room curing).

The compressive strength values were somewhat lower than expected even for the no fly ash mixture. The reason is believed to be the size effect. Local block manufacturing companies have also documented such reduction in strength when small blocks are tested. However, mix no. 3 with Class C fly ash showed compressive strength comparable to the control mix.

The bulk density measurements showed that the blocks containing fly ash are slightly lighter. The lower bulk density translates to better insulating properties, improved resistance to freezing and thawing, lower heat losses, and lower dead load in structures.

The water absorption for all the mixes are within the limits of ASTM C-55. Dimensional stability tests did not show any change. These tests should also be performed on full-size blocks to verify the results.

CalStar Green Bricks and Pavers Using We Energies' Fly Ash

CalStar opened its first fly ash brick manufacturing plant in Racine, Wisconsin in January 2010. The plant makes the architectural bricks and pavers using Class C fly ash sourced from We Energies OCPP. CalStar green bricks and pavers are non-fired and do not use clay. They are made from ASTM C-618 Class C fly ash, a self-cementing byproduct of coal combustion. Fly ash, aggregate, mineral oxide pigments, and proprietary ingredients are mixed with water, vibro-compacted, and cured into a stable solid.

CalStar brick is used to build in the time-honored tradition of masonry construction. Masonry's inherently sustainable qualities include its acoustic performance, high thermal mass and exceptional durability. Its thermal mass can stabilize indoor temperatures, saving energy and improving thermal comfort. CalStar pavers are used to construct walkways, plazas, patios and driveways, on flexible or pervious bases providing a beautiful durable surface. The end product can reduce runoff, stormwater impacts, and erosion when laid in open configurations. Light colors can reduce the heat island effect, helping keep cities and developments cooler. CalStar bricks and pavers therefore, add great environmental value to projects because they are manufactured with fly ash and convert it to a strong, beautiful building material instead of mining virgin clay and firing it. Structures constructed using CalStar bricks and pavers have long service lives because of proven durability. Manufactured by CalStar Products, Inc. in Caledonia, Wisconsin using fly ash, both CalStar bricks and pavers save production energy, preserve natural materials, conserve landfill space, reduce carbon emissions, and provide a market for byproduct materials.

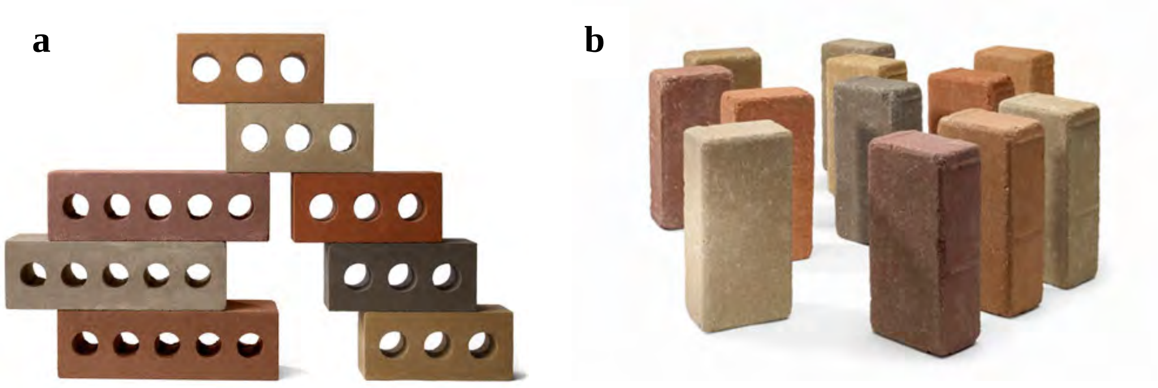


Figure 4-27: Environmentally green CalStar bricks (a), and CalStar pavers (b) made from We Energies' OCPP Class C fly ash.

CalStar bricks offer a green material choice with performance properties and dimensions that meet or exceed requirements of ASTM C-216 for SW (Severe Weathering) and ASTM C-216 Type FBX (the most precise dimensional tolerance criteria) respectively, making it suitable for use as a face brick in severe and freeze-thaw conditions. CalStar pavers equally offer a green material choice with performance which meet or exceed performance requirements of ASTM C-902 for Class SX clay pavers and ASTM C-936 for interlocking concrete paving units, suitable for pedestrian and light vehicular traffic, in severe climates and freeze-thaw conditions.

Why CalStar bricks and CalStar pavers are environmentally green materials

One increasingly useful way to measure a product's environmental impact is to audit its 'embodied energy' and 'carbon footprint'—the amount of energy consumed and CO_2 released in the extraction, processing and transportation of raw materials and manufacture of the finished product. One focus of materials research and development is finding ways to reduce the environmental footprint without sacrificing other product benefits.

Clay brick is high in both embodied energy and carbon footprint. Clay brick manufacturing is energy-intensive because clay requires firing for up to three days to become hard and durable. Brick firing kilns operate at about 2,000 ^{o}F, and are generally kept hot even when not in use. The heat for most kilns is generated by burning natural gas, while some brick producers use fuels such as coal and petroleum coke. All of these fuel sources emit CO_2 during combustion.

The National Institute of Standards and Technology (NIST) Building for Environmental and Economic Sustainability (BEES) database lists the average embodied energy for a common fired clay brick at 8,800 BTUs. The Brick Industry Association (BIA) notes that a clay brick plant operating at optimal efficiency might reduce this figure to 5,000 BTUs. For purposes of these calculations, a middle ground of 6,000 BTUs of embodied energy was selected. CO_2 emissions are often a by-product of energy consumption; each clay brick fired with fossil fuel conservatively releases 0.9 lbs of CO_2 into the atmosphere.

Producing bricks from recycled fly ash consumes less energy and emits less CO_2 because it does not require firing to harden the masonry units, and does not use cement with its CO_2 emissions. Since CalStar bricks and CalStar pavers are not fired, all the energy which could have been used for this purpose is saved, and CO_2 emissions are reduced. This makes CalStar bricks and pavers green products.

For more information visit the manufacturer's website at www.calstarproducs.com.

Fly Ash Concrete for Precast/Prestressed Products

We Energies' fly ash has also been used to produce precast/prestressed concrete products. We Energies initiated a study to develop mixture proportioning information for the production of high early strength concrete with high fly ash content for precast/prestressed concrete products (39).

Materials

The ASTM C-618 fly ash used in this project was produced by We Energies at the Pleasant Prairie Power Plant. A Type I cement was used and the replacement quantities with Class C fly ash were 0, 10, 15, 20, and 30%. Twelve different mixture proportions were developed based upon a nominal 5000 psi control mixture that contained no fly ash. Table 4-49 shows the first six mixture proportions.

Concrete Mixing and Specimen Preparation

Concrete was produced at two different precast/prestressed concrete plants. Standard batching and mixing procedures for ready mixed concrete were followed, in accordance with ASTM C-94. Fresh concrete tests included slump and air content. Cylinders were cured following the actual practice of the individual precast/prestressing plant.

Compressive Strength

The test results indicated that the compressive strength of the concrete mixtures increased with the increase of replacement percentage of cement with Class C fly ash after 3 days (5060 psi) and 28 days (8435 psi) of curing as shown in Table 4-50. The maximum compressive strength was obtained for a 25% Class C fly ash replacement. Therefore, Class C fly ash usage increased the early strength of concrete. The strength results also indicated that cement replacement with up to 30% of Class C fly ash increased the early strength relative to the mixture without fly ash.

Workability

Workability was observed and noted throughout the project. All the concrete produced was homogeneous and cohesive. The fly ash replacement did not affect these properties. Slump measurements show variations because of the use of a superplasticizer. Even though the water to cementitious ratio decreased as the fly ash was increased, clearly acceptable workability was maintained.

There are several advantages of using Class C fly ash in concrete precast/prestressed products:

1. Improved economics are possible as a result of reduced raw material costs resulting in the use of more competitive products over a wider geographical region.
2. Class C fly ash usage in concrete provides higher quality products which include higher density with reduced permeability, increased strength and other properties.
3. Fly ash concrete mixes are handled more easily because of improved workability. Faster release of prestressing tendons is also possible because of increased early age strength with use of Class C fly ash.

Table 4-49: Concrete Mixture Proportions

Mix No.	1	2	3	4	5	6
Specified design strength (psi)	5000	5000	5000	5000	5000	5000
Cement (lbs)	628	572	554	528	491	459
Fly ash (lbs)	0	77	119	160	198	238
Water (lbs)*	283	263	253	248	237	227
Sand @ SSD (lbs)	1278	1294	1328	1343	1332	1370
1 inch aggregates @ SSD (lbs)	1807	1830	1877	1899	1884	1887
W/(C + FA)	0.45	0.41	0.38	0.36	0.34	0.33
Slump (in.)	2¾ **	6½	6¾	4¾	7	4¼
Air content (%)	5.4	4.5	2.4	2.0	2.1	1.6
Air temperature (ºF)	70	70	70	70	70	70
Concrete temperature (ºF)	69	66	70	69	69	69
Concrete density (pcf)	148.0	149.5	153.0	154.7	153.4	154.9

*90 fluid oz. of a nominal 42% solid sodium naphthalene condensate ASTM C-494 Type F admixture (superplasticizer) was added to all mixes

**Reduced slump because of delay in testing; actual slump approximately 5 inch initially when truck arrived

Table 4-50: Concrete Strength Using Prestressed Concrete

Mix No.	**1**		**2**		**3**		**4**		**5**		**6**	
Specified strength (psi)	**5000**		**5000**		**5000**		**5000**		**5000**		**5000**	
Fly Ash (%)	**0**		**10**		**15**		**20**		**25**		**30**	
Test age (days)	**Compressive Strength (psi)**											
	Act.	**Avg.**	**Act.**	**Avg.**	**Act.**	**Avg.**	**Act.**	**Avg.**	**Act.**	**Avg.**	**Act.**	**Avg.**
19 hours	2720		2950		3330		4170		3860		3110	
22 hours	2790		3180		3750		4140		3400		3290	
3	3040	3235	3710	3800	4100	4095	4900	4890	4900	5060	4280	4475
	3430		3890		4090		4880		5130		4670	
7	3860	3750	4210	4155	5590	5520	5160	5640	6510	6315	6260	6170
	3640		4100		5450		6120		6120		6080	
14	4070	4210	4740	4685	6650	6615	5910	6175	7110	7075	7110	7305
	4350		4630		6580		6440		7040		7500	
28	4740	4774	5270	5395	7360	6830	8450	8080	8770	8435	8520	8365
	4810		5520		6300		7710		8100		8210	

Conductive Concrete Containing We Energies High Carbon Fly Ash

(US Patent 6,461,424 B1) (40)

Materials

Materials utilized in this project consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, steel fibers, and taconite pellets. Materials were characterized for chemical and physical properties in accordance with the appropriate ASTM standards. Table 4-51 shows the mixture proportions.

Type I cement (Lafarge Cement Co.) was used throughout this investigation. Its physical and chemical properties were determined in accordance with applicable ASTM test methods.

One source of fly ash was used for this project (We Energies, Port Washington Power Plant, Units 2 and 3). The ash selected for this project was non-standard (not meeting all requirements of ASTM C-618). This selection was made to develop and encourage additional uses for under-utilized sources of fly ash in Wisconsin.

In one concrete mixture, steel fibers were used to enhance electrical resistance. The steel fibers measured about 2” in length by ¼” wide.

All concrete ingredients were manually weighed and loaded in a laboratory rotating-drum concrete mixer for mixing following the procedures of ASTM C-192. The resulting mixture was then discharged into a pan where the concrete was further tested and test specimens were cast.

Table 4-51: Concrete Mixture Proportions

Mixture No.	**40**	**50**	**60**
Laboratory Mixture Designation	40	50	60
Steel Fiber (lb/yd^3)	0	105	0
Fly Ash (lb/yd^3)	265	260	265
Cement (lb/yd^3)	355	350	350
Fly Ash [FA/(C+FA)], (%)	43	43	43
SSD Fine Aggregate (lb/yd^3)	1285	1275	1265
SSD Coarse Aggregate (lb/yd^3)	1510	1485	1980*
Water, W (lb/yd^3)	39	395	420
[W/(C+FA)]	0.63	0.65	0.68
Air Temperature (°F)	80	78	78
Concrete Temperature (°F)	80	80	76
Slump (in.)	2	3.25	1.75
Air Content (%)	1.5	1.0	4.1
Unit Weight (lb/ft^3)	140.2	142.4	158.6

*Heavyweight aggregate (taconite pellets)

Fresh concrete properties were also measured for the mixtures. Properties measured included: air content (ASTM C-231), slump (ASTM C-143), unit weight (ASTM C-138), and temperature (ASTM C-1064). Air temperature was also measured and recorded. Cylindrical test specimens 6 inches dia. x 12 inches in length were prepared from each mixture for compressive strength (ASTM C-39) and density tests. All test specimens were cast in accordance with ASTM C-192. Concrete specimens were typically cured for one day at about 70 ± 5°F. These specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73 ± 3ºF temperature until the time of test (ASTM D-4832).

Electrical Resistance Measurements

In order to test the effect of the moisture on the electrical resistance of the material and the reliability of the measurements, six identical cylinders were made from each concrete mixture. Three specimens were left to air dry after demolding and three were placed in water to remain in a saturated condition for testing. Both the air-dried and saturated specimens were tested at the same ages for electrical properties. Resistance measurements were taken using a Leader LCR-475-01 multimeter at one pre-determined location on all six cylinders for each mixture across its length (Fig. 4-28).

Reactance Measurement and Calculation of Permeability

Reactance of the test cylinder was measured by placing the cylinder in a copper wire coil and measuring the reactance of the coil with air as the core (L_1) and with the test cylinder as the core (L_2). The reactance, L_1 and L_2, were determined using a Leader LCR-475-01 multi-meter. The resistance measurements were converted into resistivity values (ohm-cm). The measured reactance values were then used to calculate the permeability values from the relationship:

$$\frac{\mu_0}{\mu_1} = \frac{L_1}{L_2} \Longrightarrow \mu_1 = \frac{\mu_0 L_2}{L_1}$$

where:

L_1= Reactance of the coil with air core

L_2= Reactance of the coil with the test cylinder as the core

μ_0= Permeability of air ($4 \pi \times 10^{-7}$ Henry/meter)

μ_1= Permeability of the cylinder

Figure 4–28: Electrical Resistance Measurements

Concrete Compressive Strength

The compressive strength of the three concrete mixtures is shown in Table 4-52. The compressive strength of the mixtures was 2340 psi to 2535 psi at the age of 28 days. A typical concrete used for foundations and walls construction has a minimum specified 28-day compressive strength of 3000 psi to 4000 psi. The concrete strengths achieved for the mixtures developed as part of this project are below this usual strength level. The primary focus of this project was to determine the effect of various materials on the electrical properties of the concrete. Therefore, the compressive strength of the mixtures was considered secondary at this stage of the study. Mixtures can be revised in future phases to produce a higher strength material. The compressive strength of the concrete may be increased by increasing the cementitious materials and/or reducing the amount of water in the mixture (reducing the water to cementitious materials ratio). This may also be achieved by using chemical admixtures such as a mid-range or high-range water reducing admixtures (superplasticizer). The strength at various ages for these three mixtures is quite similar due to the fact that the cementitious materials and water to cementitious materials ratios are essentially the same.

Table 4-52: Compressive Strength of Concrete Mixtures

Mixture No.	Fly Ash [FA/(C+FA)], (%)	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
40	43	1115	1025	1395	1455	1760	1810	2590	2535
		980		1485		1810		2460	
		990		1490		1855		2555	
50	43	1000	970	1425	1380	1960	1850	2390	2385
		965		1300		1785		2370	
		940		1420		1810		2395	
60	43	805	830	1360	1370	1695	1760	2352	2340
		850		1460		1825		2242	
		-		1300		1760		2427	

Electrical Properties of Concrete Mixtures

The electrical properties of the concrete mixtures are shown in Tables 4-53 and Figure 4-29. The electrical resistivity of the air dried concrete is in the range of 1 to 128 x 10^3 ohm-cm. The air dried conventional concrete typically has a resistivity of the order of 10^6 ohm-cm, with oven dried conventional concrete having a resistivity of the order of 10^{11} ohm-cm. Therefore, it is apparent that the electrical resistivity of concrete is less than the electrical resistivity of conventional concrete. In other words, by incorporating high carbon fly ash into a concrete mixture, a more electrically conductive concrete is produced. The permeability of a concrete prepared with high carbon fly ash exceeds that of air, indicating a greater capability to carry an electrical current. The use of fly ash having greater levels of carbon would further decrease the resistivity of the resulting concrete. In addition, the increased concentration of high carbon fly ash in the composition will result in increased conductivity.

Table 4-53: Electrical Properties of Concrete Mixtures

Mixture No.			40	50	60
Fly Ash Content wt., % [FA/(FA+C)]			43	43	43
Fly Ash Content wt., % [FA/(FA+C+S+G)]			7.76	7.72	6.87
Resistivity (ohm-cm)	Air-Dried	3	4588.5	1715.8	3152.2
		7	7955.5	3590.8	4628.0
		14	14263	6403.7	9974.8
		28	2733.0	10672	127674
	Saturated	3	1376.5	997.7	1336.4
		7	1875.0	1017.4	1376.5
		14	2793.1	1156.8	1416.6
		28	4069.6	1486.0	1695.5
Relative Permeability	Air-Dried	3	1.004	1.082	1.048
		7	1.004	1.082	1.048
		14	1.004	1.082	1.048
		28	1.004	1.082	1.048
	Saturated	3	1.006	1.089	1.051
		7	1.006	1.089	1.051
		14	1.006	1.089	1.051
		28	1.006	1.089	1.051

Conductive Concrete Containing We Energies High Carbon Fly Ash and Carbon Fibers (US Patent 6,821,336) (41)

Testing of concrete using carbon fibers was conducted for concrete mixtures. The goal of this testing work was to determine the feasibility of incorporating high carbon fly ash and carbon fibers in concrete to lower electrical resistance of these construction materials. The lowered electrical resistance of concrete mixtures will reduce the required length of, or entirely replace, the grounding electrodes currently in use for protection of electrical equipment from lightning strikes. Other uses can potentially include grounding, heating bridges, sidewalks or airport runways, sensors, and various other applications.

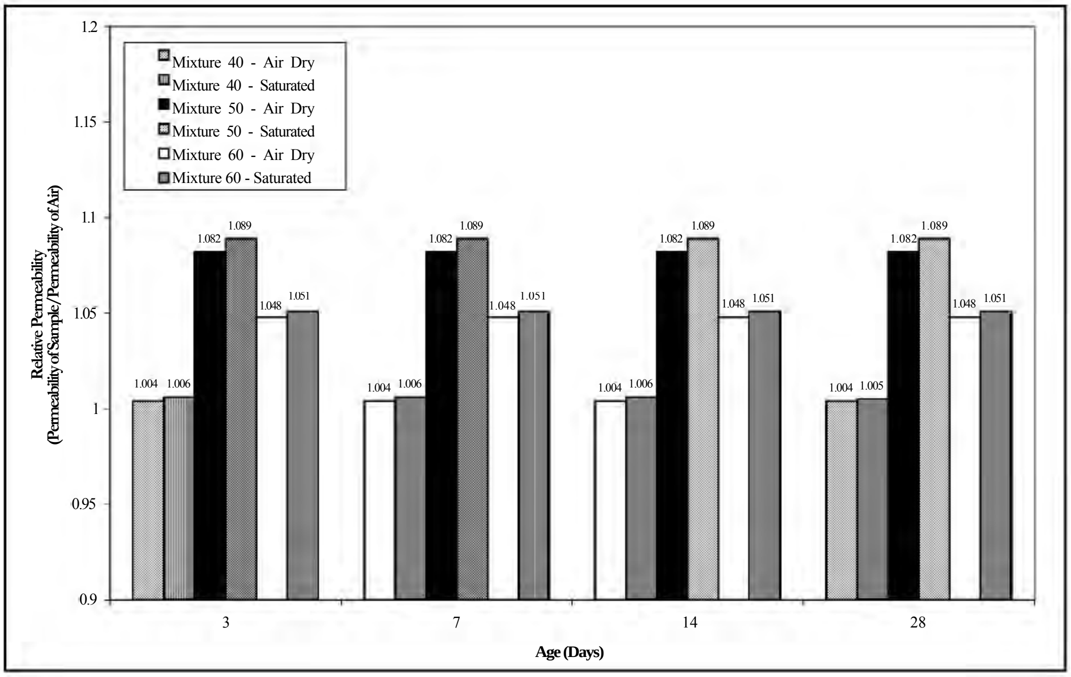


Figure 4–29: Relative Electrical Permeability of Concrete Mixtures

Materials

Materials utilized consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, and carbon fibers. One source of clean concrete sand was utilized in this investigation as fine aggregate for concrete mixtures. The aggregate used was a crushed quartzite limestone with a maximum size of ¾" meeting ASTM C-33 requirements. Type I cement (Lafarge Cement Co.) was used throughout this investigation. One source of fly ash was used for this project (We Energies, Presque Isle Power Plant). This selection was made to represent a typical high-carbon fly ash available from We Energies.

The fibers used for this project were Panex 33 chopped carbon fibers manufactured by the Zoltek Corporation, St. Louis, MO. The carbon fibers were pan-type fibers ½" long and approximately 0.283 mils (7.2 microns) in diameter. The density of the fibers reported by the manufacturer was 0.065 lb/in^3.

All concrete ingredients were manually weighed and loaded in a laboratory rotating-drum concrete mixer following the procedures of ASTM C-192. The test concrete was also manufactured. A high-range water reducing admixture was used for the concrete mixture to achieve the desired slump.

The amount of carbon fibers incorporated into the concrete mixture was determined by We Energies. Mixture CON-C contained approximately 40% fly ash by weight of total cementitious materials, a high-range water reducing admixture, and the addition of 14 lb/yd^3 of carbon fibers. Table 4-54 shows the mixture components.

Table 4-54: Concrete Mixtures

Mixture No.	**CON-C**
Laboratory Mixture Designation	WF-C
Mixture Description	High-Carbon Fly Ash Concrete with Carbon Fibers
Fly Ash, FA (lb/yd^3)	240
Cement, C (lb/yd^3)	330
SSD Fine Aggregate, S (lb/yd^3)	1200
SSD Coarse Aggregate, G (lb/yd^3)	1405
Carbon Fibers (lb/yd^3)	14
Fly Ash Content, % [FA/(FA+C)]100	42
Water, W (lb/yd^3)	470
High-Range Water Reducing Admixture (oz/yd^3)	170
[W/(C+FA)]	0.82
Air Temperature (°F)	73
Fresh Concrete Temperature (°F)	65
Slump (in.)	1
Air Content (%)	2.0
Unit Weight (lb/ft^3)	135.0
Hardened Concrete Density (lb/ft^3)	130

Mechanical Properties

Compressive strength of the concrete was measured using standard cylinders, 6" diameter x 12" long, following the method of ASTM C-39. The compressive strength of concrete Mixture CON-C is shown in Table 4-55. The compressive strength of the mixture was very low at the early age and could not be measured until the age of 16 days. At the age of 16 days, the compressive strength was only 60 psi. The compressive strength increased at the age of 28 days to 135 psi, and then significantly increased at the 42-day age to 1345 psi. This indicates that the setting time of the concrete mixture was significantly delayed, and reflects the pozzolanic effect of 40% fly ash content contributing to this increase in strength. The delay in setting was attributed to the amount of high-range water reducing admixture (HRWRA) required to be added to the mixture. The amount of HRWRA exceeded the maximum amount recommended by the manufacturer (136 oz/yd^3 versus 170 oz/yd^3 actually used in the laboratory mixture). Another possibility investigated was to determine if the water-soluble chemical coating on the carbon fibers had any effect on the setting time of the mixtures. The water-soluble “sizing” coating is applied to prevent the agglomeration of the fibers but yet sustain electrical contact of the fibers in the concrete mixture. The sizing (coating) that was used on the carbon fibers was provided by the manufacturer, Zoltec.

A test was conducted on cement mortar cubes per ASTM C-109 using water that was obtained from soaking the carbon fibers for 24 hours. The compressive strength of the cement mortar cubes at the age of seven days was 5070 psi. This indicates that the water-soluble sizing probably did not have any time of setting delay effect on the compressive strength of cement mortar. The concrete compressive strength achieved for the Mixture CON-C tested for this project is below its normally expected strength level. The primary focus of this project was to determine the effect of carbon fibers on the electrical properties of the concrete. Therefore, the compressive strength of the mixtures was considered secondary at this stage of the study. The amount of fibers can be revised in the future phases to produce a good-quality structural-grade concrete. The amount of carbon fibers may be reduced and optimized for electrical properties. Compressive strength of the concrete may be increased by increasing the cementitious materials and/or reducing the amount of water in the mixture.

Table 4-55: Compressive Strength of Concrete Mixture

Mixture No.	Fly Ash Content, % [FA/(C+FA)]	Compressive Strength (psi)							
		3-day		16-day		28-day		42-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CON-C	42	--	--	80	60	145	135	1265	1345
		--		50		145		1355	
		--		50		120		1410	

Electrical Properties

The electrical resistivity obtained for the concrete Mixture CON-C are given in Table 4-56 and Figure 4-30. Overall, resistivity of both air-dried and saturated specimens were comparable with approximately 40 to 50 ohms-cm at the age of 16 days and 60 to 70 ohms-cm at the age of 42 days. Although the compressive strengths were much lower for the Mixture CON-C than a typical concrete used for many construction applications, the lower resistivity values achieved through the incorporation of high-carbon fly ash and carbon fibers are very promising for potential grounding applications. Further refinement of the carbon fiber content to optimize the resistivity and strength properties of the concrete is needed as a part of future laboratory studies. The permeability values show only a slight increase between 16 and 28 days. The relative electrical permeability of air-dried and saturated specimens were very close to each other as shown on Figure 4-29.

For CON-C, the air-dried specimens also had a higher electrical resistivity at the age of 42 days, but the difference between saturated and air-dried specimens was less. Typically the difference between air-dried and saturated specimens was 10 ohm-cm or less. This may be attributed to the conductivity of the carbon fibers used in the mixtures.

Table 4-56: Electrical Resistivity of High Carbon Concrete Mixture with Carbon Fibers

Mixture No.	Fly Ash Contents, % [FA/(C+S+G)]	Resistivity (Ohm-cm)							
		7-day		16-day		28-day		42-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CON-C	93	Air –Dried Specimens							
		---	---	42.45	42.8	47.3	47.6	77.2	72.1
		---		43.1		47.9		67.0	
		Saturated Specimens							
		---	---	52.7	48.5	49.7	44.9	65.2	67.3
		---		44.3		40.1		69.4	

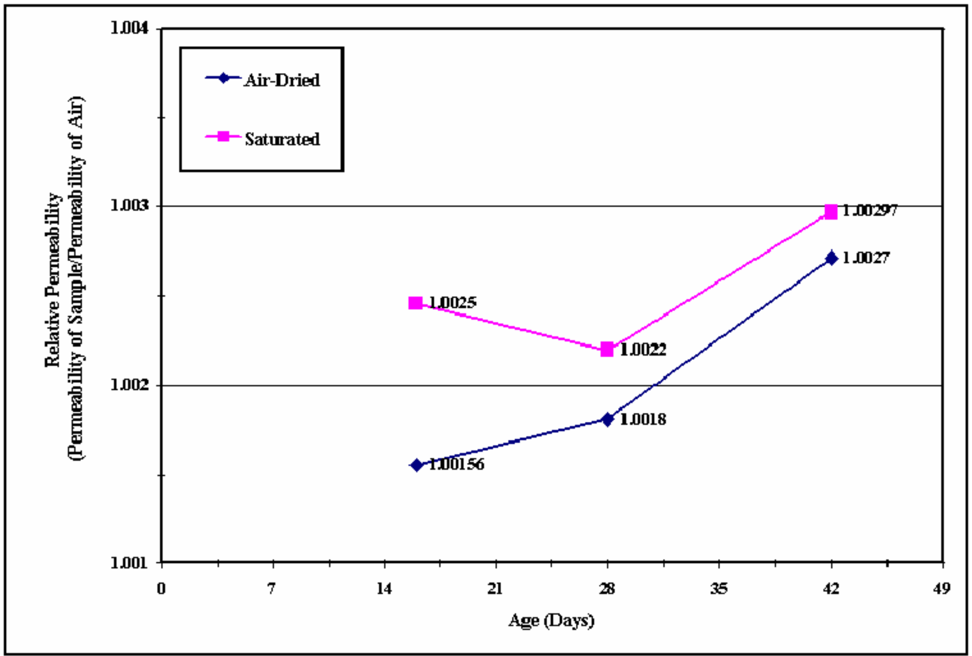


Figure 4–30: Electrical Permeability of High Carbon Fly Ash Concrete Contained Carbon Fibers, Mixture CON-C

Conductive Concrete Containing We Energies Fly Ash and Spent Carbon Sorbent (US Patent 7,578,881) (42)

Testing of concrete using spent carbon sorbent (having small amounts of mercury absorbed/entrapped by the sorbent) was conducted for concrete mixtures. The goal of this work was to determine if the carbon and mercury in the spent carbon sorbent would lower electrical resistance of these construction materials when incorporated in concrete. The lowered electrical resistance of concrete mixtures has the potential to reduce the required length, or entirely replace the grounding electrodes currently in use for protection of electrical equipment from lightning strikes. Other uses can potentially include lowering the impedance conduction path to earth for electric system protection, and stabilization.

Materials

Materials utilized consisted of one source of fly ash, cement, clean concrete sand, gravel aggregates, and a particulate material including fly ash and a spent activated carbon sorbent having small amounts of adsorbed mercury. One source of clean concrete sand was utilized in this investigation as fine aggregate for the concrete mixture, meeting the ASTM C-33 requirements. The coarse aggregate used was natural river gravel with a maximum nominal size of ⅜ inch. Type I Portland cement was used throughout this investigation. A cementitious fly ash was also used for this project (We Energies, Pleasant Prairie Power Plant) meeting the requirements of ASTM C-618, Class C fly ash.

The spent activated carbon particulate material included some Class C fly ash that had passed through the electrostatic precipitator and was captured with the carbon sorbent in the baghouse.

All concrete ingredients were manually weighed and mixed by hand in a mixing bowl. For fresh concrete, an estimate was made of the unit weight for determination of approximate mixture proportions and a general visual observation of the workability was made. Table 4-57 shows the mixture components.

Table 4-57: Concrete Mixture Proportions

Mixture No.	Concrete
Cement, C (lb/yd^3)	474 (13.13 wt %)
Class C Fly Ash, FA (lb/yd^3)	190 (5.27 wt %)
Particulate Matter Having Fly Ash & Spent Carbon sorbent, SC (lb/yd^3)	285 (7.90 wt %)
Water (lb/yd^3)	520 (14.41 wt %)
[W/(C + FA + SC)]	0.55
Carbon Fibers (lb/yd^3)	4.7 (0.13 wt %)
Sand SSD (lb/yd^3)	950 (26.33 wt %)
⅜-in. Aggregate, SSD (lb/yd^3)	1185 (32.84 wt %)
Fresh Density (lb/ft^3)	133.6

Note: The weight percent are the percent of the total mixture

Table 4-58: Concrete Mixture Test Results

Test	Concrete
Electrical Resistance (ohms)	69.6
Electrical Resistivity (ohms-cm)	208
Compressive Strength @ 50-day (psi)	3070

Mechanical Properties

A test cylinder of 3 inch diameter by 6 inch length was cast with the concrete mixture following air curing in the laboratory at 70º F ± 5ºF until the time of testing. Table 4-58 shows the test results for the mixture. Electrical resistance of the concrete was measured using copper plates (3-in. diameter on each end) across the 6 inch length of the concrete sample. The test indicated a resistance of 69.6 ohms at the age of 39 days. The electrical resistivity was calculated to be 208 ohms-cm from the measured resistance, using the following equation below:

$$R = \frac{\rho L}{A}$$

where: ρ = resistivity; L = length; A = cross section area

Using the standard method, concrete per ASTM C-39 and ASTM per ASTM D-4832, the compressive strength for the concrete cylinder sample resulted in a compressive strength of 3070 psi at the age of 50 days. These results show another way to increase the electrical conductivity of concrete by using spent activated carbon sorbent and carbon fibers.

Long Term Field Performance Testing of Conductive Concrete Resistivity at Three We Energies Sites

We Energies has performed ground resistance testing at three of its sites in different soil environments. Factors such as the soil type, moisture content and temperature influence soil resistivity. Table 4-59 shows the typical resistivity versus the soil type. The locations of the sites selected included, Caledonia Landfill with a clay environment, Pewaukee SCC Landfill with a sand and gravel environment, and Germantown Power Plant with a near surface limestone bedrock environment. An ongoing project is being conducted in these three different environmental conditions where conductive concrete foundation blocks were installed for impedance measurement.

Table 4-59: Soil Resistivity Based on Soil Type*

Soil Type	**Resistivity (ohm-m)**
Clays	10-150
Sandy Clays	150-600
Pure Sand	600-5000
Gravel	5000-30,000
Shale/Slate	400-1,000
Limestone	1,000-5,000
Sandstone	5,000-50,000
Granite	1,000-80,000

*Data from SAE Inc. Grounding Systems (http://materias.fi.uba.ar/6209/download/Solid.pdf)

Ground Resistivity Testing (43)

This test is performed by using the four-pole testing method in which two voltage and two current poles are used. The actual resistivity is the average of the resistivity calculated for each measurement point.

I. Caledonia Landfill

This site is located near the landfill's leachate collection load out station in the Town of Caledonia near Oak Creek Power Plant. The texture of soil at this location is primarily clay. During the testing, the soil was moist due to rain. The average soil resistivity calculated at this site was 37.1 ohm-meter. Figure 4-31 shows the variation of the resistivity versus probe spacing.

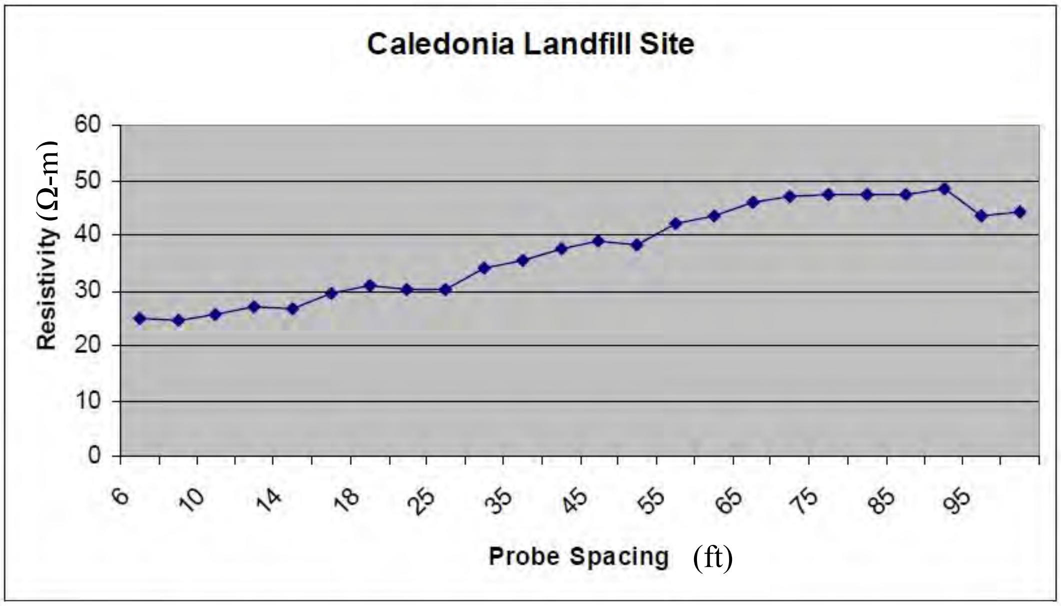


Figure 4–31: The ground resistivity profile at Caledonia Landfill site in clay soil

II. Pewaukee System Control Center Landfill

This site is located at System Control Center landfill in Pewaukee. The soil texture is sand and gravel with thin layers of silt and clay overburden. Due to the sand and gravel texture, the measured resistance is higher than that at the Caledonia Landfill site. The average soil resistivity calculated at this site is 126.8 ohm-meter. Figure 4-32 shows the resistivity profile.

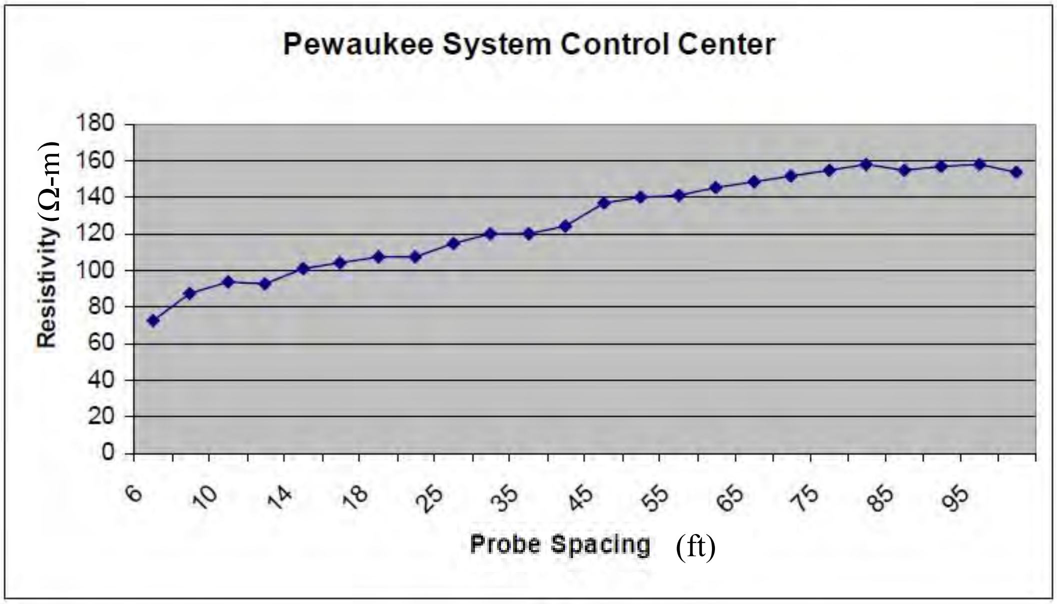


Figure 4–32: The ground resistivity profile at Pewaukee System Control Center site in sand-gravel soil.

III. Germantown Power Plant

This site is located at N96 WI9298 County Line Road, Germantown near Germantown power plant. The site has bedrock near the ground surface. The measured resistance did not show consistency, which is normal in grounds with high resistivity. The average resistivity calculated at this site is 538.5 ohm-meter. Figure 4-33 shows the resistivity profile.

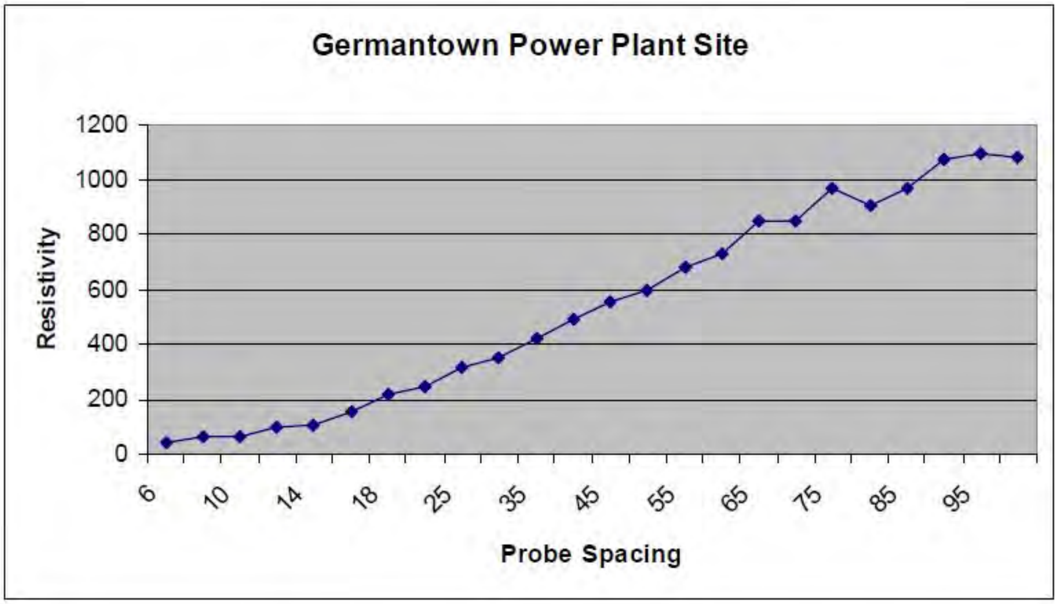


Figure 4–33: The ground resistivity profile at Germantown Power Plant site in soil near surface bedrock

Test Results

The electrical resistivity results for each test site are consistent with the texture of the soil. Typically, grounding systems are designed to have a resistance of below 5 ohms. Hence, it is important to understand the soil environment when designing a grounding system. In sites with higher resistivity, like Germantown power plant, larger grounding grids are typically required to lower the total resistance.

The next phase of this testing was the installation of a conductive concrete block at each of the three sites and measuring the seasonal resistance, inductance and capacitance for a period of time to obtain the grounding characteristics for this material.

Conductive Concrete Resistivity Field Testing (44)

The purpose of this test is to characterize the impedance profile of conductive concrete for electrical grounding. It is performed by installing conductive concrete foundation blocks at the three sites with different soil environments. The conductive concrete is designed to have a compressive strength of 3,000 psi and has the following components in the mixture: cement (Class C fly ash and Portland cement), aggregate ($^3/_8$ inch aggregate and torpedo sand), water, and additives include Class F – high carbon fly ash with LOI of about 20%, carbon fibers, paper manufacturing wastewater residual fiber, and superplasticizer. The paper manufacturing wastewater microfibers residual reinforces and substitutes for an air/void system for freeze/thaw protection in the concrete.

Seasonal ground resistance measurements were conducted to properly characterize the grounding resistance profile of the conductive concrete. The first test was performed in fall on December 8, 2010, a second test in winter on March 3, 2011, a third test in summer on August 26, 2011 and finally a follow up study will be conducted in spring 2013. A rebar cage was built in a 5' long x 2' wide x 5' deep foundation with a copper test lead welded to the cage and cast into the conductive concrete foundation. The copper test lead provides the electrical connection to the conductive concrete foundation. Figure 4-34 shows the conductive concrete foundation at the Caledonia Landfill site. The testing was performed by measuring the resistance between the test lead connecting to the conductive concrete and a test lead connecting to the utility network ground (neutral). A variable frequency power supply was used to apply a voltage between conductive concrete and the utility ground. The impedance of the conductive concrete block has been measured at a frequency range of DC through 800 kHz. During this test, the conductive concrete slab has shown higher impedance for DC current than AC current. The impedance values beyond 100 kHz were not trusted due to signal attenuation, noise, and interference. A Fluke meter and an oscilloscope were used for voltage and current measurements.

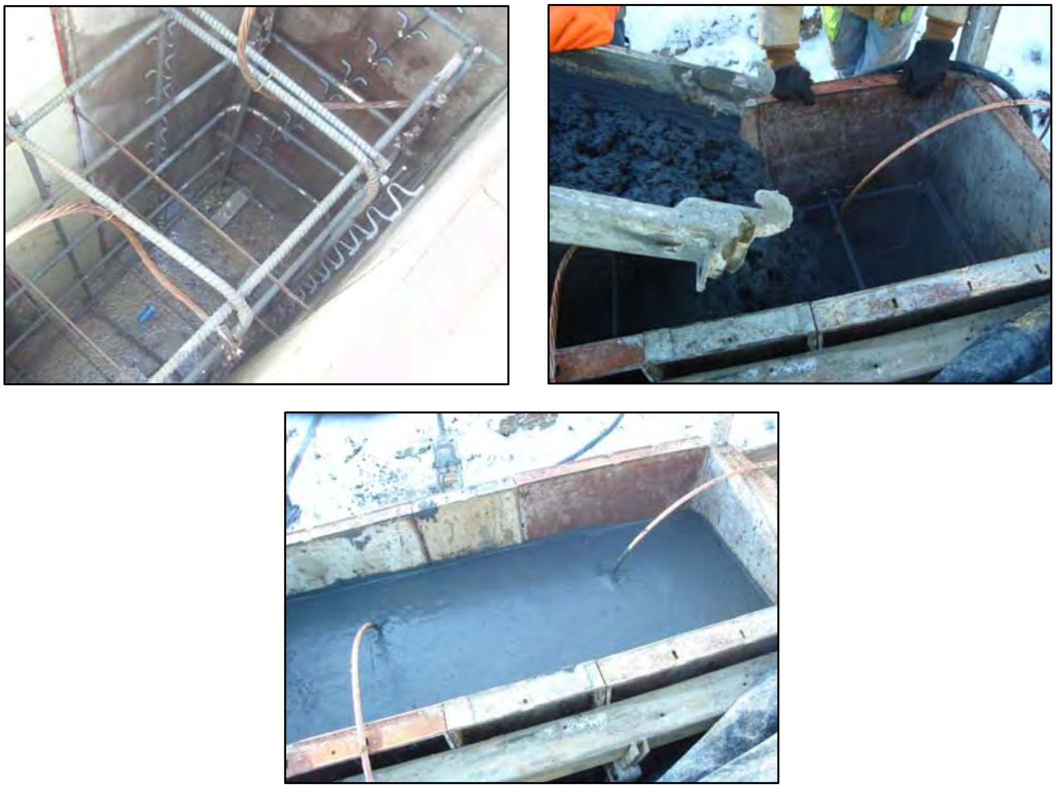


Figure 4–34: The placement of conductive concrete slab during construction at the Caledonia Landfill site

I. Caledonia Landfill

This site is located near the landfills leachate collection load out station in the Town of Caledonia near Oak Creek Power Plant. The texture of soil at this location is primarily clay. For the Fall measurement, it had snowed several days before the testing and snow was on the ground but the soil was not frozen. For the Winter measurement, there was snow on the ground and the ground was frozen. For the Summer measurement, it was sunny but it had rained for several days before that and the soil was moist. Figure 4-35 shows the impedance profile for fall, winter and summer seasons.

II. Pewaukee SCC Landfill

This site is located at the SCC landfill in Pewaukee. The soil texture is sand and gravel with thin layers of silt and clay overburden. Figure 4-36 shows the impedance profile for fall, winter and summer season.

III. Germantown Power Plant

This site is located at N96 W19298 County Line Road, Germantown near Germantown power plant. It has bedrock near the surface ground. As shown in Figure 4-37, the impedance is higher than the other two sites, due to rocky soil. For comparison to the conductive concrete, a ground rod was also installed near the concrete slab. Figure 4-37 shows the impedance profile for fall, winter and summer seasons, and Figure 4-38 shows the impedance profile for the ground rod for comparison.

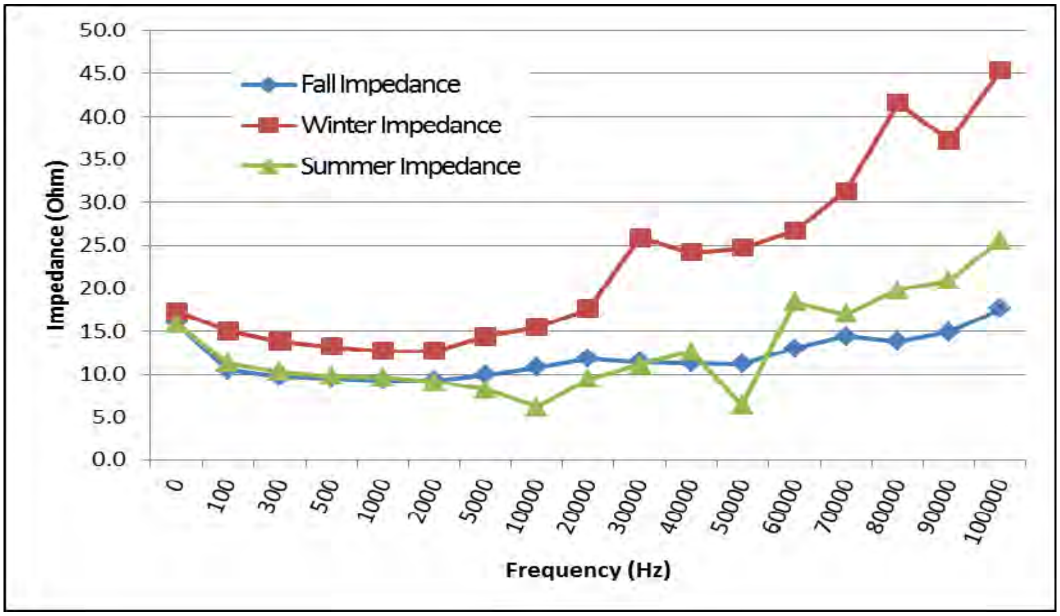


Figure 4–35: The impedance profile of the conductive concrete vs. applied frequency for fall, winter and summer at Caledonia Landfill

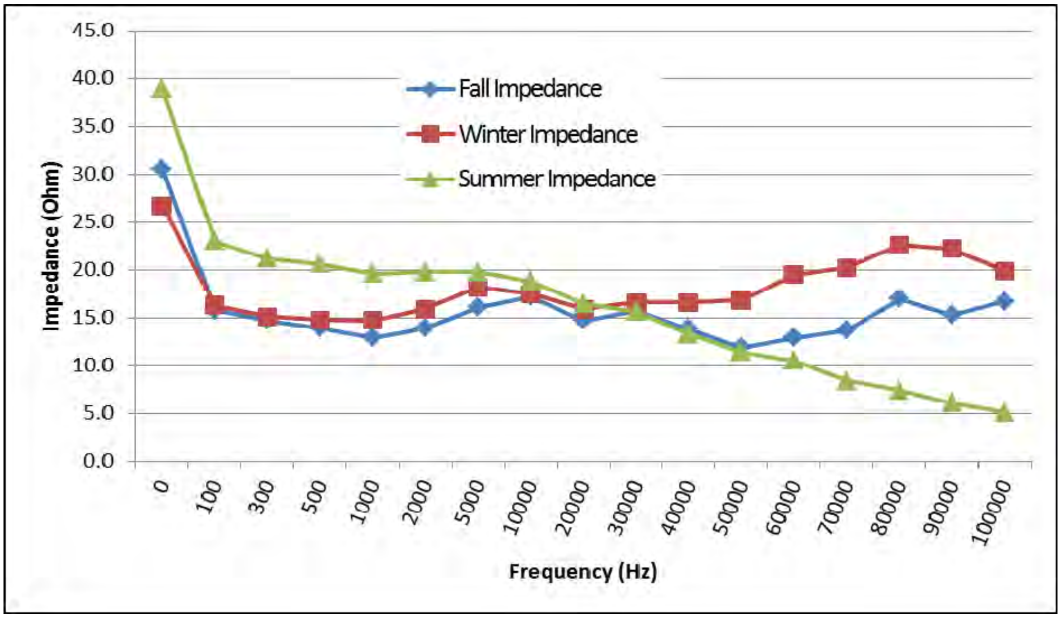


Figure 4–36: The impedance profile of the conductive concrete vs. applied frequency for fall, winter and summer at Pewaukee System Control Center Landfill

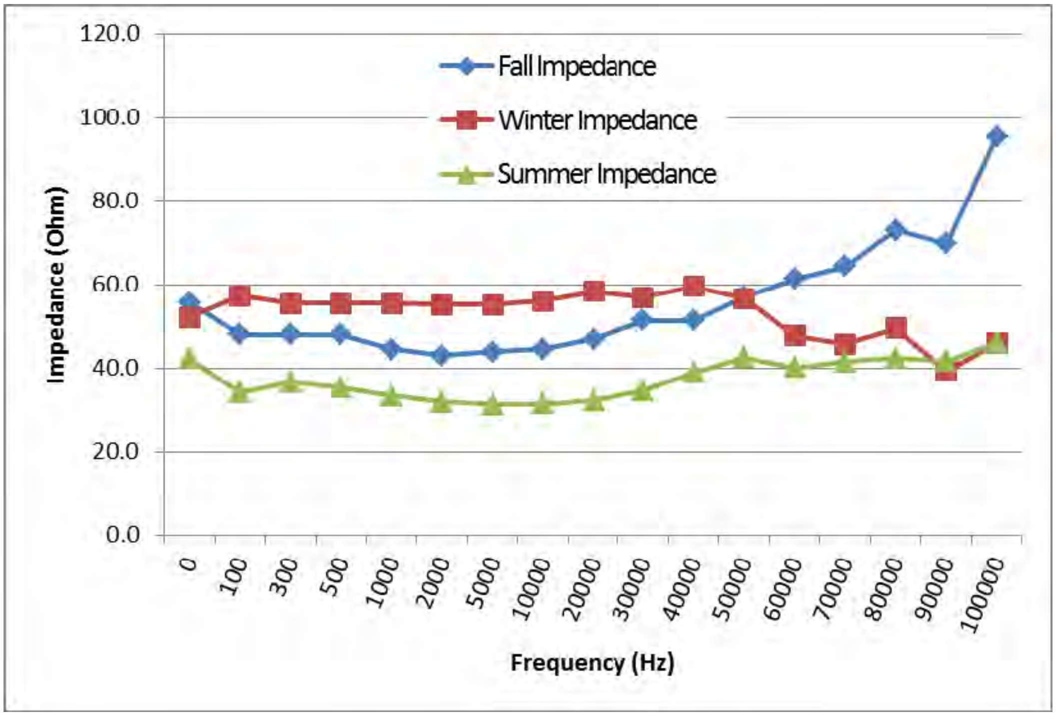


Figure 4–37: The impedance profile of the conductive concrete vs. applied frequency for fall, winter and summer at Gemantown Power Plant site

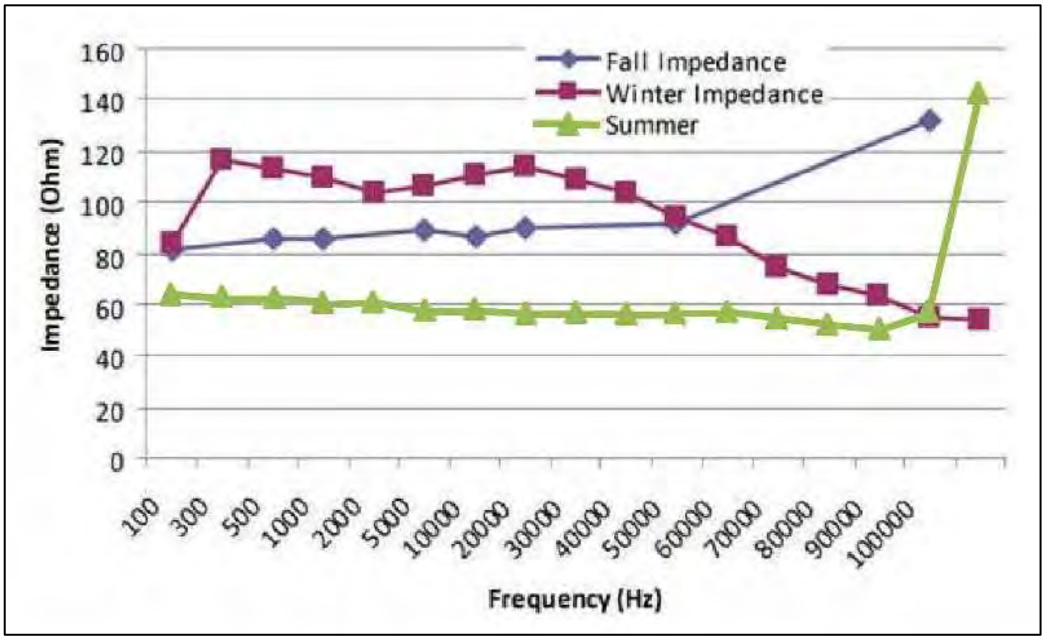


Figure 4–38: The impedance profile of a ground rod installed during fall, winter and summer season at Gemantown Power Plant site

Impedance Test Results on Conductive Concrete

After applying voltage with variable frequencies, the results have shown that there is ohmic resistance at higher frequencies during both fall and winter seasons. There is greater impedance in winter than fall due to frozen ground. As seen in the Figures 4-34 to 4-36, the impedance value is stable at low and mid frequencies (100 Hz – 50 kHz). At the Pewaukee site, the summer impedance is slightly less than winter and fall impedances for lower frequencies; and the summer impedance is less than winter and fall for higher frequencies. At the Germantown site, the impedance for summer is calculated less than the impedance in winter and fall seasons. Also, the impedance of the ground rod is 60% higher when compared with the conductive concrete block.

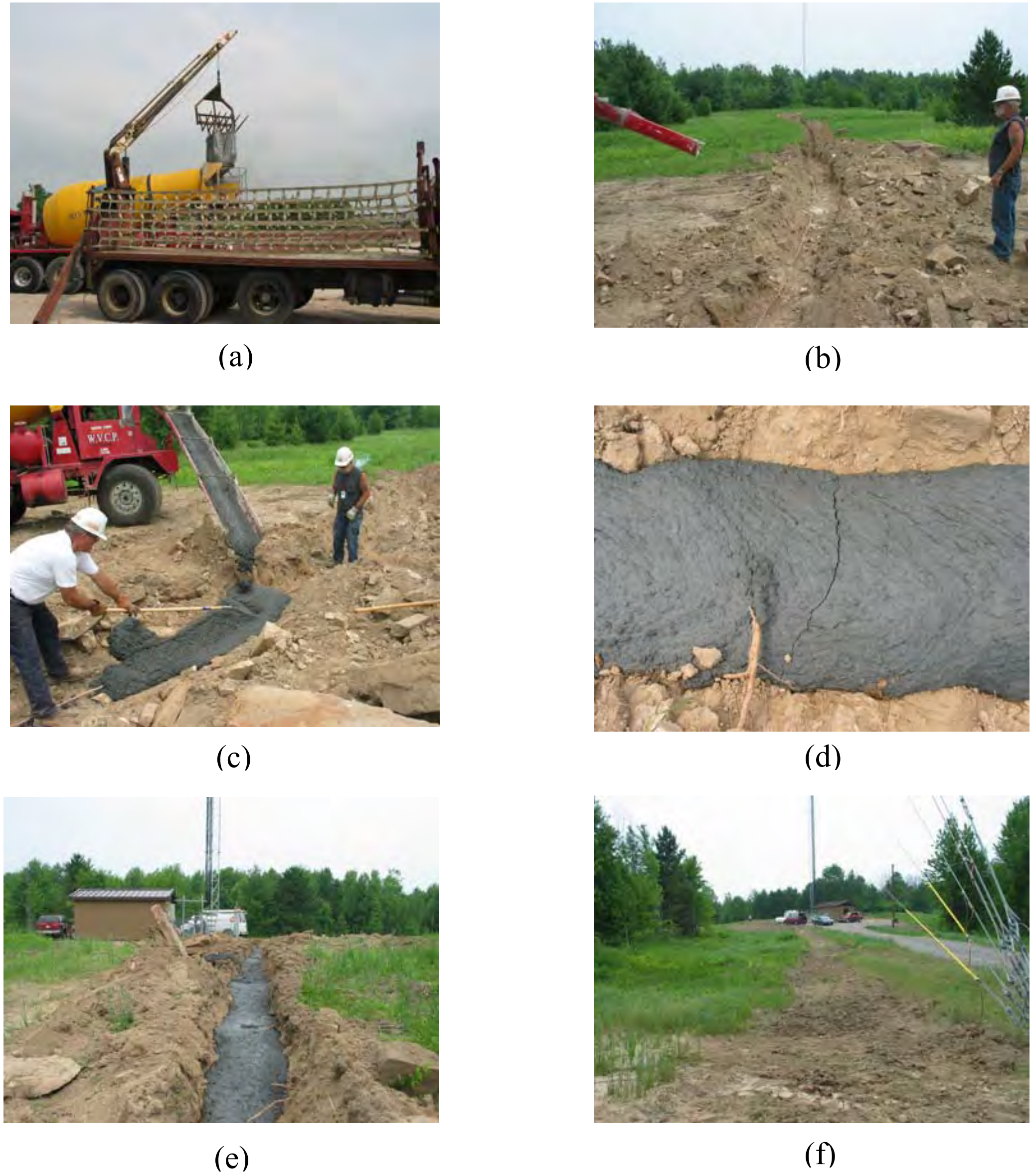
Electrically Conductive High-Carbon Fly Ash (HCFA) Concrete Used at a Telecommunication Tower

A telecommunication tower in Rudolph, Wisconsin was frequently struck by lightning causing damage and communication outages. Copper grounding wires had been installed underground from each guy wire anchor to the base of the tower. The guy wiring was configured radially in trios, with equal spacing from the tower (as a tripod structure). “The grounding system must comprise a conductor with sufficient conductivity and cross section to handle the energy of a lightning strike, and the interface between the conductor and earth must have sufficient surface area to transfer the energy into the ground. Since, the earth is not a good conductor, the interface must be large” (45). Therefore, for two of the grounding legs a trench (1ft wide x 6 in. deep) was dug where the copper wire and the high-carbon fly ash concrete is placed. Figure 4-39 shows the placement of the HCFA conductive concrete in the grounding trench for the Rudolph Tower.

Table 4-60 shows the conductive concrete mixture used for this site. It was estimated that within 28 days, the compressive strength would reach 3000 psi.

Table 4-60: Conductive Concrete Mix Design

Component		Quantity
Cementitious	Class C Fly Ash (lbs.)	300
	Portland Cement (lbs.)	500
Aggregate	$^{3}/_{4}$" Aggregate (lbs.)	1375
	Torpedo Sand (lbs.)	1075
Water		400
Additives	Class F – High Carbon Fly Ash (lbs.)	300
	(LOI ~ 20%)	
	Carbon Fiber (lbs.)	6
	Paper Residual Fiber (lbs.)	20
	Superplasticizer (lbs.)	20
	Slump (in.)	4



(a) (b) (c) (d) (e) (f)

Figure 4–39: Construction with electrically conductive high-carbon fly ash concrete as a grounding enhancement for a telecommunication tower in Rudolph, WI.

(a) Carbon Fiber is added to the concrete mix on site
(b) Placement of copper wire in the trench
(c) Filling the trench with the high-carbon fly ash conductive concrete
(d) Normal shrinkage cracking due to carbon fiber mix
(e) Completion of concrete placement
(f) Cover installation above the grounding

Conductive Concrete Tests: Compressive Strength and Ground Resistance

The compressive strength for the HCFA conductive concrete at the Rudolph tower was measured at ages of 3, 7, 14, 28, 56, and 91 days for two batches. Figure 4-40 shows the average compressive strengths over the time period. As shown, the compressive strength surpassed the estimated strength at 28 days and attained 4155 psi. An overall ground resistance measurement was taken over two time periods and is shown on Figure 4-41. On the second test day (9/5/2006), the overall resistance had decreased, providing an effective grounding resistance for the tower.

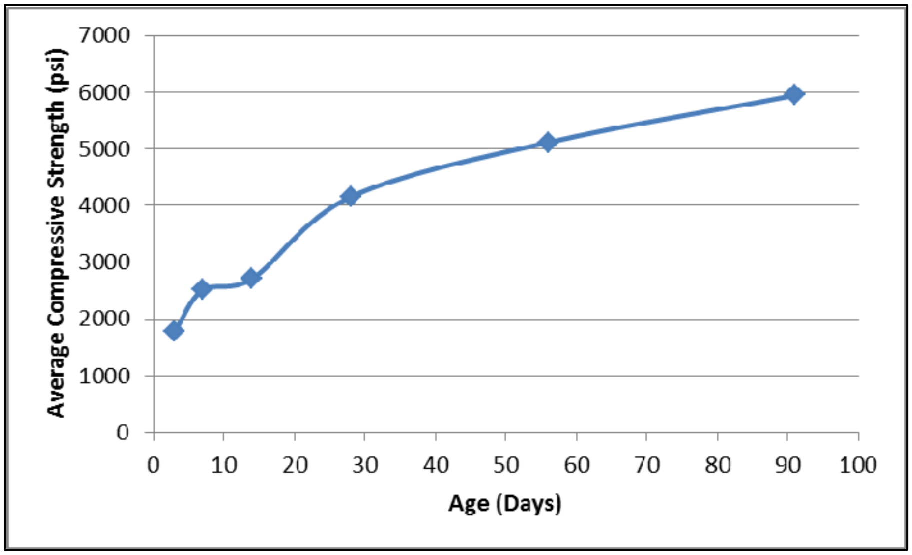


Figure 4–40: Average compressive strength of the HCFA conductive concrete versus the age at Rudolph Tower

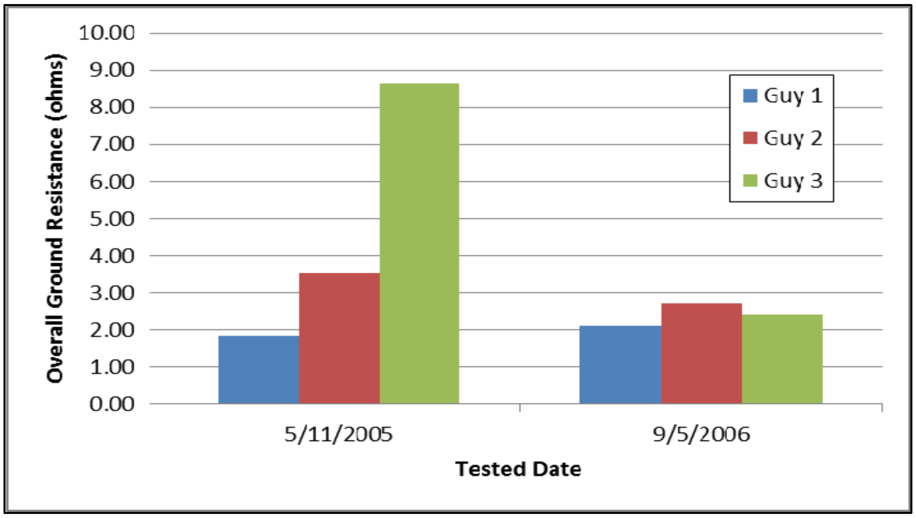


Figure 4–41: The overall ground resistance of the HCFA conductive concrete over two test dates at the Rudolph Tower.

Use of Conductive Concrete for Energy Storage – Electric Cell (46)

Electrically conductive concrete is a relatively new material when compared to the long history and development of conventional concrete materials. In fact, in the past emphasis was placed on preventing conductivity and providing concrete with a focus on resistance. More recently, conductive concrete has been developed with the goal of providing pavements with snow and ice melting capabilities. Design efforts have also been focused on development of enhanced electrical grounding systems for the power industry. Researchers have also been considering the potential for monitoring structural members for stress, strain, and cracking by monitoring a change in resistance of the concrete member.

The conductive concrete applications described above are all in introductory research, development, and demonstration stages. The potential for new applications is bright for this revolutionary new material. Imagine bridges that never get icy, buildings that are never harmed by lightning, and electric vehicles that recharge while driving. Such scenarios are possible with electrically conductive concrete and backfill materials using high-carbon fly ash. This innovative new material can also serve for potential energy storage purposes (47).

The main objective of this research was to evaluate the potential of a conductive concrete-zinc electric cell (in a saturated brine electrolyte) for storing electric power. The capability of the battery was evaluated by measuring the cell electrode potential as it is charging and discharging.

Materials and Methods

The mix design on a cubic yard basis for the 3 in. (76.2 mm) by 6 in. (152.4 mm) conductive concrete cylinder that was used as a cathode was composed of 300 lb Class C fly ash, 500 lb Portland cement, 1375 lb 3/8 in. Aggregates, 1075 lb Torpedo sand, 300 lb Class F fly ash (High Carbon fly ash), 400 lb of the City of Milwaukee water and 36 lb Carbon Fibers with a water to cementitious materials ratio of 0.36. These ingredients were homogeneously mixed dry before adding the measured amount of water.

Forty percent by weight of iodized NaCl was dissolved in de-ionized water in a plastic container to make a saturated NaCl brine electrolyte. The conductive concrete was placed into the electrolyte and centered in the middle of the plastic container. A cylindrical galvanized zinc plate was inserted into the electrolyte and clipped at the wall of the electrolyte container. A voltmeter was then connected in the circuit (Figure 4-42). The cell was then charged for 45 minutes using a12.8V battery, and the rate of charging was recorded initially after 5 minutes, then every 10 minutes for 45 minutes. After the charging process, the battery was disconnected, and the conductive concrete-zinc cell was allowed to discharge for 36 minutes, and the rate of discharge recorded.

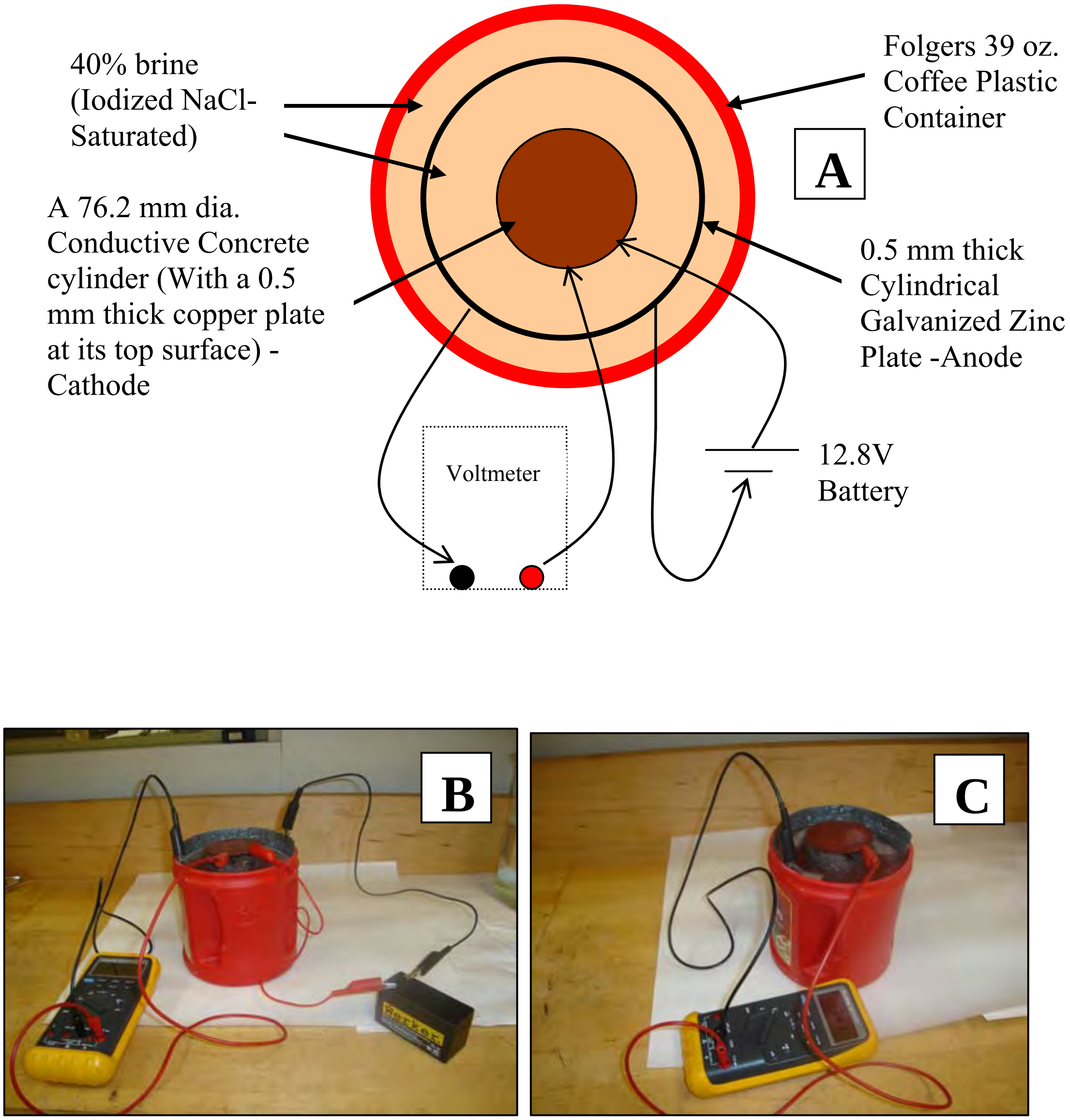


Figure 4-42: The experimental set-up showing the charging and discharging process.
A: A plan view sketch **B**: The charging set-up, and **C**: The discharging set-up.
The spacing between the galvanized zinc plate and the conductive concrete cylinder was approximately 35 mm. The copper plate atop the conductive concrete cylinder is used only as wire attachment aid.

Results and Discussion

Figure 4-43 shows the charging process graph. The voltage increased steadily from 11.17V to 11.72V in 45 minutes when charged using a 12.8V battery. When power was disconnected, the cell discharged monotonically from 1.069V to 1.044V in 36 minutes (Figure 4-44). No drop in voltage was observed in the 12.8V battery after charging the Conductive Concrete-Zinc cell. These results indicate that the conductive concrete-zinc cell has the potential of storing electrical power. However, a longer charging time is required to provide more charge to the cell. Alternatively, an AC-DC transformer may be used to charge the cell for a longer period of time before it is allowed to discharge.

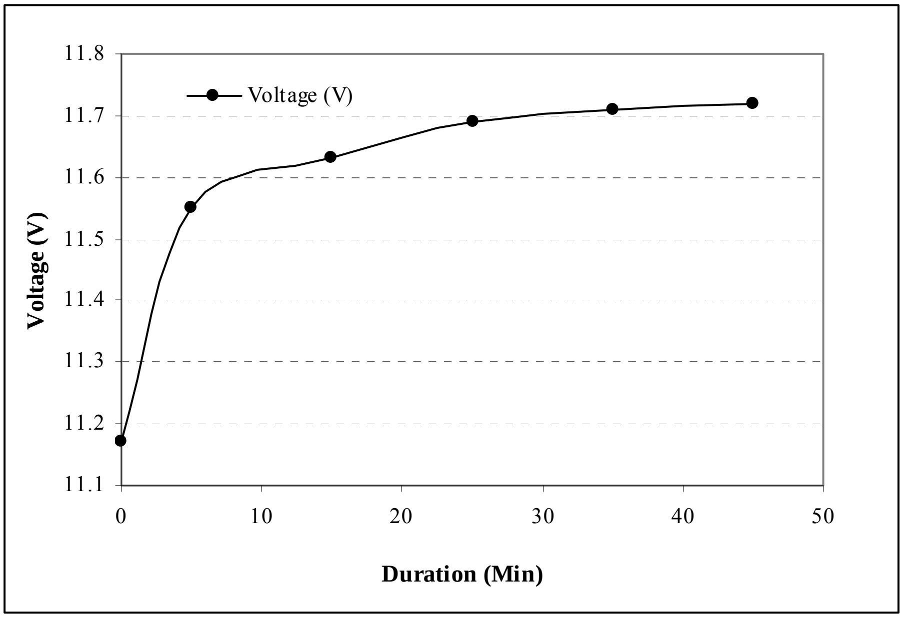


Figure 4-43: Change in voltage with time as the Conductive Concrete-Zinc cell is charged with a 12.8V battery

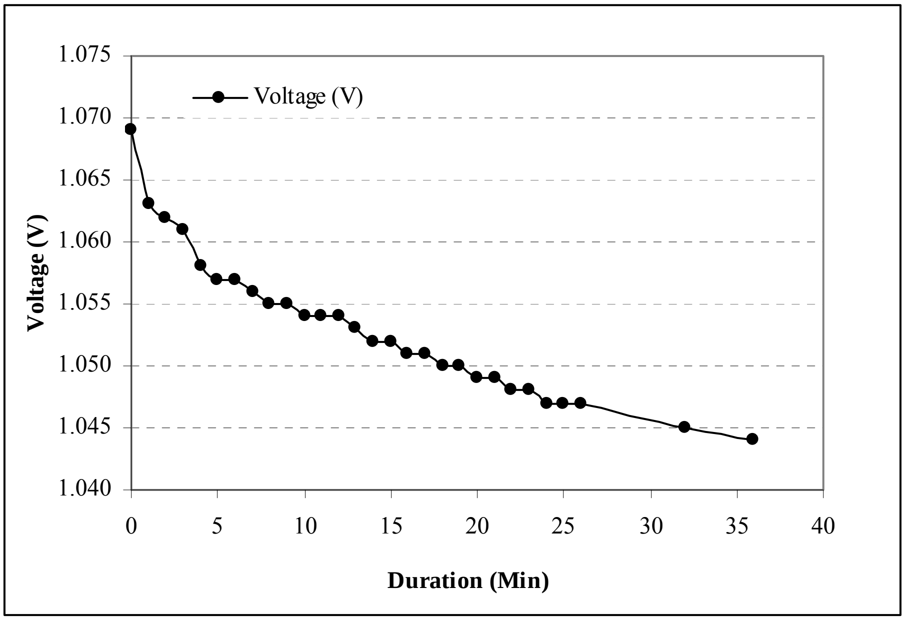


Figure 4-44: Change in voltage with time as the Conductive Concrete-Zinc cell is discharging after removal of the 12.8V battery

Conductive Concrete Containing We Energies High-Carbon Fly Ash and Pulp Mill Residuals In Place of Air Entraining Agent for High Durability Concrete (48)

This research work was performed by the Center for By-Products Utilization at the University of Wisconsin-Milwaukee and involved the testing and usage of high-carbon fly ash (HCFA) in non-air entrained concrete with microfibers from residual wastewater treatment solids from pulp and paper mills to produce high-durability concrete as a substitute for specialty chemical air-entraining admixtures. An air-entraining agent is a manufactured chemical admixture (AEA) added to the concrete mixture to resist the freezing and thawing environment. But AEA limits the effectiveness in the presence of HCFA in a concrete mixture. An air-entrained concrete has to meet specified criteria such as bubble size and spacing within the mortar fraction of the concrete to provide the necessary durability. Thus the incorporation of the pulp and paper mill residual solids in the presence of the high-carbon fly ash can produce a “green” concrete that provides freezing and thawing resistance to the concrete.

Materials

Materials utilized consisted of one source of Portland cement, clean concrete sand, HCFA, fibrous residual, and a high-range water-reducing admixture (HRWRA). ASTM Type I Portland cement was used that met the requirements of ASTM C-150. Natural sand was used from a source in southeastern Wisconsin meeting ASTM C-33 requirements as the fine aggregate ingredient. For the coarse aggregates, a crushed quartzite with a maximum nominal size of 19 mm was obtained from a source in south-central Wisconsin, again meeting the ASTM C-33 requirements. One source of HCFA was used in the concrete mixture for this project from We Energies Valley Power Plant. The HCFA was collected from burning bituminous coal at the plant. The chemical composition and physical properties of the HCFA are presented in Table 4-61 and Table 4-62, respectively, along with the requirements of ASTM C-618 for coal fly ash. The HCFA did not meet the LOI, fineness, and the strength activity index requirements. The source of fibrous residual was from a fiber reclaim process and was obtained from Biron, Wisconsin. The as-received moisture content of the residual solid is 253% of the oven-dry mass. Since cellulose fibers can decompose readily in a warm and humid environment, the residual solid was stored at 4ºC until its use in the concrete mixtures. Before adding the residual solids to the concrete, the fibers are first deflocculated by mixing in water. A water-reducing and set-retarding admixture was used in three of the concrete mixtures made with Valley Power plant HCFA. The admixture is a modified sodium gluconate, and meets the requirements of ASTM C-494 for Type B (retarding admixtures) and Type D (water-reducing and retarding admixtures). The manufactures recommended dosage rate of the water-reducing admixture is 125-375 mL/100kg of cement (2-6 fluid oz/100lb).

Table 4-61: Chemical Composition of High-Carbon Fly Ash

Constituent	Valley HCFA (% by mass)	Requirement of ASTM C-618	
		Class F fly ash	Class C fly ash
SiO_2	39.7	---	---
Al_2O_3	19.0	---	---
Fe_2O_3	5.6	---	---
$SiO_2 + Al_2O_3 + Fe_2O_3$	64.3	70 Min.	50 Min.
CaO	4.1	---	---
MgO	1.3	---	---
Na_2O	1.2	---	---
K_2O	1.3	---	---
TiO_2	0.7	---	---
SO_3	0.5	5.0 Max	5.0 Max
LOI @ 750ºC	26.2	6.0 Max*	6.0 Max

*Under certain circumstances, up to 12.0% max. LOI may be allowed.

Table 4-62: Physical Properties of High-Carbon Fly Ash

Source		Valley HCFA	Standard Requirement of ASTM C-619 for Class F fly ash and Class C fly ash
Fineness, amount retained on 45 μm (No.325) sieve, (% by mass)		46.9	34 Max.
Strength Activity, (% of Control)	7 days	59.8	75 Min.
	28 days	64.0	75 Min.
Water requirement (% of Control)		112	105 Max.
Autoclave expansion (%)		-0.02	Between -0.80 to +0.80
Density (g/cm^3)		2.12	---
As-received moisture content (%)		0.5	3.0 Max.

There were three non-air-entrained concrete mixtures containing approximately 550 kg/m^3 of Valley HCFA and one reference mixture, Ref-2, which did not contain fly ash or residual solids. The concrete mixtures containing the HCFA are V-8, V-9 and V-10; and contain increasing amounts of fibrous residuals from 7 to 21 kg/m^3 (0.30% to 0.88% of residuals by mass % of concrete). All concrete mixtures contain HRWRA and the dosage was approximately the same, regardless of the residual content. However, the dosage of HRWRA in V-8 to V-10 is much higher than Ref-2. The density of the fresh concrete decreased as the amount of residuals increased in the mixture. Table 4-63 shows the mixture proportions.

Table 4-63: Mixture Proportions and Fresh Properties of Concrete Made with Valley HCFA

Mixture	**Ref-2**	**V-8**	**V-9**	**V-10**
Fibrous Residual, BR (mass % of concrete)	0	0.30	0.59	0.88
Cement, C (kg/m^3)	349	298	293	289
Valley High-Carbon Fly Ash, V (kg/m^3)	0	48	48	47
Water, W (kg/m^3)	152	155	157	159
Sand, SSD (kg/m^3)	879	871	858	846
Crushed Stone, 19mm max., SSD (kg/m^3)	1070	1060	1040	1030
Fibrous Residual, (kg/m^3)	***0***	***7***	***14***	***21***
HRWRA (L/m^3)	0.94	5.66	5.61	5.77
Water/Cement material ratio	0.43	0.45	0.46	0.47
Slump (mm)	120	25	10	120
Air Content (%)	1.0	1.1	1.5	1.0
Air Temperature (ºC)	26	26	26	26
Concrete Temperature (ºC)	---	26	25	---
Fresh Concrete Density (kg/m^3)	2451	2435	2419	2387

Discussion of Test Results

Compressive strength of the concrete mixture was evaluated at the ages of 7, 28, 91 days as shown in Table 4-64 and Figure 4-45. As shown, the compressive strength of all three mixtures containing HCFA was lower than the reference mixture, which contained none of the HCFA and fibrous residuals. As the amount of fibers was increased in the concrete mixtures, the compressive strength decreased. However, at the age of 91 days, the strength ranged from 29.8 to 34.7 MPa, which was 60 to 70% of the strength of the reference mixture. Therefore, new mixture proportioning is necessary to achieve a compressive strength higher than 30 MPa.

Table 4-64: Compressive Strength of Concrete Made with Valley HCFA

Age (days)	**Compressive Strength (MPa)**			
	Mixture (Residual Content, kg/m^3)			
	Ref-2 (0)	**V-8 (7)**	**V-9 (14)**	**V-10 (21)**
7	44.4	25.0	27.0	20.8
28	47.5	30.6	30.2	25.6
91	49.8	34.7	34.1	29.8

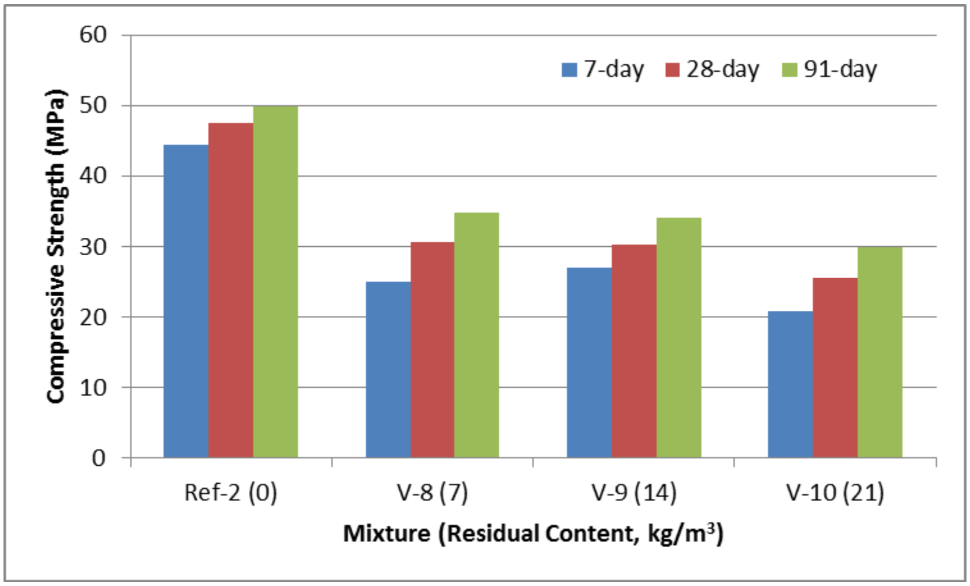


Figure 4-45: Compressive Strength of concrete containing Valley HCFA and fiber residue

The test mixtures were evaluated for resistance to freezing and thawing cycles in accordance with ASTM C-666, Procedure A. Results are shown in Table 4-65. All concrete mixtures containing HCFA and the fibrous residuals had a higher resistance to freezing and thawing than the reference material. Mixture V-8 containing 7 kg/m^3 of fibrous residuals (0.30 mass % of concrete), had the highest resistance to freezing and thawing and had the lowest compressive strength compared to the reference material. The resistance to freezing and thawing can potentially be increased if the compressive strength is increased to a level comparable to the reference mixture, greater than 35 MPa.

Table 4-65: Freezing and Thawing of Concrete Made with Valley HCFA

Mixture (Residual Content, kg/m^3)	**Relative Dynamic Modulus of Elasticity, (%)**							
	Number of Freezing and Thawing Cycles							
	0	**31**	**59**	**90**	**120**	**150**	**180**	**210**
Ref-2 (0)	100	74.8	60.2	52.0	---	---	---	---
V-8 (7)	100	93.2	90.0	84.9	82.4	75.6	69.1	64.7
V-9 (14)	100	91.0	77.0	74.5	56.7	33.6	---	---
V-10 (21)	100	91.1	79.0	69.9	51.9	41.2	---	---

The concrete mixtures were also tested for the resistance to surface scaling when subjected to de-icing chemicals. Table 4-66 shows the results from the tests for the resistance to salt-scaling. Through 50 cycles of freezing and thawing, the two mixtures that achieved the highest resistance to scaling were the mixtures with the lowest amount of fibrous residuals, mixture V-8 and V-9. Mixture V-8 contained 7kg/m^3 (0.30 mass % of concrete) and mixture V-9 contained 14kg/m^3 (0.60 mass % of concrete). The lowest amount of residuals contained in mixture V-8 has the best performance, with a visual rating still at zero (no visible scaling) at 50 cycles. Overall, all concrete mixtures containing fiber residuals and HCFA performed better than the reference concrete mixture.

Table 4-66: Salt-Scaling Resistance of Concrete Made with Valley HCFA

Cycle	**Visual Rating (VR) and Cumulative Spall (CS), (kg/m^2)**							
	Mixture (Residual Content, kg/m^3)							
	Ref-2 (0)		**V-8 (7)**		**V-9 (14)**		**V-10 (21)**	
	VR	**CS**	**VR**	**CS**	**VR**	**CS**	**VR**	**CS**
5	0	0	0	0.01	0	0.01	0	0.67
10	0	0	0	0.01	0	0.02	0	0.86
15	1	0.01	0	0.01	0	0.02	0.5	1.01
20	1.5	0.02	0	0.01	0	0.02	0.5	1.10
25	1.5	0.02	0	0.02	0	0.02	1.5	1.32
30	1.5	0.05	0	0.02	0	0.02	1.5	1.36
35	3	0.06	0	0.02	0	0.03	2	1.58
40	3	0.27	0	0.02	0	0.03	2	1.93
45	3	0.45	0	0.02	0.5	0.03	2.5	2.16
50	4	0.58	0	0.03	0.5	0.04	2.5	2.77

Development of Self-Consolidating Concrete Containing We Energies Class C Fly Ash (49)

Self-Consolidating Concrete (SCC) is a relatively recent innovation in concrete technology and was originally developed in the late 1980s at the University of Tokyo, Japan. Self-consolidating concrete is defined as a "concrete which can be placed and compacted into every corner of a form work, purely by means of its self-weight thus eliminating the need of vibration or other types of compacting effort"(49). It is also referred to as self-compacting concrete, self-leveling concrete, super-workable concrete, highly flowable concrete, non-vibrating concrete. The reason for developing this concrete was the concern of maintaining homogeneity and encapsulating into highly reinforced structural elements with complete compaction through the action of gravity thus improving the overall durability of the concrete.

Adjustments to the traditional mix design with the right water-to-cementitious ratio and use of superplasticizer creates flowable cement paste as well as susceptibility to segregation. Superplasticizers contain sulfonic acid groups that neutralize the surface charge on the cement particles and cause dispersion, thus releasing the water tied up in the cement particle agglomeration and reduction of viscosity. On the other hand, amendment to the aggregate proportion with a decrease in coarse aggregate and use of mineral admixtures such as fly ash, blast furnace slag, limestone powder and other similar fine powder additives, increases the fine materials in the concrete mixture thus generating high flowabilty. The spherical characteristic of fly ash particles helps in reducing friction during the flow of the mortar fraction in the concrete to increase fluidity in the SCC with segregation avoidance. Nonetheless, the slump-flow has to be maintained similar to the concrete using Portland cement when utilizing fly ash in SCC resulting in a decreased dosage of superplasticizer. Usually, the benefit of using fly ash in concrete is for "improved rheological properties and reduced cracking of concrete due to the reduced heat of hydration of concrete" (49). Therefore, the incorporation of one or more mineral additives "having different morphology and grain-size distribution can improve particle-packing density and reduce inter-particle friction and viscosity" (49). The use of such mineral additives also reduces the cost of cement due to the abundance of coal fly ash in the USA and other countries.

SCC can incorporate several minerals and chemical admixtures such as high range water reducing admixture (HRWRA) and viscosity modifying admixture (VMA). The HRWRA ensures high-fluidity and reduces the water-to-cementitious material ratio. The VMA enhances the yield value by reducing bleeding and segregation and increases the viscosity of the fluid mixture. The high-fluidity and segregation-resisting power are the key characteristics in maintaining the homogeneity and the uniformity of the self-consolidating concrete.

Fibers are sometimes used in SCC to "enhance its tensile strength and delay the onset of tension cracks due to heat of hydration resulting from high cement content in SCC" (49). Also for the development of economical and environmentally friendly SCC, high-volumes of fly ash can be utilized.

Self-Compactability Test of Self-Consolidating Concrete

To evaluate the rheological properties of SCC, a number of test methods can be employed such as the slump-flow, U-flow, V-flow time, L-box and J-ring test. These test methods measure the self-compactability by evaluating the filling ability, passing ability (resistance to blocking) and stability (segregation resistance).

Slump-flow test is a common test method used for evaluating the flowability of SCC using ASTM C-1611. It measures "the capability of concrete to deform under its own weight against the friction on the surface of the base plate with no other external resistance present" (49). This way the consistency and cohesiveness of the concrete can be determined. The concrete is filled in an ordinary Abram's slump cone without tamping. Then the cone is lifted and the diameter of the concrete after the flow has stopped is measured. SCC is characterized by a slump-flow of 650-700 mm (26-28 in.). A slump-flow ranging from 500 to 700 mm (20-28 in.) is considered as a proper slump required for a concrete to qualify for use in SCC. At more than 700 mm (28 in.), the concrete might segregate and at less than 500 mm (20 in.) the concrete is considered to have insufficient flow to pass through congested reinforcement. However, this test cannot distinguish between SCC mixtures and superplasticized concrete.

U-flow test characterizes SCC by examining the behavior of the concrete in a simulated field condition. In this test, the degree of compactability can be indicated by the height that the concrete reaches after flowing through an obstacle as shown in Figure 4-46. First, the concrete is filled in the left chamber with the sliding door completely closed. Then the door is opened and the concrete flows past the reinforcing bars into the right chamber. For highly congested reinforcing areas, SCC should flow to about the same height in the two chambers. According to the dimensions in Figure 4-46, the concrete with a final height of more than 200 mm is considered SCC. At the end, this test measures the filling, passing, and segregation properties of SCC.

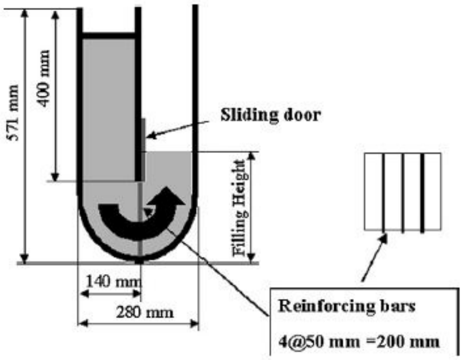


Figure 4-46:U-flow test apparatus.

V-flow test measures the flow time of the SCC. The apparatus is a v-shaped funnel with a rectangular cross-section. The concrete is poured into the funnel completely with a gate blocking the bottom opening. Then once filled, the gate is opened and the time for the concrete to flow out of the funnel is recorded, which is known as the V-flow time. “A flow time of less than 6 seconds is recommended for a concrete to qualify as a SCC” (49).

L-box test is another test method that indicates the filling, passing and segregation-resisting ability of the concrete. Concrete is placed inside the vertical portion of the testing apparatus as shown in Figure 4-47. The gate placed at the horizontal portion simulates reinforcement. Once the concrete has flowed to a resting position, the heights of concrete H1 and H2 are measured. The ratio of H2/H1 is used as a measurement of passing ability. Ratio values of 0.75 and higher are considered to qualify as SCC.

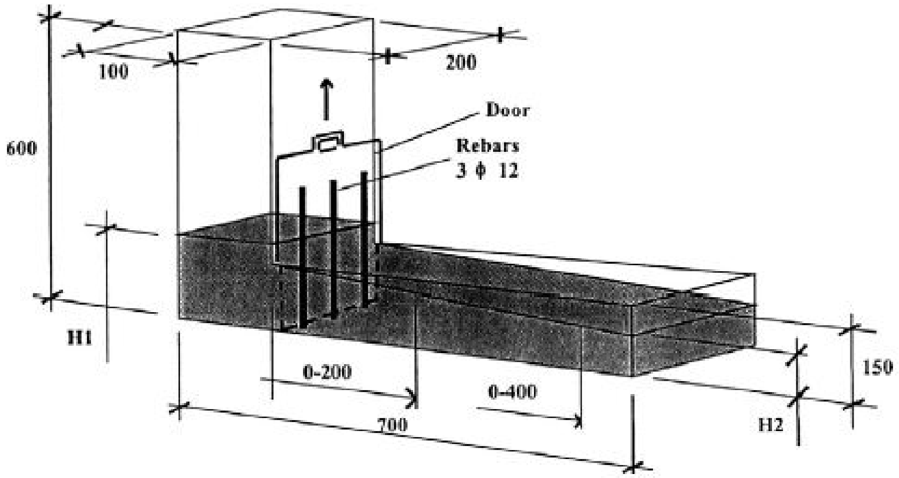


Figure 4-47: L-Box apparatus.

J-ring test assesses the blocking behavior/passing ability of SCC. The apparatus of this test consists of a reinforcing bar ring that is placed around the base of standard slump cone. The slump flow with and without the J-ring is measured and the difference is calculated which measures the passing ability of SCC.

Advantages and Disadvantages of Using Self-Consolidated Concrete

The mechanical properties of SCC are similar to a regular concrete with similar water-to-cementitious ratios. Studies related to “durability aspects such as chloride permeability, deflection, rupture behavior, freezing-and-thawing resistance and chloride diffusivity and other properties of SCC reported either comparable or better results compared with conventional concrete, mainly due to improved homogeneity of the self-consolidated concrete”.

The advantages of using self-consolidating concrete over traditionally placed and compacted concrete are as follows:

- Cost savings on machinery, energy, and labor related to consolidation of concrete by eliminating this step during concrete placement operations.
- High-level of quality control due to more sensitivity of moisture content of ingredients and compatibility of chemical admixtures.
- High-quality finish, which is critical in architectural concrete, precast construction, as well as for cast-in-place concrete construction.
- Reduces the need for surface defect patching.
- Increased service life of the mold/formwork.
- Promotes the development of a more rational concrete production
- Industrialized production of concrete.
- Covers reinforcement effectively, thereby ensuring better quality of cover for reinforcing bars.
- Reduction in the construction time.
- Improves the quality, durability, and reliability of concrete structures due to better compaction and homogeneity of concrete
- Easily placed in thin-walled elements or elements with limited access.
- Ease of placement results in cost savings through reduced equipment and labor requirement.
- Improves working environment at construction sites by reducing noise.
- Eliminate noise due to vibration; effective especially at precast concrete products plants, hence reducing the need for hearing protection.
- Improves working conditions and productivity in construction industry.
- It can enable the concrete supplier to provide better consistency in delivering concrete, thus reducing the need for intervention at the plants or at the job sites.
- Provides opportunity for using high-volumes of by-product materials such as fly ash, quarry fines, blast furnace slag, limestone dust and other similar fine mineral ingredient materials.
- Reduces workers compensation insurance premiums due to the reduction in chances of accidents.

The disadvantages of using self-consolidating concrete are as follows:

- More stringent requirements on the selection of materials compared with normal concrete.
- More precise measurement and monitoring of the constituent materials. An uncontrolled variation of even 1% moisture content in the fine aggregate could have a much larger impact on the rheology of SCC.
- Requires more trial batches at laboratory as well as at the ready-mixed concrete plant.
- Costlier than conventional concrete based on concrete ingredient and testing costs.

Development of Economical High-Strength Self-Consolidating Concrete

Materials and Mixture Proportions

Type I Portland cement was used in this investigation that met the requirements of ASTM C-150. ASTM Class C fly ash (from OCPP) was used in this study as a partial replacement for Portland cement. Cement was replaced by fly ash at a ratio of 1:1.25 by mass. Table 4-67 shows the physical properties of the fly ash. Natural sand (fine aggregate) and pea gravel (coarse aggregate) were used as aggregates where physical properties conformed to ASTM C-33 requirements. Two chemical admixtures, Glenium 3200 HES and Rheomac VMA 362, were used as a HRWRA and a VMA, respectively. The dosage of admixtures varies based on the desired properties for the SCC mixtures. Table 4-68 shows the mixture proportions and fresh properties of self-consolidating concrete. Each mixture (SC 1 – 4) was batched and mixed in the laboratory in accordance with ASTM C-192.

Table 4-67: Physical Properties of Class C Fly Ash

Property	**OCPP Class C Fly Ash (%)**	**ASTM C-618 Limits (%)**
Fineness retained on 45 µm sieve (%)	13	≤ 34
Specific gravity	2.56	-
Strength activity index with cement, 28-day (% of control)	113	≥ 75

Table 4-68: Self-Consolidating Concrete Mixture Proportions and Fresh Properties

Mixture No.	SC 1	SC 2	SC 3	SC 4
Replacement of cement with fly ash (%)	0	35	45	55
FA/(C + FA) (%)	0	40	50	60
Cement, C (kg/m^3)	431	265	228	182
Class C fly ash, FA (kg/m^3)	0	178	233	285
Sand (kg/m^3)	971	923	942	939
9.5 mm Pea gravel (kg/m^3)	871	845	863	862
Water (kg/m^3)	147	142	136	126
HRWRA (L/m^3)	8.1	4.8	3.0	3.0
VMA (L/m^3)	3.7	3.0	2.0	1.8
W/C (water/(cement + fly ash))	0.34	0.35	0.33	0.31
W/C [a] (water/(cement + fly ash))	0.36	0.37	0.34	0.32
Slump-flow (mm)	679	686	686	699
Segregation	Some	N/A	N/A	N/A
Bleeding	Some	Some	Some	None
U-Flow, H1-H2 (mm)	5	6	6	6
U-Flow, H2/H1 (%)	98	98	98	98
Air content (%)	1.7	1.5	1.4	2.7
Density (kg/m^3)	2360	2339	2369	2377
Material cost [b] (\$/m^3)	106	78	68	64

SC 1: control mixture without fly ash, SC 2-4: mixtures with Class C fly ash at 35%, 45%, and 55% replacement of cement by mass

N/A: Not Available

[a] Considering water in chemical admixtures

[b] Calculated by using the following pricing information: \$0.1/kg of cement, \$0.045/kg of Class C fly ash, \$0.009/kg of sand, \$0.009/kg of pea gravel, \$4.5/L of HRWRA, and \$2.7/L of VMA

Mechanical Properties

As shown in Table 4-68 and Figure 4-48, each mixture was tested for both fresh and hardened concrete properties, respectively. For the fresh concrete properties, slump-flow and U-flow tests were performed to determine the flow and the self-compactability behavior. Additionally, the air content and the fresh density of SCC were determined by the applicable ASTM test method. The hardened SCC was tested for compressive strength using 4” diameter x 8” long cylindrical specimens meeting the requirements of ASTM C-39. The concrete strength was obtained at the ages of 3, 7, and 28 days.

Higher densities were observed as the replacement of cement by the Class C fly ash in the concrete mixture was increased with densities of 2339, 2369, and 2377 kg/m^3. The use of high-volume Class C fly ash in SCC significantly reduces the requirements of superplasticizer as well as viscosity-modifying agent. This indicates that it is possible to manufacture economical self-consolidating concrete by using high-volumes of Class C fly ash. It is further obvious that the use of high-volumes of Class C fly ash not only reduces the amount of cement but also reduces the superplasticizer and viscosity-modifying agents significantly while maintaining the desired 28-day strength of about 7000 psi (48MPa) or higher.

As expected, the compressive strength increased with age as shown in Figure 4-48. In general, the SCC strength decreased with increasing fly ash amounts at the very early ages (ie: 3 and 7 days). The SCC made by replacing 35% of cement with fly ash (SC 2) showed a strength of 4200 psi (29MPa) at the age of 3 days. However, this mixture resulted in higher strength than the control mixture (SC1) at 28 days with a compressive strength of 9000 psi (62MPa). SCC mixtures containing 50% fly ash (SC3) of the total mass of cement plus fly ash also performed well compared to the control SCC mixture at the age of 28 days. The SCC mixture containing 60% fly ash also showed a comparative strength at the age of 28 days with the control SCC mixture. Without any doubt, as the age progresses the SCC with fly ash will outperform the control mixture. In general, all the SCC mixtures containing high-volumes of Class C fly ash developed high-strength in the range of 7000 – 9000 psi (48-62 MPa). This type of high-strength, economical, self-consolidating concrete has many applications in the construction industry, including the precast concrete industry.

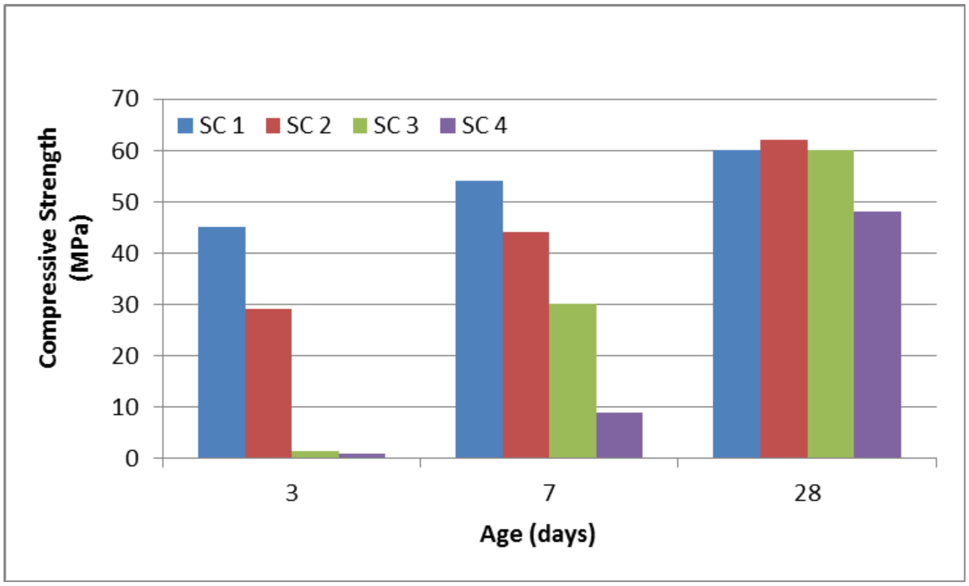


Figure 4-48: Compressive strength (MPa) of self-consolidated concrete mixture

Summary

Based on the experimental study for development of high-strength, economical, self-consolidating concrete incorporating high-volumes of Class C fly ash, the following general conclusions can be made:

1. Use of high-volumes of Class C fly ash in the manufacturing of SCC reduces the cost of the SCC production by significantly reducing the amount of superplasticizer and viscosity-modifying agents compared with the normal dosage for such admixtures in SCC, because of decreased friction between paste and large aggregate particles resulting from the ball bearing effects of spherical fly ash particles.

2. High-strength, economical SCC for strengths of about 9000 psi (62 MPa) at 28 days can be manufactured by replacing at least 35% of cement by Class C fly ash.

3. High-strength, economical SCC in the range of 7000 - 9000 psi (48-62 MPa) at a 28-day age can be manufactured by replacing up to 55% of cement by Class C fly ash. High amounts of fly ash in concrete leads to lower early age strength.

4. High-strength, economical SCC can be beneficial for many applications in construction, including the precast industry, as it can be manufactured by replacing high-volumes of Portland cement with Class C fly ash.

Sample Specifications are included in Appendix 12.6 for an SCC mixture.

Chapter 5

Controlled Low-Strength Material (CLSM) Containing We Energies Fly Ash

Introduction

During the past two decades fly ash has been increasingly used in the manufacture of controlled low-strength material (CLSM). CLSM is defined by ACI Committee 229 as a “self-compacted cementitious material used primarily as a backfill material in lieu of compacted fill with a compressive strength of 1200 psi or less.” However, where future excavation is anticipated, the ultimate compressive strength of CLSM should be less than 300 psi. This level of strength is very low, compared to concrete, but very strong when compared to soils. The composition of CLSM can vary depending on the materials used in the mixture. CLSM has the unique advantage of flowing and self-leveling. Hence, in applications like filling abandoned underground tanks or voids under pavements, CLSM may be the only viable method of completely filling the void. Additionally, there is no cost associated with vibrating or compacting the material in place.

CLSM may be known by such names as: unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry and K-Krete (50). We Energies has used the registered trademark, Flo-Pac® for its CLSM. The range of strength required varies with the type of application. However, CLSM is normally designed to develop a minimum of at least 20 psi strength in 3 days and 30 psi at 28 days (ASTM C-403 penetration resistance numbers of 500 to 1500).

A compressive strength of 100 psi is equivalent to the load bearing capacity of a well compacted soil with a capacity of 14,400 psf which is comparable to a densely compacted gravel or hard pan type soil. Where CLSM is used as a support layer for foundations, a compressive strength of 300 psi to 1200 psi is sometimes used. However, applications involving CLSM with strength in this range are very limited and often not necessary.

The CLSM mixture selected should be based on technical and economic considerations for a specific project. The desired strength level and flowability are two significant considerations for CLSM. Permeability, and shrinkage or expansion of the final product (hardened CLSM) are additional considerations.

We Energies CLSM Developments

The development of CLSM containing We Energies fly ash has been a long process involving manufacturing several trial mixes and studying their properties. Various parameters were considered; however, compressive strength and excavatability are primary considerations. In the early trials, a wide variety of sample strengths were developed, some of which were higher than normally recommended for CLSM.

Several CLSM mix designs were developed and tested using We Energies fly ash at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM). The scope of these tests was to evaluate fly ash, the properties of the mixes and to study potential field applications. The mixes were prepared using various percentages of Class C and Class F fly ash with various proportions of other ingredients. It is important to note that Class F fly ash can be used in much higher proportions (sometimes replacing aggregate) than cementitious Class C fly ash which is introduced primarily as a binder.

CLSM production is an excellent use for fly ash that does not meet all of the ASTM C-618 requirements for use in concrete. The strength level required for CLSM is low when compared to concrete and can be easily obtained with off-spec fly ash. High carbon content can be a reason for concern in air-entrained concrete where air entraining admixtures are absorbed yielding inadequate or variable concrete air content. In CLSM, air content is often not a requirement and hence the presence of carbon particles does not affect its properties.

CLSM Produced with We Energies High-Lime (ASTM C-618 Class C) Fly Ash

The mixtures shown in Table 5-1 were developed using ASTM C-618 Class C fly ash produced at We Energies Pleasant Prairie Power Plant from burning western United States sub-bituminous coal. The chemical and physical properties of the PPPP fly ash are listed in Chapter 3, Tables 3-1 and 3-2. The mixtures were produced at a commercial batch plant using standard procedures that were monitored to assure homogeneity of the products.

Table 5-1: Mixture Proportions and Field Test Data for CLSM (and Low-Strength Concrete) Produced With Class C Fly Ash

Mix No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength at 28-Day Age, (psi)	500	1000	1200	500	750	1000	500
Cement, (lb./yd^3)	74	89	104	70	81	96	129
Fly Ash, (lb./yd^3)	128	158	189	118	159	195	239
Water, (lb./yd^3)	332	293	283	345	337	338	351
SSD Sand, (lb./yd^3)	1763	1671	1609	1728	1611	1641	1543
SSD Pea Gravel, (lb./yd^3)	1773	1832	1863	1778	1761	1813	1721
Slump, (in.)	1¾	¾	1¼	7½	6¼	6½	9¼
Air Content, (%)	3.2	2.7	2.6	2.1	2.3	2.2	1.0
Air Temperature, (°F)	40	45	49	37	40	38	32
Concrete Temperature, (°F)	64	62	58	55	60	60	58
Concrete Density, pcf	150.7	149.8	149.9	149.6	146.3	151.2	147.5
Concrete Weight, (lb./yd^3)	4070	4044	4048	4039	3969	4083	3983
W/(C+FA)	1.64	1.19	0.97	1.84	1.16	1.16	0.95

The first three mixtures were produced with low cement content and relatively low water content.

Mixtures C-1 to C-3 showed very low slump and did not flow as desired in a flowable slurry. Hence, new mixtures were developed, taking into consideration the drawbacks of previous mixes. (51)

The new mixes C-4 to C-7 showed good to very good flowability. A detailed discussion of the research can be obtained from reference 51.

Figure 5-1 is a graph showing compressive strength vs. age for these mixtures. Figure 5-2 shows 28-day compressive strength vs. total cementitious material, and Figure 5-3 shows 28-day compressive strength vs. water to cementitious materials ratio for these mixtures. Table 5-2 shows the CLSM compressive strength test results.

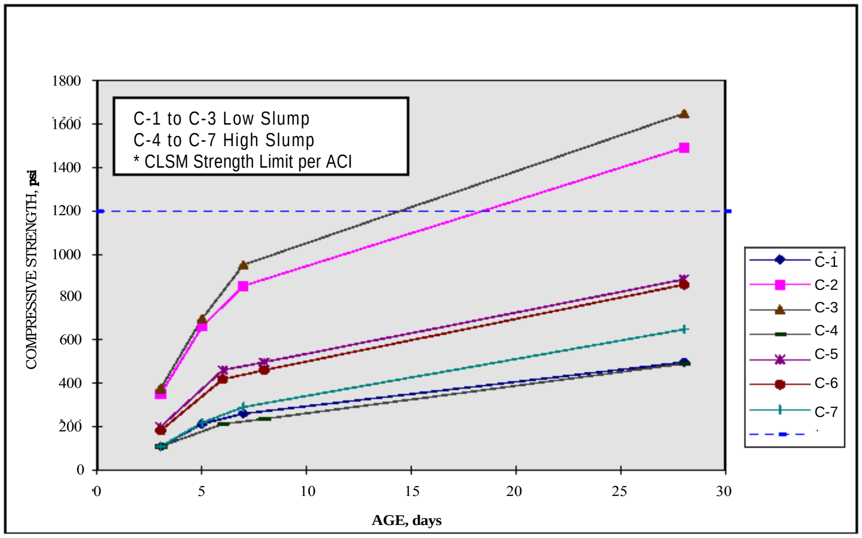


Figure 5-1: CLSM Compressive Strength vs. Age Comparison (Class C Fly Ash)

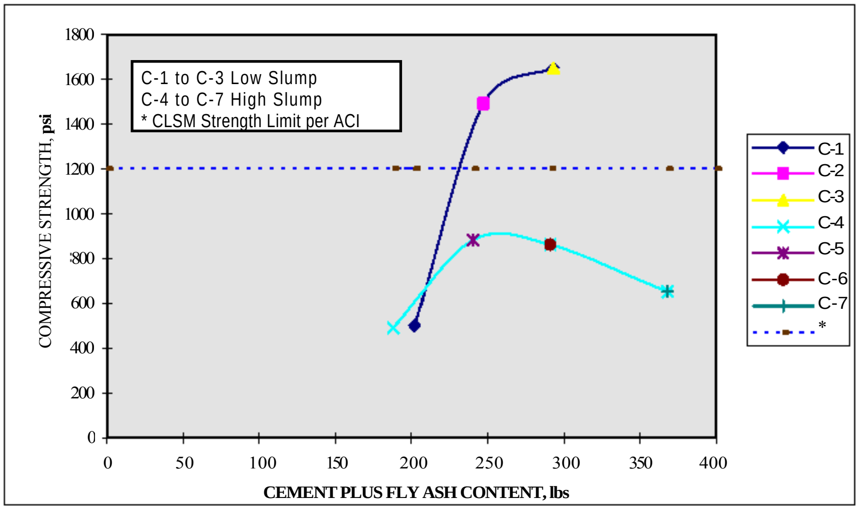


Figure 5-2: CLSM 28-Day Compressive Strength vs. Total Cementitious Material (Class C Fly Ash)

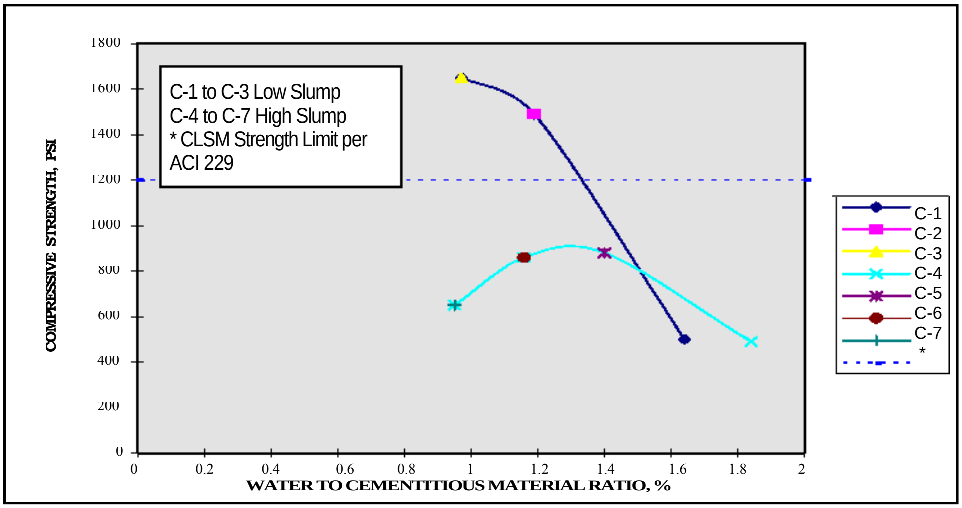


Figure 5-3: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

Table 5-2: High Fly Ash CLSM Test Data
500-1200 psi Specified Strength Range at 28-Day Age

MIX No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength, (psi)	500	1000	1200	500	750	1000	500
Class of Ash	C	C	C	C	C	C	C
Slump, (in.)	1¾	¾	1¼	7½	6¼	6½	9¼
TEST AGE, (days)	COMPRESSIVE STRENGTH, (psi)						
3	110	350	375	110	200	180	110
5	210	660	700				220
6				210	460	420	
7	260	850	950				290
8				240	500	460	
28	500	1490*	1650*	490	880	860	650

* Exceeds CLSM strength cap of 1200 psi specified by ACI 229.

It can be concluded from these test results that:

1. As the water to cementitious materials ratio increases, the compressive strength decreases for the low slump mixtures.
2. The compressive strength did not change significantly for the higher slump mixtures as the water to cementitious materials ratio increased between 1.0 and 2.0.

3. All mixtures behaved well and can be used as a basis for selection of mixtures for CLSMs or low-strength high fly ash content concrete for non-structural applications.
4. The compressive strength results for all these trial mixtures are at a level where easy excavation will not be possible.

CLSM Containing We Energies Valley Power Plant Off-Spec (ASTM C-618 Class F) Fly Ash

The mixture proportions used in this project were designed to have a compressive strength of 500 psi to 1500 psi. This strength level is similar to the strength levels of many natural rock formations and can be used as foundation support, capable of distributing the load uniformly.

The CLSM mixtures were produced at a commercial batch plant in New Berlin, Wisconsin. The mixtures contained ⅜" (maximum size) pea gravel, in addition to fly ash, cement, sand and water. The final mixtures were designed with high slump (7" to 9".).

From each concrete mixture, 6" diameter by 12" high cylinders were prepared for compressive strength and other tests. Cylinders were tested from each mixture at the ages of 3, 5, 7 and 28 days. Shrinkage was noted to be very low, ranging from 0 to $^1/_{32}$" for the 12" high cylinders. A detailed discussion of this research can be obtained from reference 52.

Table 5-3 gives the chemical and physical test data for mixtures produced with off-spec ASTM C-618 Class F fly ash from Valley Power Plant. Tables 5-4 and 5-5 show mixture proportions, field test data, and compressive strength data for the various mixtures.

Figure 5-4 is a graph showing compressive strength vs. age for these mixtures. Figure 5-5 shows compressive strength vs. total cementitious material for the same mixtures, and Figure 5-6 shows compressive strength vs. water to cementitious material ratio for the above mixtures.

Table 5-3: Chemical and Fineness Test Data for Class F Fly Ash from Valley Power Plant

Chemical Composition	No. of Samples	Range, %	Average, %	ASTM C-618
Silicon Oxide, SiO_2	4	50.06 - 50.20	50.14	-
Aluminum Oxide, Al_2O_3	4	25.24 - 25.36	25.27	-
Iron Oxide, Fe_2O_3	4	14.66 - 15.39	14.93	-
Total, $SiO_2+Al_2O_3+Fe_2O_3$	4	89.96 - 90.82	90.36	50 Min
Sulfur Trioxide, SO_3	4	0.20 - 0.33	0.26	5.0 Max
Calcium Oxide, CaO	4	1.18 - 1.44	1.27	-
Magnesium Oxide, MgO	4	0.70 - 0.74	0.71	5.0 Max
Carbon	4	3.59 - 6.94	5.08	6.0 Max
Available Alkalis as Na_2O	4	1.61 - 1.70	1.65	
Sulfur	4		0.22	
Physical Tests				
Fineness: % Retained on #325 Sieve	1	25		34.0 max

Table 5-4: Mixture Proportions and Field Test Data for Class F Fly Ash CLSM

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength at 28-Day Age, (psi)	1000	1500	2000	1500	1500	1500
Cement, (lb./yd^3)	102	151	229	138	211	263
Fly Ash, (lb./yd^3)	499	519	500	452	459	446
Water, (lb./yd^3).	439	375	422	323	294	320
SSD Sand, (lb./yd^3)	1206	1198	1111	1090	1053	1060
SSD Pea Gravel, (lb./yd^3)	1614	1697	1680	1783	1774	1688
Slump, (in.)	9	7-3/4	8-1/4	9	7-1/4	8-1/4
Air Content, (%)	1.0	1.8	1.9	0.5	1.4	1.7
Air Temp., (ºF)	38	36	35	32	33	33
Concrete Temperature, (ºF)	65	64	64	58	60	62
Concrete Density, pcf	143.0	145.9	146.0	140.2	140.4	139.5
Concrete Weight, (lb./yd^3)	3861	3940	3942	3786	3791	3777
W/C	4.3	2.5	1.8	2.34	1.39	1.22
W/(C+FA)*	0.73	0.56	0.58	0.55	0.44	0.45

* May not be meaningful because all of the Class F fly ash probably should not be accepted as cementitious

Table 5-5: Class F Fly Ash CLSM Test Data

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength, (psi)	500	1000	1500*	500	1000	1500*
Class of Ash	F	F	F	F	F	F
Slump, (in.)	9	7¾	8¼	9	7¼	8¼
Test Age, (days)	Compressive Strength, (psi)					
3	110	270	500	123	263	420
5				200	383	630
6	210	470	820			
7				237	443	693
8	220	510	880			
28	490	930	1640*	677	900	1210*

* Exceeds CLSM strength cap specified by ACI 229 of 1200 psi

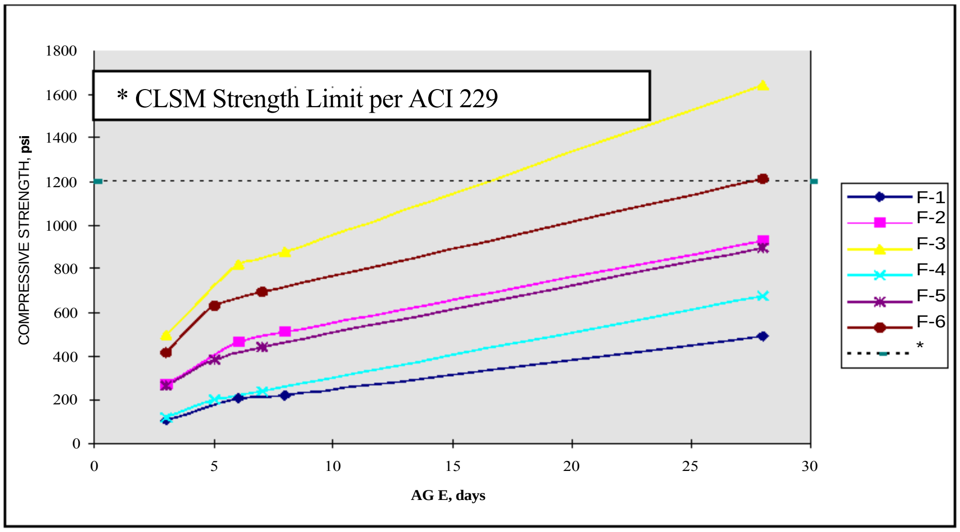


Figure 5-4: CLSM Compressive Strength vs. Age Comparison (Class F Fly Ash)

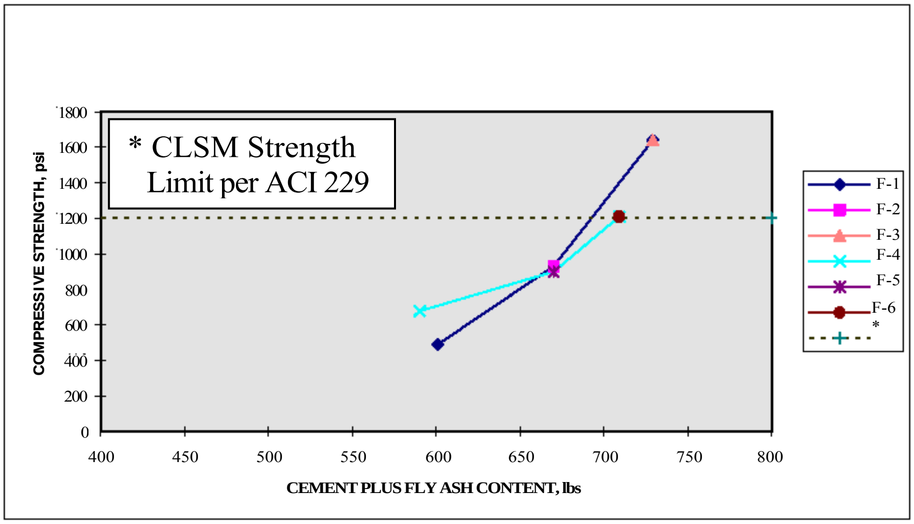


Figure 5-5: CLSM 28-Day Compressive Strength vs. Total Cementitious Material

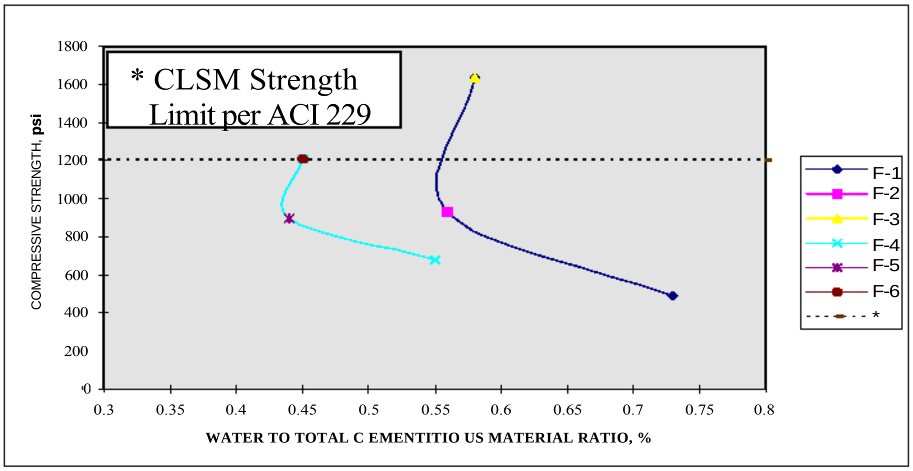


Figure 5-6: CLSM 28-Day Compressive Strength vs. Water to Cementitious Material Ratio

The following conclusions were made from this research (52).

1. The compressive strength decreased as water to cementitious material ratio increased.
2. All mixtures showed good flowability and workability.
3. Shrinkage was minimal.
4. The mixture designs developed performed well and can be used as a basis for selecting mixture proportions for CLSMs or low-strength concrete with high slump for non-structural applications, using the same materials.
5. All of these mixtures will not be easily excavatable.

CLSM Made with We Energies Port Washington Power Plant Off-Spec (ASTM C-618 Class F) Fly Ash

This study was conducted by We Energies with a local ready mix firm to determine various properties of CLSM material containing off-spec ASTM C-618 Class F fly ash from Port Washington Power Plant (PWPP). CLSM fly ash slurry was initially used for limited applications in filling abandoned underground facilities and voids such as tunnels, manholes, vaults, underground storage tanks, sewers and pipelines. Another obvious application is the backfilling of trenches for underground utility lines. For this application it is important that the backfill material be compatible with the underground utility line material. Also, the material should be easily excavatable and also provide for special needs such as high thermal conductivity for underground high-voltage transmission lines.

ASTM C-618 chemistry tests were not performed on PWPP fly ash at the time of this research because this fly ash was not used for the production of concrete. However, fly ash from Valley Power Plant that used the same coal was tested. The chemical composition is shown in Table 5-3 for reference purposes. The physical properties of PWPP fly ash are shown in Table 5-6.

Table 5-6: Physical Properties of Port Washington Power Plant Class F Fly Ash

Test	Class F Fly Ash	ASTM C-618	
		Min	Min
Fineness	28.8	-	34
% Retained on #325 Sieve	30.2	-	
Pozzolanic Activity Index			
With Cement (28 days), (%)	99.4	75	-
With Lime (7 days), (psi)	*	800	-
Water Requirement, (% of Control)	109	-	105
Autoclave Expansion, (%)	0.05	-	0.8
Specific Gravity	2.33 2.34	- -	- -
Variation from Mean			
Specific Gravity, (%)	0.214	-	5
Fineness, (%)	2.290	-	5

* Not enough material was available to do this test

CLSM laboratory trial mixtures using PWPP fly ash were also developed at the Center for By-Products Utilization (CBU) at the University of Wisconsin-Milwaukee (UWM) laboratory in November of 1991. The mixture proportions and corresponding compressive strength test results are shown in Table 5-7 (laboratory tests) and Table 5-8 (ready-mix plant production tests). Figure 5-7 is a graph showing compressive strength vs. age for these mixtures.

Table 5-7: Laboratory CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Ingredient	Actual Weight	Cubic Yard Basis
Cement (Type 1)	2.2 lbs	69 lbs
Fly Ash	44.2 lbs	1389 lbs
Water	34.0 lbs	1069 lbs
Water/Cement Ratio	15.45	15.45 lbs
Water/Cementitious Material ratio	0.73	
Compressive Strength Data		
Test Age, (days)	Max. Load, (lb)	Compressive Strength, (psi)
7	640	23
28	1150	41
56	1090	38

Table 5-8: Ready Mix CLSM Mixture Proportions for PWPP Class F Fly Ash and Compressive Strength Data

Mix No.	1	2	3	4
Cement (Type 1), (lbs)	94	94	94	94
Fly Ash*, (lbs)	1731	1329	1153	699
Water, (lbs)	853	644	617	372
Sand (SSD), (lbs)	-	1000	-	1200
¾" Aggregate (SSD), (lbs)	-	-	1000	1700
Slump, (in.)	9	9	10	8 ¾
Average Compressive Strength, (psi)				
1-Day	0	6	5	43
3-Day	7	22	17	96
4-Day	4	10	11	117
7-Day	16	36	30	162
28-Day	39	62	50	276

* Dry Weight

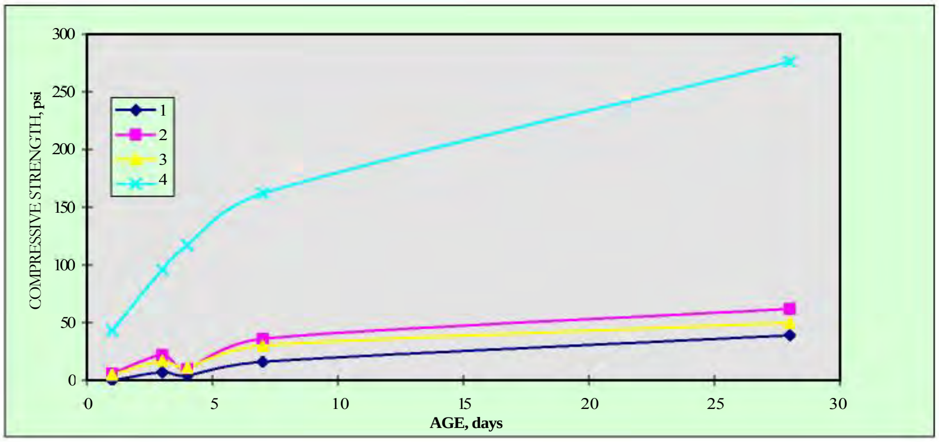


Figure 5-7: Compressive Strength vs. Age Comparison (Class F Fly Ash with One Bag)

The compressive strength test results for mixtures 1 – 3 at a 28-day age ranged from 39 – 62 psi and are comparable to many undisturbed or re-compacted soils, which makes it suitable as a backfill material. Mixture 4, with a 28-day compressive strength of 276 psi, may be suitable in applications below foundations where future excavation concerns are not important. It is important to note that all four mixtures contained only one bag of Portland cement and that mixture 4 contained both coarse and fine aggregates.

Electric Resistivity, Thermal Conductivity and Plastics Compatibility Properties of CLSM Produced with We Energies Fly Ash

Figure 5-8: CLSM flows into place and completely filled this underground equipment vault.

Electric resistivity, thermal conductivity and plastics compatibility evaluations were performed on solidified CLSM fly ash slurry produced from a mixture of 1,275 lbs. of Valley Power Plant fly ash, 150 lbs. of Type 1 Portland cement and 1,050 lbs. of water per cubic yard (53).

Compressive strength tests were also performed per ASTM C-39 for comparison of these special properties. Electrical resistivity tests were performed in accordance with California Test 643-1978. Moisture content in the selected samples varied from 20% to 100%. Thermal conductivity tests were conducted using the thermal needle test method (Mitchell and Kao, 1978). Electrical resistivity test values are used to predict corrosiveness of soils. The electrical resistivity values obtained from the tests indicate that CLSM fly ash slurry is not considered corrosive. Table 5-9 shows commonly used soil corrosivity vs. resistivity values.

Table 5-9: Electrical Resistivity vs. Soil Corrosivity*

Resistivity (ohm-cm)	Corrosivity
Below 500	Very Corrosive
500 – 1,000	Corrosive
1,000 - 2, 000	Moderately Corrosive
2,000 - 10,000	Mildly Corrosive
Above 10,000	Progressively Less Corrosive

*Data from Unites States Department of Agriculture (www.usda.gov/rus/telecom/publications/html/1751f670.htm)

Thermal conductivity results exhibited a near linear relationship with moisture content. Thermal conductivity increases with an increase in moisture content and dry density. In applications like backfill for underground power cables where high thermal conductivity is desired, high-density, low porosity mixtures are preferable. Thermal conductivity values of high-volume flowable fly ash slurry are typically lower than sand, silt and clays but higher than peat.

A study conducted by Dr. Henry E. Haxo, Jr. of Matrecon, Inc., Alameda, California, concluded that high-density polyethylene-coated steel gas pipe, medium-density polyethylene gas pipe and low-density polyethylene jacketed cable would not be adversely affected by CLSM fly ash slurry (53).

Figure 5-9: Excavating hardened CLSM with a backhoe at We Energies Valley Power Plant in downtown Milwaukee, Wisconsin.

Tables 5-10 and 5-11 show the electrical resistivity test results and thermal conductivity test results respectively.

Table 5-10: Resistivity Test Results
CLSM Fly Ash Slurry (ohm-cm)

Moisture Content, (%)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
20	213606	-	-	-	-	-
30	133504	-	-	-	-	-
40	13478	-	-	-	-	-
50	73427	-	-	150859	173555	106803
60	60077	140847	94788	134171	146854	101463
70	56739	126161	120821	108138	140179	100128
80	60077	108138	118151	97458	132169	92118
90	60077	95455	120154	86778	120154	86778
100	60077	94120	120154	87445	120154	86778
Dry Wt. (pcf)	50.74	54.81	50.74	52.28	55.73	68.29

Table 5-11: Thermal Conductivity Test Results
CLSM Fly Ash Slurry (BTU/hr-ft-°F)

Moisture Content, (%)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
0.0	0.08	0.08	0.08	0.1	0.09	0.09
2.6	-	0.09	-	-	-	-
3.0	0.08	-	-	-	-	-
16.0	-	-	0.19	-	-	-
16.1	-	-	-	-	-	0.18
17.7	-	-	-	0.22	-	-
25.0	-	-	-	-	0.2	-
62.9	-	0.53	-	-	-	-
65.0	0.42	-	-	-	-	-
66.9	-	-	0.46	-	-	-
75.3	-	-	-	-	0.47	-
76.0	-	-	-	0.49	-	-
77.4	-	-	-	-	-	0.46
Dry Density, pcf	55.6	55.9	55.1	50.6	50.2	50.4

It can be concluded from this research that:

1. Good quality CLSM fly ash slurry for utility trench backfill can be produced with off-spec Class F fly ash produced at PWPP and VAPP.
2. CLSM fly ash slurry using PWPP or VAPP fly ash has less corrosion potential than typical soil used for trench backfill.
3. High-density, very low porosity CLSM should be used where high thermal conductivity is desired, such as backfill around underground power cables.
4. CLSM fly ash slurry has no adverse effect on polyethylene plastics used for underground gas lines and power cables.

Conductive CLSM Containing We Energies High Carbon Fly Ash (US Patent 6,461,424 B1) (40)

Materials

Materials used in this project consisted of one source of fly ash, cement, clean concrete sand, crushed quartzite limestone aggregates, and taconite pellets. Materials were characterized for chemical and physical properties in accordance with the appropriate ASTM standards. Table 5-12 shows the mixture proportions.

Type I cement (Lafarge Cement Co.) was used throughout this investigation. One source of fly ash was used for this project (We Energies, Port Washington Power Plant, Units 2 and 3).

The CLSM mixtures were proportioned to maintain a practical value of flow that would not have excessive segregation and bleeding. The flow was reduced for mixtures containing sand and gravel to maintain the cohesiveness and the workability of the mixture.

Fresh CLSM properties such as air content (ASTM D-6023), flow (ASTM D-6103), unit weight (ASTM D-6023), and setting and hardening (ASTM D-6024) were measured and recorded. All test specimens were cast in accordance with ASTM D-4832. These specimens were typically cured for one day in their molds at about 70 ± 5°F. The specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73 ± 3°F temperatures until the time of test (ASTM D-4832).

Table 5-12: CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	100	100S	100SG
Laboratory Mixture Designation	100-5	100S-5	100SG-5
Fly Ash, FA (lb/yd^3)	1365	665	660
Cement, C (lb/yd^3)	100	65	45
SSD Fine Aggregate, S (lb/yd^3)	0	1335	865
SSD Coarse Aggregate, G (lb/yd^3)	0	0	1430
Fly Ash Content, % [FA/(FA+C+S+G)]	93	32	22
Water, W (lb/yd^3)	1045	525	480
Air Temperature (ºF)	78	79	78
Fresh CLSM Temperature (ºF)	77	77	84
Flow (in.)	11¼	10¼	6¾
Air Content (%)	1.7	1.2	0.9
Unit Weight (lb/ft^3)	92.8	95.7	129.2

Mechanical Properties of CLSM with We Energies High Carbon Fly Ash

The CLSM strength increased with increasing age. In general, the rate of strength increase was the highest for the mixtures containing aggregates (sand and/or stone) content. Compressive strength for Mixture 100 (fly ash and cement) was 50 psi at the 28-day age. Compressive strength of Mixture 100S and 100SG were higher, 140 psi and 130 psi, respectively, even with reduced cement content, as shown in Table 5-13.

Table 5-13: Compressive Strength of CLSM Mixtures with We Energies High Carbon Fly Ash

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
100	93	15	15	35	35	60	60	60	50
		15		35		60		40	
		15		30		65		45	
100S	32	30	30	105	100	130	120	135	140
		30		100		115		135	
		30		95		115		140	
100SG	22	15	17	140	110	105	110	135	130
		15		95		110		115	
		20		100		110		145	

The compressive strength of Mixture 100S and 100SG at the age of 28-days indicates that a backhoe may be required to excavate these mixtures in the future. However, standard excavation practices typically do utilize a backhoe for excavations for efficiency. Therefore, the 28-day strength levels of the 100S and 100SG mixtures should not be expected to pose a problem for future excavations with mechanical equipment.

Electrical Properties of CLSM with We Energies High Carbon Fly Ash

The electrical properties of the CLSM mixtures are shown in Table 5-14. The electrical resistivity of the air dried CLSM prepared is in the range of 3 - 6 x 10^3 ohm-cm. The resistivity values of the saturated specimens were lower than that obtained for air dried specimens. The permeability of most CLSM specimens prepared with high carbon fly ash exceeds that of air, indicating a greater capability to carry an electrical current. The use of fly ash having greater levels of carbon would further decrease the resistivity of the resulting CLSM. In addition, the increased concentration of high carbon fly ash in the composition will result in increased conductivity. The most significant decrease in resistivity occurs when increasing the high carbon fly ash content in the controlled low-strength materials from 22%–32%. This is evident in the high carbon fly ash controlled low-strength material mixtures for both the saturated and air dry specimens.

Table 5-14: Electrical Properties of CLSM Mixtures

Mixture No.			100	100S	100SG
Fly Ash Content wt., % [FA/(FA+C)]			93	91	93.6
Fly Ash Content wt., % [FA/(FA+C+S+G)]			93	32	22
Resistivity (ohm-cm)	Air Dried	3	40.1	65.8	151.4
		7	225.6	309.4	863.6
		14	837.9	911.5	1430.4
		28	3890.1	3417.9	5824.9
	Saturated	3	40.1	65.8	151.4
		7	40.1	85.6	161.6
		14	40.1	103.5	168.8
		28	48.5	101.7	183.7
Relative Permeability	Air Dried	3	1.001	1.004	1.006
		7	1.001	1.004	1.006
		14	1.004	1.004	1.006
		28	1.012	1.004	1.006
	Saturated	3	1.001	1.004	0.999
		7	0.999	1.004	1.008
		14	1.001	1.004	1.005
		28	1.012	1.004	1.006

Conductive CLSM Containing We Energies High Carbon Fly Ash and Carbon Fibers (US Patent 6,821,336) (41)

Electrically conductive CLSM is advantageous where lower electrical resistance is sought, such as for use in structures where it is necessary to protect electrical equipment from lightning strikes. Ideally, electrically conductive CLSM has the following features:

(1) Provides low inductance, low resistance and subsequently low impedance values for all frequencies up to 1 MHz,

(2) Conducts energy efficiently across and through its surface without damage while providing true equalized ground potential rise values,

(3) Conducts energy efficiently into the earth quickly and seamlessly by providing the lowest impedance-coupling path,

(4) Compatible with copper, aluminum and galvanized steel products, and

(5) Fully excavatable, without heavy equipment

Conductive CLSM is made by using electrically conductive materials in close contact with each other throughout the CLSM. Electrically conductive additives include carbon fibers, steel fibers, steel shavings, carbon black, coke breeze, and other similar types of materials.

Since high carbon content fly ash is readily available as a coal combustion product, and carbon is known to be highly conductive, its use as an additive to CLSM to lower electrical resistance has been investigated. The goal of this testing work was to determine the feasibility of incorporating carbon fibers in the CLSM to lower electrical resistance of these construction materials. The lower electrical resistance of these construction materials can potentially reduce the required length, or entirely replace, the grounding electrodes currently in use for protection of electrical equipment from lightning strikes.

Materials

Materials utilized in this project consisted of one source of fly ash, cement, and carbon fibers. One source of fly ash was used for this project (We Energies, Presque Isle Power Plant). This selection was made to represent a typical high-carbon fly ash available from We Energies. Type I cement (Lafarge Cement Co.) was used throughout this investigation. Carbon fibers were used in one CLSM mixture (Mixture CLSM-B) to attempt to enhance the electrical resistance characteristics.

All CLSM ingredients were manually weighed and loaded in a rotating-drum concrete mixer. The CLSM was mixed using a rotating-drum mixer. Fresh CLSM properties such as air content (ASTM D-6023), flow (ASTM D-6103), and unit weight (ASTM D-6023) were measured and recorded. Air and CLSM temperature were also measured and recorded. CLSM test specimens were prepared from each mixture for compressive strength (ASTM D-4832) and density. Compressive strengths of the CLSM mixtures were evaluated at the designated ages of 3, 7, 14, and 28 days. All test specimens were cast in accordance with ASTM D-4832. Three CLSM test specimens were tested at each test age. These specimens were typically cured for one day in their molds in the University of Wisconsin at Milwaukee – Center for By-Products Utilization laboratory at about 70° ± 5°F. After setting, the test specimens were then demolded and placed in a standard moist-curing room maintained at 100% relative humidity and 73° ± 3°F temperature until the time of test.

Mixture Proportions

Two different types of electrically conductive CLSM mixtures were tested. CLSM mixture proportions and fresh CLSM test results are shown in Table 5-15. The CLSM mixtures were proportioned to maintain a "practical" value of flow that would not lead to excessive segregation and bleeding.

Table 5-15: Electrically Conductive CLSM Mixtures

Mixture No.	**CLSM-A**	**CLSM-B**
Laboratory Mixture Designation	W-1	WF
Mixture Description	High-Carbon Fly Ash CLSM	High-Carbon Fly Ash CLSM with Carbon Fibers
Fly Ash, FA (lb/yd^3)	1250	490
Cement, C (lb/yd^3)	97	95
Carbon Fibers (lb/yd^3)	--	23
Fly Ash Content, % [FA/(FA+C)]100	93	82
Water, W (lb/yd^3)	1010	1370
[W/(C+FA)]	0.75	2.3
Air Temperature (°F)	79	72
Fresh CLSM Temperature (°F)	76	60
Flow (in.)	11	8
Air Content (%)	1.7	0.6
Unit Weight (lb/ft^3)	87.2	73.6
Hardened CLSM Density (lb/ft^3)	85	90

Mechanical Properties

The compressive strength data for the CLSM mixtures are presented in Table 5-16. Compressive strength of the high-volume fly ash CLSM mixture (Mixture CLSM-A, fly ash and cement) increased slightly between the ages of 3 and 28 days. Compressive strength for Mixture CLSM-A was 70 psi at the 3-day age, and increased to 85 psi at the 28-day age. When carbon fibers were introduced into the CLSM mixture, compressive strength was significantly reduced, to approximately 10 psi. The 28-day strength levels achieved for the CLSM-A and CLSM-B mixtures should not be expected to pose a problem in case of future excavation.

Due to the addition of carbon fibers, the flowability of the CLSM was significantly reduced for Mixture CLSM-B. In order to obtain flow characteristics for a typical CLSM, water for Mixture CLSM-B needed to be increased by approximately 30% over the amount used for Mixture CLSM-A (CLSM without fibers). Reduced flowability is to be expected since the fibers would tend to interlock and restrict the flow of the mixture.

Table 5-16: Compressive Strength of CLSM Mixtures

Mixture No.	Fly Ash Content, % [FA/(C+FA)]	Compressive Strength (psi)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	75	70	85	75	80	75	85	85
		70		70		70		80	
		65		70		75		90	
CLSM-B	82	--	--	10	10	10	10	10	10
		--		5		10		10	
		--		10		10		10	

Electrical Properties of CLSM Mixtures

The electrical resistivity values of the CLSM mixtures shown in Table 5-17 and Figure 5-10 are for air-dried specimens and Table 5-18 and Figure 5-11 are for saturated specimens. Electrical resistivity of high-carbon fly ash mixture CLSM-A, increased from 162.8 ohm-cm at the age of three days to over 55000 ohm-cm at the age of 28 days. Saturated specimens increased from 162.2 ohm-cm to only 535.7 ohm-cm at the age of 28 days. A significant improvement in the electrical resistance of CLSM occurred when carbon fibers were incorporated in Mixture CLSM-B. Both air-dried and saturated specimens exhibited very low resistivity of approximately 13.2 ohm-cm or less when tested at ages between 3 and 28 days. These results illustrate that using carbon fibers in CLSM has a greater positive effect on lowering the resistivity above that normally achieved through the use of high-carbon fly ash alone. Electrical permeability decreased slightly when carbon fibers were used (Mixture CLSM-B).

Table 5-17: Electrical Resistivity of CLSM Mixtures – Air-Dried Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	167.0	165.0	456.6	597.5	3357.4	4967.6	44706.0	55458.6
		159.8		544.0		4500.5		43568.9	
		168.2		791.8		7050.0		78100.8	
CLSM-B	82	6.6	6.4	7.8	7.8	9.0	8.8	13.2	13.4
		6.0		7.8		8.4		13.2	
		6.6		7.8		9.0		13.8	

Table 5-18: Electrical Resistivity of CLSM Mixtures - Saturated Specimens

Mixture No.	Fly Ash Content, % [FA/(C+S+G)]	Resistance (Ohm-cm)							
		3-day		7-day		14-day		28-day	
		Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
CLSM-A	93	159.8	164.0	239.4	263.9	350.1	383.4	482.4	535.0
		168.2		293.3		420.7		583.5	
		164.0		259.1		379.4		541.0	
CLSM-B	82	10.2	10.8	7.2	7.6	9.0	8.8	9.6	9.2
		9.0		7.8		8.4		9.6	
		13.2		7.8		9.0		8.4	

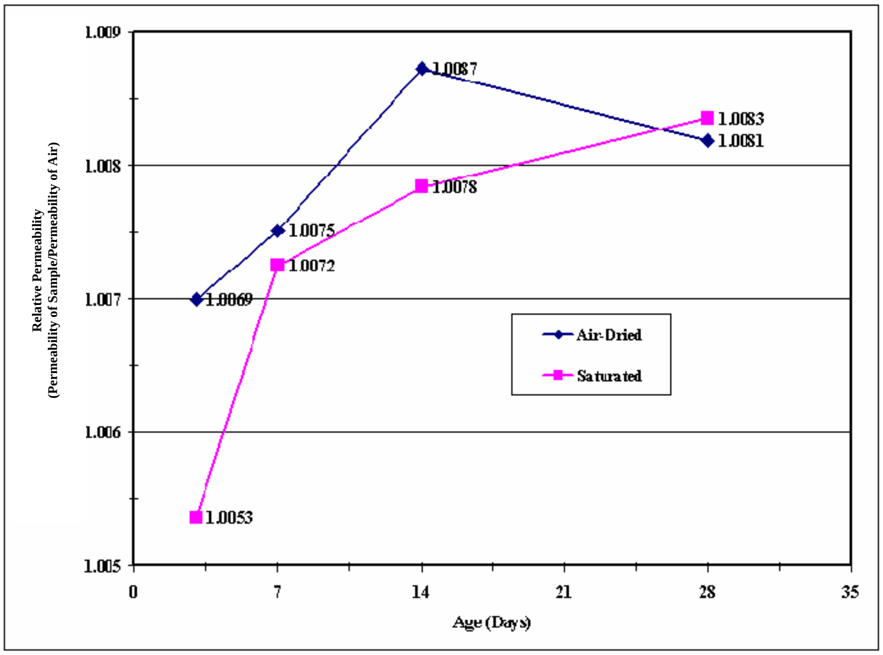


Figure 5-10: Electrical permeability of High Carbon Fly Ash CLSM Mixture CLSM-A

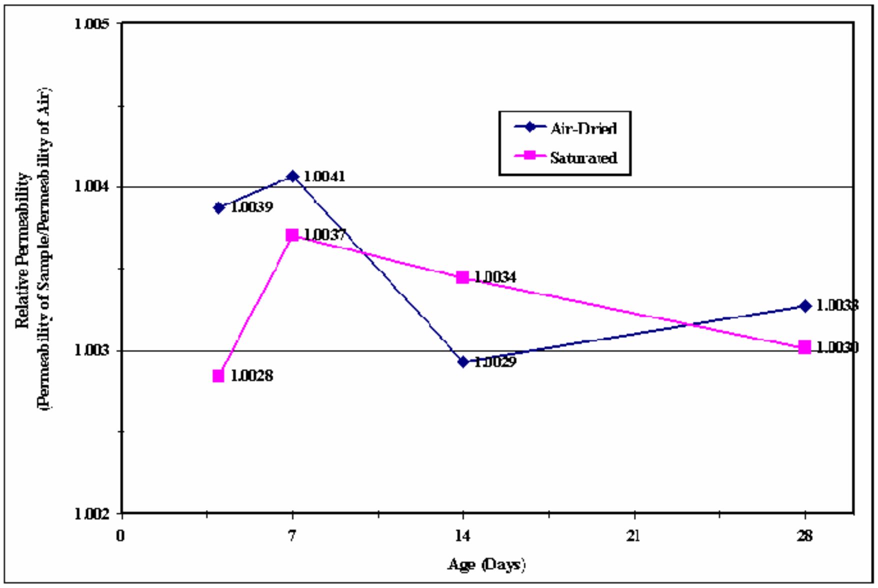


Figure 5-11: Electrical Permeability of High Carbon Fly Ash CLSM Mixture Containing Carbon Fiber CLSM

Dried vs. Saturated Specimens

Measurements taken for saturated CLSM specimens produced significantly smaller resistivity values compared to the air-dried specimens when tested without carbon fibers (Mixture CLSM-A). For the dried specimens, the aging process affected the resistivity significantly; the older the specimens, the higher the resistivity. The aging process affected the dried specimens more than the saturated ones. This indicates adding moisture to the material in place improves its conductivity. For the mixture containing carbon fibers, Mixture CLSM-B, air-dried specimens also had a higher electrical resistivity, but the difference between saturated and air-dried specimens was much less. Typically the difference between air-dried and saturated specimens was one ohm-cm or less. This can be attributed to the conductivity of the carbon fibers used in the mixtures.

Conductive CLSM Containing We Energies Fly Ash and Spent Carbon Sorbent (US Patent 7,578,881) (42)

This patent involves the testing of CLSM for increased electrical conductivity with the presence of both We Energies HCFA and spent carbon sorbent. The goal of this work was to determine the carbon and mercury in the spent carbon sorbent incorporated in CLSM to provide an electrical pathway throughout the CLSM for conducting electricity, without a severe deleterious effect upon mechanical properties (such as compressive strength), thus permitting the use of the electrically conductive CLSM in construction materials and applications.

Materials

Materials utilized consisted of one source of fly ash, cement, clean concrete sand, gravel aggregates, and a particulate material including fly ash and a spent activated carbon sorbent having adsorbed mercury. One source of clean concrete sand was utilized in this investigation as fine aggregate, meeting the ASTM C-33 requirements. The coarse aggregate used was natural river gravel with a maximum nominal size of ⅜ inch. Type I Portland cement was used throughout this investigation. One source of cementitious fly ash was used for this work from We Energies Pleasant Prairie Power Plant that met the requirements of ASTM C-618, Class C fly ash.

The spent activated carbon sorbent particulate material including fly ash that passed the electrostatic precipitator and was captured in the downstream baghouse was obtained from a coal fired electric generation facility that uses activated carbon sorbent to capture mercury. All CLSM ingredients were manually weighed and mixed by hand in a mixing bowl. For fresh CLSM, an estimate was made of the unit weight for determination of approximate mixture proportions and a general visual observation of the workability was made. Table 5-19 shows the mixture components.

Table 5-19: Concrete Mixture Proportions

Mixture No.	**CLSM**
Cement, C (lb/yd^3)	46 (1.46 wt %)
Class C Fly Ash, FA (lb/yd^3)	46 (1.46 wt %)
Particulate Matter Having Fly Ash & Spent Carbon sorbent, SC (lb/yd^3)	640 (20.26 wt %)
Water (lb/yd^3)	692 (21.91 wt %)
[W/(C + FA + SC)]	0.94
Carbon Fibers (lb/yd^3)	4.5 (0.14 wt %)
Sand SSD (lb/yd^3)	1730 (54.77 wt %)
⅜-in. Aggregate, SSD (lb/yd^3)	0
Fresh Density (lb/ft^3)	116.8

Note: The weight percent is the percent of the total mixture

Table 5-20: Concrete Mixture Test Results

Test	**CLSM**
Electrical Resistance (ohms)	95.9
Electrical Resistivity (ohms-cm)	286
Compressive Strength @ 50 days (psi)	50

Mechanical Properties

A 3 inch by 6 inch test cylinder was cast with the CLSM mixture where it was air-cured in the laboratory at 70º F ± 5ºF until the time of testing. Table 5-20 shows the test results for the mixture. Electrical resistance of the CLSM was measured using copper plates (3-in. diameter on each end) across the 6 inch length of the concrete sample. The tests resulted in a resistance of 95.9 ohms at the age of 39 days. The electrical resistivity was calculated to be 286 ohms-cm from the measured resistance, using the following equation:

$$R = \frac{\rho L}{A}$$

where: ρ = resistivity; L = length; A = cross section area

Using the methods of ASTM C-39 and ASTM D-4832, the compressive strength for the concrete cylinder sample resulted in a compressive strength of 50 psi at the age of 50 days.

Commonly-Used CLSM Mixtures

We Energies has been testing and utilizing controlled low-strength materials containing fly ash for construction for over 25 years. Though several mixture proportions have been tried, a few mixtures are commonly used that are excavatable by ordinary methods. These mixtures usually are required to be self-leveling and essentially free from shrinkage after hardening. The mixtures that are most commonly used are designed to reach a state of hardening such that they can support the weight of a person in less than 24 hours.

We Energies has developed and marketed three different CLSM mixtures under the commercial name Flo-Pac. Flo-Pac is self-leveling and self-compacting and is placed to lines and grades shown on the construction plans. Table 5-21 shows the mix designs for Flo-Pac 1, Flo-Pac 2 and Flo-Pac 5.

Table 5-21: Commonly Used High Carbon* Class F Fly Ash Mixtures and Proportions

Mixtures (lbs./ ft^3)	Flo-Pac 1	Flo-Pac 2	Flo-Pac 5**
Portland Cement	100	70	200
PWPP or VAPP Class F Fly Ash	1450	925	700
SSD Stone	0	0	1500
SSD Sand	0	1175	750
Water	950	832	533
Total Weight	2500	3002	3683

*Carbon content exceeds ASTM C-618 requirements
**Not excavatable

Pilot Projects Using We Energies CLSM

We Energies has utilized CLSM fly ash slurry on the following projects, where low strength and flowability were essential.

Abandoned Steam Service Tunnels

Figure 5-12: ASTM D-6103, Standard Test for CLSM Flow Consistency

This was the first documented We Energies pilot project utilizing CLSM fly ash slurry. The project involved filling two obsolete brick lined steam service tunnels in downtown Milwaukee in December 1983. One tunnel was 6 ft. in diameter by 290 ft. long and the other had a 5 ft. by 4 ft. wide ellipsoid cross section.

Over 420 cubic yards of CLSM slurry material were produced from a mixture of 2,152 lbs. of dry Class F fly ash, 859 lbs. of water, and 88 lbs. of Type I Portland cement. The fly ash was loaded directly into the ready-mix truck. The cement and water were also added directly and the drum was rotated at least 60 times during transit.

The CLSM flowable fly ash slurry was pumped into the tunnel. The maximum distance of CLSM flow was approximately 130 ft. Cylinders measuring 6” x 12” were prepared, and unconfined compression tests were run on the cylinders after 7 and 28 days, showing strengths between 50 and 100 psi, and greater than 100 psi, respectively. The project was completed over 25 years ago and no problems have been detected.

Figure 5-13: CLSM flowing through a funnel to fill an underground tunnel in downtown Milwaukee, Wisconsin.

Figure 5-14: We Energies' Flo-Pac CLSM being placed in a direct buried steam pipe trench in downtown Milwaukee, Wisconsin.

Sidewalk Cavity

This project was undertaken in 1984 and involved filling a hollow sidewalk cavity containing former locker room facilities in downtown Milwaukee. The CLSM flowable fly ash fill covered a length of about 80 ft., width of 14 ft. and a depth of 7 ft. The final top leveling layer was filled with sand (54).

Figure 5-15: CLSM being placed in lifts to manage the load on basement walls.

About three hundred cubic yards of CLSM slurry were prepared using 1,950 lb. of dry Class F fly ash, 1,000 lb. of water and 128 lb. of Type 1 Portland cement. This mixture was placed directly into the cavity from ready mix trucks. Though minor shrinkage cracks were observed the following day, no voids or settlement was noticed.

The site was excavated, using a tractor mounted backhoe, after several months to install a water supply lateral. The hardened slurry was easily rippable and the excavation had straight walls on each side. CLSM slurry with a compressive strength of less than 300 psi at 28 days worked well for this type of an application.

WisDOT Low Permeability CLSM with We Energies Fly Ash (55)

To ensure containment of contaminated soils and groundwater, WisDOT developed a CLSM with low permeability for use as a migration/contamination barrier during normal construction and construction emergencies. Strict physical requirements were specified for the WisDOT low permeability CLSM. The material needed to be flowable, with a maximum compressive strength of 100 psi, a maximum permeability of 1 x 10^{-6} cm/s and less than a 24-hour time of set.

Class C fly ash from We Energies' Pleasant Prairie Power Plant (PPPP) was used extensively during WisDOT low permeability CLSM mixture design study. The mixture using We Energies' PPPP Class C fly ash was one of two mixture designs which meet the above engineering properties requirement, as shown in Table 5-22.

Table 5-22: WisDOT Low Permeability CLSM Mixture Design with We Energies Class C Fly Ash

Weight (lbs/yd^3)	Material
50	Type I Portland Cement
700	Class C Fly Ash from We Energies Pleasant Prairie Power Plant
2640	Fine Aggregate per section 501.3.6.3 of the Wisconsin Standard Specifications
390	Water per section 501.3.5 of the Wisconsin Standard Specifications

Precautions to be Taken When Using CLSM Flowable Fly Ash Slurry

When properly mixed and placed, CLSM can provide construction savings by eliminating the need for labor intensive compaction efforts with standard granular materials. However, the following important construction considerations must be followed for success.

Figure 5-16: CLSM compression test cylinders. Note the color difference between those CLSMs based on Class F (dark) and Class C (light).

1. CLSM is placed as a liquid. Hence it exerts fluid pressure. If CLSM is placed against basement walls or other structures, verify that the structure is capable of taking this lateral pressure. If the structure is not capable of handling this pressure, it can be braced externally until the CLSM slurry solidifies, or the CLSM slurry may be placed in multiple lifts so that one lift hardens before the next is placed.
2. Secure tanks, pipes and cables so they don't float in the excavation.
3. Fresh CLSM flowable fly ash slurry that is placed in deep excavations behaves like "quick-sand" so it must be protected from accidental entry until it hardens.
4. Low-strength CLSM material where future excavation may be required at a later age should be specified with a maximum strength (or a range of strength) that will allow for easy excavation with normal equipment. The addition of coarse aggregate to the mixture generally makes excavation more difficult.
5. When transporting CLSM flowable slurry in a ready-mix truck, the driver should be aware of the liquid nature of the material being transported. CLSM may spill out of the back of a ready mix truck with quick stops or while travelling up hills. It is better to transport CLSM stiff and add water at the job site for high flow requirements.

Advantages of Using CLSM Fly Ash Slurry

CLSM fly ash slurry has several advantages when compared to conventional compacted backfill. The slurry mixture can be designed to meet the requirements of particular applications. The following are the major advantages:

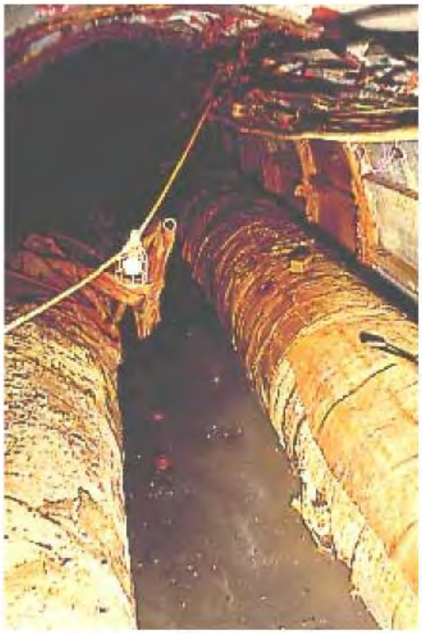


Figure 5-17: Filling a tunnel with twin 30" diameter steam mains in Milwaukee, Wisconsin

1. CLSM fly ash slurry is flowable. The flowability can be increased or decreased by varying the water content. Hence, it can be used to fill inaccessible areas like retired sewer mains and tunnels where conventional ways of backfilling are difficult or economically not feasible. The flowable slurry fills voids completely, thus avoiding future settlement.
2. The level of strength can be increased or decreased depending on the application. Where future excavation is required, the strength may be limited to the range of

50 to 300 psi maximum. Where higher strength is specified, such as base material for foundations, changing the cementitious and aggregate proportions may increase the strength.

3. Unlike conventional backfilling methods, no tamping or vibration is required to place CLSM.
4. Long-term settlement is virtually nonexistent. Except for the initial shrinkage settlement of less than $^1/_8$ inch per foot, there is no additional settlement after hardening. Hence, on pavement repairs and similar applications, a smoother ride can be expected.
5. There are substantial cost savings in using CLSM slurry, when compared to labor intensive conventional methods of backfilling. Fly ash slurry does not need compaction or vibration.
6. Utilizing fly ash for this application is making beneficial use of a coal combustion product, which is helpful to the environment. It preserves sand and gravel pits, crushed stone quarries, valuable landfill space; saves land that would otherwise be dedicated for these uses; and contributes to sustainable development by completely utilizing this resource and preserving virgin materials for future generations.

Figure 5-18: Volumetric mixer used for production of fast setting and excavatable CLSM in the Chicago area.

Sample Specifications are included in Appendix 12.4 for the current CLSM mixtures.

Chapter 6

Commercial Applications of We Energies Bottom Ash

Introduction

We Energies bottom ash can be beneficially utilized in a variety of manufacturing and construction applications. These applications include both confined and unconfined geotechnical uses, as an ingredient for the production of soil products and as an aggregate for concrete products. When using bottom ash, it is important to compare the applications and material properties to local and state regulations and specifications. In order to evaluate potential applications, We Energies has studied the properties and performance of its materials with the assistance of several consulting firms and research institutions. We Energies bottom ash is predominantly used for the following applications:

1. Road base and sub-base
2. Structural fill
3. Pipe Bedding/Backfill
4. Drainage media
5. Aggregate for concrete, asphalt and masonry
6. Abrasives/traction
7. Manufactured soil products

Road Base and Sub-Base

STS Consultants, Ltd. conducted a study for We Energies to evaluate the potential use of Pleasant Prairie Power Plant bottom ash as a base course in road construction (56). The study evaluated potential applications, and initiated durability and structural testing of bottom ash from We Energies Pleasant Prairie Power Plant.

The following tests were performed:

- Particle size analysis (ASTM D-422)
- Moisture-density relationship test - to establish maximum dry density (ASTM D-698-78, Method A).
- California Bearing Ratio (CBR) test - to develop a basis for comparison of bottom ash material with conventional base course aggregates (ASTM D-1883).
- Laboratory permeability test (ASTM D-2434)
- Direct shear test - to determine the angle of internal friction (ASTM D-3080)

The scope of this study included establishing an equivalent thickness of bottom ash compared to conventional aggregates in road construction. To address frost susceptibility in a meaningful manner, a sample of bottom ash was compacted into a 6” mold at its optimum moisture content. The mold with its perforated base was placed in a container of water for three days to allow the sample to absorb water. The sample was then frozen and subsequently thawed. Volume change measurements were made after both freezing and thawing.

The gradation of bottom ash tested was comparable to a silty fine to coarse sand with little gravel. However, bottom ash was considerably finer grained than the conventional gradation for fine aggregate.

The PPPP bottom ash exhibited a maximum dry density of 88.5 lbs/cu ft. and optimum water content of 28%. Conventional aggregates have maximum densities in the range of 105 to 120 lbs/cu ft. at optimum moisture contents typically in the range of 8% to 16%.

The CBR test results showed PPPP bottom ash had a CBR value on the order of 30% of that of conventional aggregate. In general, more coarsely graded and more angular materials tend to exhibit greater stiffness and tend to distribute load more evenly. The results showed that when used in a comparable thickness, bottom ash exhibits less favorable load distribution characteristics and would be more flexible, i.e., greater surface deformation under a load, than for conventional aggregates.

However, based on accepted pavement design principles, it was estimated that this source of bottom ash can be used at approximately 1.5 times the thickness of conventional aggregates achieves a comparable stress level in the underlying clay subgrade. For equivalent deformation, it was estimated that the thickness of bottom ash should be two times the thickness of conventional aggregates to maintain similar deflection at the surface of the base course layer (56). Figure 6-1 shows the stress penetration CBR curve for PPPP bottom ash.

The report also evaluated frost susceptibility, since bottom ash contains more fine-grained particles than conventional aggregates. The permeability study of compacted bottom ash was in the same range as conventional base course aggregates, i.e., 8 x 10^{-4} to 5 x10^{-5} cm/sec. However, due to the presence of slightly higher fines when compared to conventional materials, it is recommended that bottom ash be used at locations with reasonably good drainage.

The direct shear test indicated an angle of internal friction of 40 degrees and cohesion of 750 psf, for the ash tested. The friction angle is consistent with this type of material. Figure 6-2 is a graph showing the normal stress vs. shearing stress relationship. However zero cohesion was expected due to its similarity to silty sand. Freeze-thaw test results showed a volumetric expansion of the compacted ash of 0.4% upon freezing. But after thawing, the net volumetric expansion was 0.1%.

Table 6-1 shows the gradation for PPPP bottom ash and crushed aggregate base course (crushed gravel) per the 1996 Wisconsin DOT Standard Specification for Highway and Structure Construction at the time of testing. A comparison of We Energies' bottom ash to crushed aggregate base course in 2012 Wisconsin DOT Standard Specifications can be found in Chapter 3.

Table 6-1: Grain Size Distribution (ASTM D-422) PPPP Bottom Ash and Comparison with WDOT Crushed Gravel Specification for Crushed Aggregate Base Course

Sieve Size	PPPP Bottom Ash % Passing	Gradation No. 1 Crushed Gravel % Passing	Gradation No. 2 Crushed Gravel % Passing	Gradation No. 3 Crushed Gravel % Passing
1.5"	100.00	100	-	-
1"	98.15	75 - 100	100	100
.75"	94.09	-	-	95 - 100
.50"	85.29	-	-	-
.375"	78.28	40 - 75	50 - 85	50 - 90
#4	57.78	30 - 60	35 - 65	35 - 70
#8	41.51	-	-	-
#10	36.99	20 - 45	25 - 50	20 - 55
#16	27.92	-	-	-
#30	17.72	-	-	-
#40	13.10	10 - 30	10 - 30	10 - 35
#50	10.56	-	-	-
#100	6.05	-	-	-
#200	3.05	3 - 10*	3 - 10*	8-15

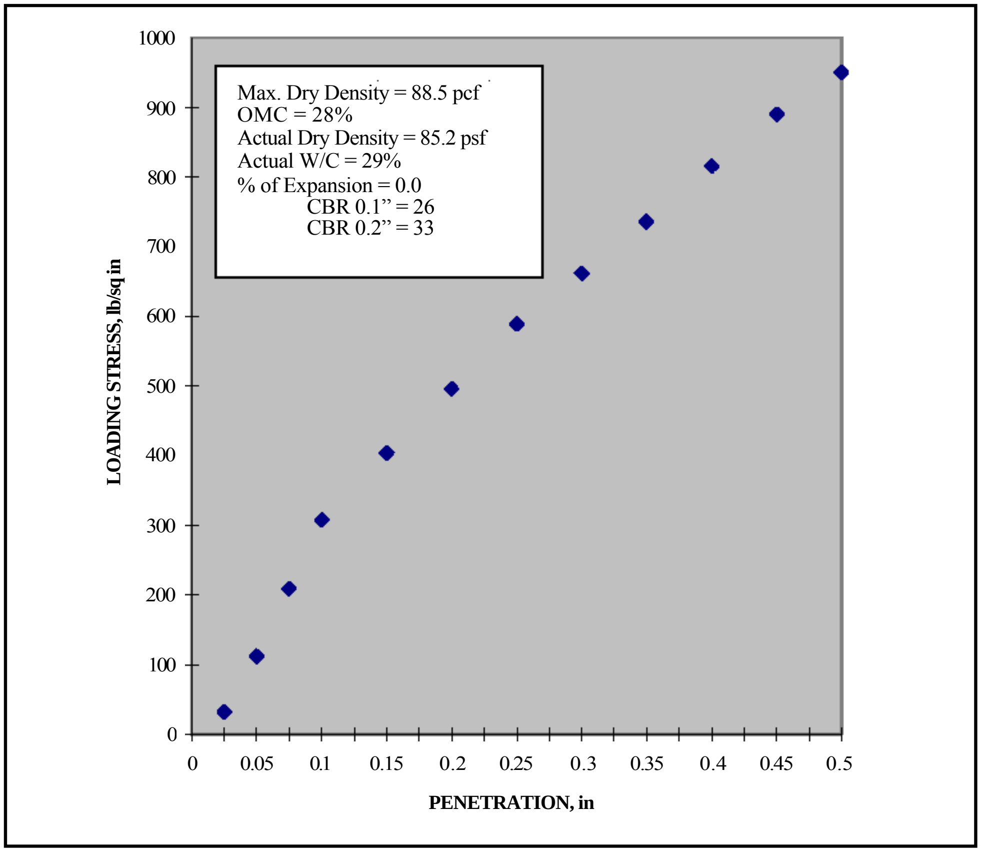


Figure 6–1: Loading Stress vs. Penetration (California Bearing Ratio) Curve for PPPP Bottom Ash

* Limited to a maximum of 8% in the base course placed between old and new pavement

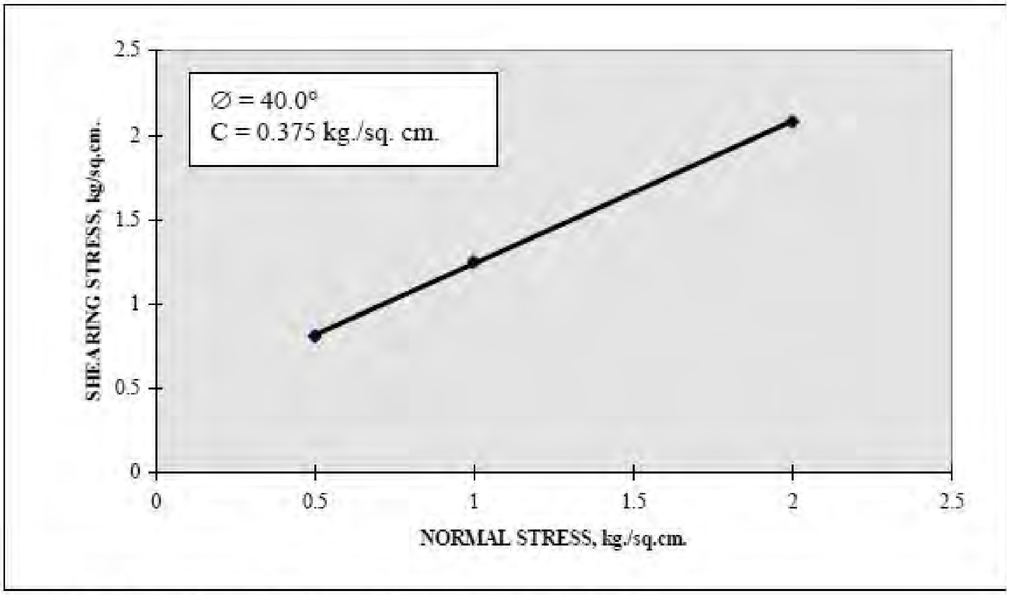


Figure 6–2: Normal Stress vs. Shearing Stress PPPP Bottom Ash

Field Study

Following the initial study conducted on the suitability of bottom ash from PPPP as a base course, another study was commenced with field observation and testing on the performance of bottom ash during construction of another roadway in the Lakeview Corporate Park (57). The purpose of the testing was:

1. To further evaluate the equivalency ratio using field plate load bearing tests.
2. To evaluate frost susceptibility during a winter season by level survey techniques.
3. To observe the general performance of the road subgrade for various thicknesses of base course.

Plate Load Test

As part of the road subgrade preparation, crushed limestone was placed in thicknesses varying from 0” to 6”. Bottom ash was placed above the proof rolled subgrade and leveled with a Caterpillar 14G grader. Bottom ash was then compacted close to its Modified Proctor maximum dry density, in the range of 83 to 95 lbs/cu ft. Crushed stone and gravel were placed in a parallel stretch of roadway and compacted to approximately 100% of its Modified Proctor maximum dry density. Plate load tests were performed in accordance with Military Standard 621A (Method 104).

Based on the test performed, a subgrade reaction modulus of 380 pounds per cubic inch (pci) was calculated. A similar test performed at the surface of the native subgrade gave a reaction modulus of approximately 212 pci. This gives a modular ratio of bottom ash to subgrade of approximately 1.9. Originally, a modular ratio of approximately 3 had been calculated. Conservatively, a modular ratio of 2 is appropriate.

Level Survey

The road surface was initially surveyed to establish a baseline for the determination of freeze-thaw effects. The level survey conducted on February 9, 1989, recorded a maximum surface heave of 0.6”, but after the spring thaw, the surface elevations were within ± 0.24”. These heaves were observed on both surfaces with and without bottom ash base course. The survey did not find any distinct pattern of response with the bottom ash experiencing neither greater nor lesser net heave during freeze-thaw cycles.

General Road Performance

The surface of the concrete road was inspected initially and found to be in competent condition, free of substantial ruts, cracking and other signs of pavement distress. The pavement was observed again after spring thaw and found to be in good condition. This indicated that the subgrade performed satisfactorily through the first winter.

It was concluded that the PPPP bottom ash materials are well suited for use as general structural fill in road subgrade preparations or below structural elements. Based on field observations, it was recommended to use bottom ash in a 2 to 1 thickness ratio compared to conventional base course material, to enhance the performance of the pavements. The reason for this recommendation is the lesser degree of stiffness of the bottom ash. It was concluded that in well-drained pavement sections, bottom ash base course (in the recommended thickness) should perform well.

Bottom Ash as Base Course Aggregate for Flexible Pavement Sections

The earlier study evaluated the performance of bottom ash as a base course material for a rigid pavement section. Though the pavement section performed well, a rigid pavement was used in that study and the performance of that section cannot be assumed to represent the behavior of less rigid pavement sections. Hence, a second pilot study was undertaken to evaluate the use of bottom ash for conventional base course aggregate in a flexible pavement section, such as parking lots and bituminous-paved roads (58).

A.W. Oakes & Son had observed that the actual performance of bottom ash in constructed haul roads was excellent. From this experience, they suggested that the ash might be effective at lesser thicknesses than recommended in the original study performed by STS Consultants, Ltd. A.W. Oakes & Son suggested that a pavement section consisting of 4” – 6” of bottom ash over 4” – 6” of open-graded crushed stone would serve as an excellent base for a heavy duty asphalt pavement.

Pavement Construction

A failed section of pavement 24 ft. wide by 55 ft. long located at the entrance drive of A.W. Oakes & Son Land Reclamation Landfill Facility in Racine, Wisconsin, was replaced with 4¾” of bituminous concrete pavement placed over 4½” – 6½” of bottom ash which was over 8” of an open-graded crushed stone base layer. The test section was constructed in November and December of 1993. Field density tests were performed by STS Consultants on the in-place bottom ash and on the in-place bituminous pavement using a nuclear density meter (58).

Figure 6-3: Bottom ash base course for concrete building slab in Racine,

Pavement Performance

The test pavement was evaluated by STS Consultants, Ltd. on March 21, 1994; November 22, 1994; April 20, 1995 and April 22, 1997. The field observations revealed that the pavement section performed well with only minor rutting in wheel traffic areas. The depth of rutting increased slightly over the years, but was not considered abnormal. The asphalt surface showed no signs of alligator cracking.

No direct correlation can be made with the adjoining pavement, since the age and construction of this pavement is unknown. However, from field observations, it was concluded that the pavement section appeared to be comparable to or better than the adjacent pavement throughout its existence until 2010.

We Energies Bottom Ash Backfill

We Energies bottom ash has been successfully used as a backfill material on numerous projects. PPPP bottom ash is a clean, durable, torpedo sand-like material. Other We Energies bottom ashes are finer or include gravel size gradation particles as well.

The suitability of bottom ash as a backfill material can be understood from its close resemblance to commonly used natural granular backfill materials. In most cases, the most critical factor is the gradation of backfill material.

Sieve analyses indicated that bottom ash from PPPP meets the gradation requirements for a granular backfill material by the WDOT. PIPP bottom ash did not meet all of the requirements, but PIPP bottom ash can be blended, washed or screened to meet the MDOT requirements. Other analyses have shown that bottom ash from OCPP also meets the WDOT gradation requirement for granular backfill. Permeability of the backfill is a common concern, especially in applications where the backfill material is subjected to a moist environment. Permeability is also one of the major reasons that sand is a preferred backfill material when compared to clay.

Figure 6-4: Bottom ash structural backfill being used for building construction in Racine, Wisconsin

Since the gradation of bottom ash and sand are similar, they tend to exhibit similar permeability. Clean fine sand has a coefficient of permeability (K) in the range of 0.004 to 0.02 cm/sec (59). The drainage characteristics associated with the above K values are considered good. Most We Energies bottom ashes have a coefficient of permeability in this range and can be considered to provide good drainage when used as a backfill material.

Table 6-2 gives the coefficient of permeability for We Energies bottom ash and conventional backfill materials.

Table 6-2: Permeability and Drainage Characteristics of Backfill Material

Type	Approximate Coefficient of Permeability K, (cm/sec)	Drainage Characteristics
Clean Gravel	5 - 10	Good
Clean Coarse Sand	0.4 - 3	Good
Clean Medium Sand	0.05 - 0.15	Good
VAPP Bottom Ash	0.0054	Good
PIPP 1-6 Bottom Ash	0.0048	Good
PPPP Bottom Ash	0.0049	Good
PWPP Bottom Ash	0.0046	Good
OCPP Bottom Ash	0.001	Good
Clean Fine Sand	0.004 - 0.02	Good
Silty Sand and Gravel	10^{-5} - 0.01	Poor to Good
Silty Sand	10^{-5} - 10^{-4}	Poor
Sandy Clay	10^{-6} - 10^{-5}	Poor
Silty Clay	10^{-6}	Poor
Clay	10^{-7}	Poor
Colloidal Clay	10^{-9}	Poor

Bottom ash has a lower density than conventional backfill materials. Conventional backfill materials (like sand) typically have a maximum dry density of 105 to 120 lbs/cu ft. We Energies bottom ash has a maximum dry density in the range of 49 to 89 1bs/cu ft. VAPP bottom ash showed the lowest dry density of 49 lbs/cu ft., and PPPP bottom ash had the highest density of 89 lbs/cu ft.

Bottom ashes from VAPP and MCPP have a higher percentage of fines and are more sensitive to moisture changes. However, bottom ash from other power plants performed well when compacted at the optimum moisture content. Soil generally exhibits lateral earth pressure. Structures such as retaining walls have to be designed, considering the lateral pressure exerted by soil retained by the structure. The angle of internal friction for various backfill materials is shown in Table 6-3.

Table 6-3: Approximate Friction Angle

Soil Type	Ø Degrees	Tan Ø
Silt or Uniform Fine to Medium Sand	26 to 30	0.5 to 0.6
Well-Graded Sand	30 to 34	0.6 to 0.7
Sand and Gravel	32 to 36	0.6 to 0.7

The friction angle of bottom ash is very similar to that of well-graded sand and gravel. The lateral earth pressure on the structure can be reduced because of the lower material density. Assume that the dry unit weight of a specific bottom ash in such a situation is only $^2/_3$ of the dry unit weight of conventional backfill material. Because the friction angle value remains more or less the same, the lateral earth pressure will also be reduced to $^2/_3$ of regular fill. Due to the reduced lateral pressure on the wall, it can be designed as a thinner section, with less reinforcement, or with a higher safety factor.

Bottom Ash as an Anti-Skid Material

Bottom ash performs as an excellent anti-skid material when spread on ice or snow covered roads. Bottom ash does not have the corrosivity of salt, as only a very small fraction of it is soluble. The performance of bottom ash as an anti-skid material is not temperature dependent. For this reason, bottom ash can be considered a better anti-skid material than road salt. The WisDOT recommends the following rate of application (60):

1. A rate of 500 pounds per mile on average snowy and icy roads.
2. A rate of 800 pounds per mile at intersections, hills, curves and extremely icy areas.

Used tires are sometimes burned with coal in some power plants. Bottom ash produced from plants that burn tires may contain steel wires that are left from the steel belted radial tires. Bottom ash containing steel wires is not suitable for use on roads as steel can puncture tires of vehicles traveling on these roads.

We Energies power plants do not burn used tires with coal. Hence, the bottom ash will not contain such steel wires and is acceptable for use as an anti-skid material on roads. Bottom ash will usually require screening to meet anti-skid material gradation requirements.

Bottom Ash as an Aggregate in Asphaltic Concrete

A.W. Oakes & Son replaced fine aggregates with bottom ash in asphaltic concrete mixtures for paving projects. Since bottom ash particles are porous, the consumption or absorption of asphalt binder is higher than when the conventional fine aggregate is used. Hence, from a purely economical point of view, We Energies bottom ash is not best suited as an aggregate for asphaltic concrete. However, other bottom ash sources have been extensively used by West Virginia Department of Transportation for asphalt roads, particularly for secondary roads (61).

Bottom Ash as a Bike Trail Base and Surface Material

Bottom ash has been successfully used as a base and surface material for bike trails and as a surface course material in parks and for running tracks.

In several states in the United States, bottom ash has been used as a finish grade surfacing material. The New River Trail in Virginia surfaced a portion of its 57-mile route with bottom ash. This project demonstrated significant savings in cost compared to a similar crushed stone surface (61).

We Energies Bottom Ash as a Manufactured Soil Ingredient

We Energies studied the properties of bottom ash and its use as a soil-amending agent to heavy clay soils to increase its workability and porosity. Studies conducted at the University of Wisconsin-Madison (62) revealed that land application of bottom ash had no negative effect on the crops or soil during the five-year period of study.

Bottom ash from the OCPP and PPPP were used on farms in Kenosha County, Wisconsin, at a rate ranging from 100 to 200 tons per acre. Bottom ash was tilled into the soil to a depth of approximately 10”.

Corn was grown on this field for two years and soybeans were grown for one year. Chemical analysis conducted on the soil throughout the three-year study revealed that there was no appreciable movement of nutrients or heavy metals below the 10” plow layer. Chemical analysis of corn and soybean seed and edible tissue for heavy metals and nutrient uptake indicated no adverse effect. Crop yield at the bottom ash treated soils was generally higher than from the non-treated soils.

The Scott’s Company of Maryville, Ohio, studied the properties of We Energies bottom ash and determined that it is suitable as an ingredient in manufactured soil products. The bottom ash from Milwaukee County Power Plant, Port Washington Power Plant and Valley Power Plant were used in their studies.

Figure 6–5: “Before” grass growing on We Energies’ landscaping with Scott’s 10% bottom ash topsoil blend at We Energies’ Milwaukee County Power Plant.

The investigation determined that the addition of 10–15% (weight basis) of bottom ash provides desired soil porosities. In addition, the ash blended soils exhibit excellent micronutrient composition.

The mixture also meets all of the state and federal limits for trace elements in composted soils. Bottom ash has been blended with peat, compost and manure to manufacture about 300 cubic yards of manufactured topsoil for We Energies landscaping projects with excellent results.

Figure 6–6: “After” grass is growing on landscaping with Scott’s Hyponex 10% bottom ash topsoil blend at We Energies’ Milwaukee County Power Plant.

Table 6-4 shows the summary of total elemental analysis results for fly ash and bottom ash with a comparison to Wisconsin DNR, NR 538 standards, together with various naturally occurring materials.

Table 6-5 shows ASTM water leach test data, in a similar fashion.

Additional information on environmental considerations is provided in Chapter 9.

Table 6-4: Total Elemental Analysis
Comparison of Sample We Energies Fly Ash, Bottom Ash and Natural Materials

Parameter	Units	NR 538 Category 1 Criteria	NR 538 Category 2 Criteria	Fly Ash	Bottom Ash	Road Gravel	Sand	Pea Gravel	Crushed Limestone	Garden Top Soil	Recycled Concrete
Antimony	mg/kg	6.3									
Arsenic	mg/kg	0.042	21	31	4.2	2.8	1.1	2.1	1.0	4.0	2.3
Barium	mg/kg	1100		2000	410						
Beryllium	mg/kg	0.014	7	11	1.4	0.2	0.2	0.3		0.8	0.8
Boron	mg/kg	1400		690	60						
Cadmium	mg/kg	7.8		2.3	0.059						
Chromium	mg/kg	14.5 as Cr^{+6}			65.5	22.4	34.1			59.1	33.2
Lead	mg/kg	50			23.6	14.1				43.3	
Mercury	mg/kg	4.7			0.11						
Molybdenum	mg/kg	78		12	1.6						
Nickel	mg/kg	310		40.4	28.1	6.4					6.2
Selenium	mg/kg	78									
Silver	mg/kg	9400									
Strontium	mg/kg	9400				71.7	65.5	74.3	25.6	129.4	113.4
Thallium	mg/kg	1.3									
Vanadium	mg/kg	110		201							
Zinc	mg/kg	4700		111	49.7	16.0	11.2	9.8	5.3	162	23.3

Note:
(1) Concentrations not shown are below the analytical detection levels
(2) The above results of the Total Elemental Analysis are from a test performed in late 1990's. For an updated Total Elemental Analysis from the NR 538 for the We Energies Fly ash and Bottom ash, see Chapter 9, Table 9-2 and 9-4, respectively.

Table 6-5: ASTM D3987 Water Leach Test Data
Comparison of Sample We Energies Fly Ash, Bottom Ash and Natural Materials

Parameter	Units	NR 538 Category I Criteria	NR 538 Category 2 Criteria	Fly Ash	Bottom Ash	Road Gravel	Sand	Pea Gravel	Crushed Limestone	Mequon Clay	Garden Top Soil	Recycled Concrete
Aluminum	mg/l	1.5	15	9.7	3.6	0.128	0.18	0.091	0.032	0.086	0.138	2.9
Antimony	mg/l	0.0012	0.012			0.0055		0.0032	0.0052	0.0026	0.0047	0.002
Arsenic	mg/l	0.005	0.05	0.003	0.004					0.0017	0.0016	
Barium	mg/l	0.4	4	0.76	0.25	0.0021	0.0017	0.0024	0.0018	0.0071	0.0135	0.146
Beryllium	mg/l	0.0004	0.004	0.0031		0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
Cadmium	mg/l	0.0005	0.005									
Chloride	mg/l	125		0.57								
Chromium	mg/l	0.01	0.1	0.11	0.0013							0.019
Copper	mg/l	1.3			0.0096							
Iron	mg/l	0.15			0.1					0.033	0.092	0.008
Lead	mg/l	0.0015	0.015		0.0016			0.0012				0.0012
Manganese	mg/l	0.025	0.25		0.0033					0.003		0.003
Mercury	mg/l	0.0002	0.002									
Molybdenum	mg/l	0.05		0.23	0.014							
Nickel	mg/l	0.02										
Selenium	mg/l	0.01	0.1	0.034	0.0013							
Sulfate	mg/l	125	1250	35	68						28.1	11
Thallium	mg/l	0.0004	0.004									

Note:
(1) Concentrations not shown are below the analytical detection levels
(2) The above results of Water Leach Test Data are from a test performed in late 1990's. For updated Water Leach Test Data from the NR 538 for the We Energies Fly ash and Bottom ash, see Chapter 9, Table 9-3 and 9-5, respectively.

We Energies Bottom Ash as a Soil Ingredient for Green Roofs

We Energies bottom ash was also used experimentally as a portion of a soil ingredient in green roofs. Green roofs involve growing plants on rooftops, thus replacing the vegetated footprint that was lost when the building was constructed. Establishing plant material on rooftops provides numerous ecological and economic benefits including storm water management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, as well as providing a more aesthetically pleasing environment to work and live. Examples of green roofs are shown in Figures 6-7 and 6-8.

Additional loading is one of the main factors in determining both the viability and the cost of a green roof installation, especially when a green roof is not part of the initial design of the building. Bottom ash is a lightweight material.

Figure 6–7: Green Roof at ABC Supply Company,

Blending bottom ash with the soil provides a lightweight growing media for the plants of the green roofs. We Energies bottom ash was used for a small portion of the green roof (as a blended soil ingredient) by ABC Supply Company, Inc. in Beloit, Wisconsin. Additional information can be found on website at: http://www.greengridroofs.com/Pages/system.htm

Figure 6–8: Green Roof at ABC Supply Company, Inc.

We Energies Recovered Ash and Reburning

Coal Ash Recovery (U.S. Patent # 6,637,354) (63)

As part of We Energies' continued effort to find innovative applications for its coal combustion products, and to preserve valuable licensed landfill capacity, We Energies has patented a process for recovery of coal combustion products from ash landfills. The PPPP ash landfill has been the primary site for ash recovery and occupies an area of approximately 163 acres. It is located north of Bain Station road and south of Highway 50.

The landfill was placed in operation in 1980 and consists of 25 cells with a total licensed capacity of 3,012,155 cubic yards of coal combustion products. Cell 1 was constructed with a natural 5 ft. thick clay liner and cells 2–4 were constructed with a 5 ft. thick recompacted clay groundwater separation liner. Currently only cells 1–3 are filled and cell 4 is partially filled. Since demand for bottom ash and fly ash has continued to increase since the 1980's, the quantity of material that goes into these landfills is limited. Since 1998, more material has been recovered from the landfill than placed in it. All the material placed originally in cells 1-2 has been recovered and the area has been restored.

The coal combustion materials landfilled in cells 1–4 consist primarily of bottom ash, solidified fly ash and wastewater treatment system solids. We Energies ash reclamation plan is to excavate the landfilled material, crush and screen if necessary, test and store for reuse in compliance with the criteria defined in NR 538, plus boron as an additional leachable parameter in

Figure 6-9: Coal ash recovery from the Pleasant Prairie Power Plant ash landfill for use as granular base course material

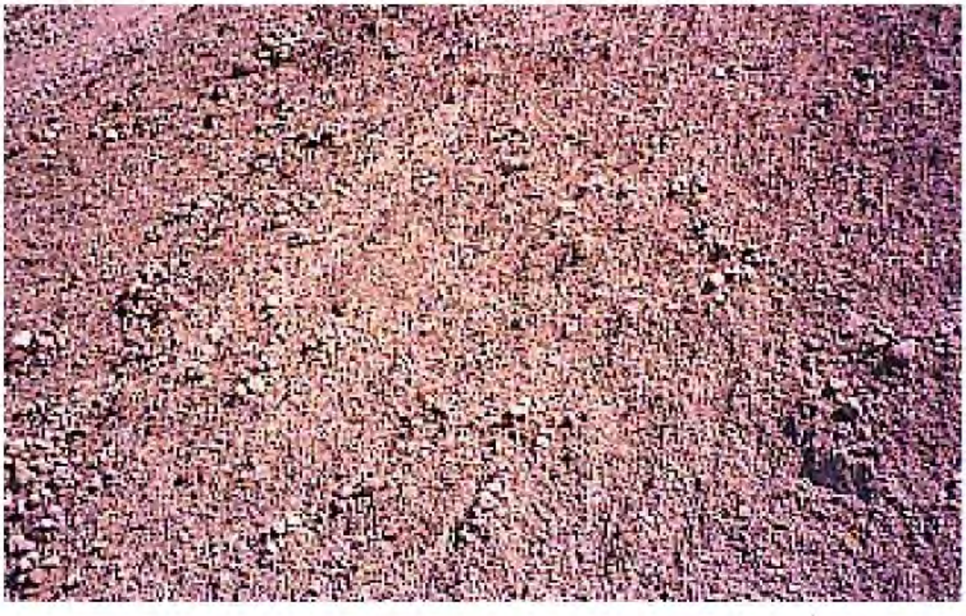


Figure 6-10: Recovered coal ash from the Pleasant Prairie Power Plant ash landfill

accordance with a cooperative agreement signed with the Wisconsin DNR (64). Any material that is found to be unsuitable for beneficial application such as miscellaneous debris or soil is separated and properly placed in designated areas within the current active cell.

The first pilot projects to reprocess landfilled combustion products were carried out in July 1998 and the second in October 1998. An earthwork contractor who was very experienced in landfill and ash management performed the work. A state certified material testing laboratory was also hired to monitor and sample the processed material. The contractor's engineer collected samples during the second operation. Samples were collected every 30 minutes from the transfer point where the ash fell onto the stacker conveyor during the entire operation per ASTM sampling procedure D-2234. A composite sample was prepared for every 5000 tons processed and tested. Both ash recovery operations worked very smoothly, and were dust free due to the residual moisture and low fines content of the material processed.

Figure 6-11 shows the grain size distribution range of the recovered ash. It is important to mention that the samples tested had excellent grain size distribution and a small amount of material passing the #200 sieve. Tests run to evaluate the environmental effects of this material also gave encouraging results. The ash met all of the NR538 category 2 criteria with the exception of dissolved aluminum. However the concentration of aluminum was only slightly above the limits (18 to 22 mg/l vs. 15 mg/l criteria).

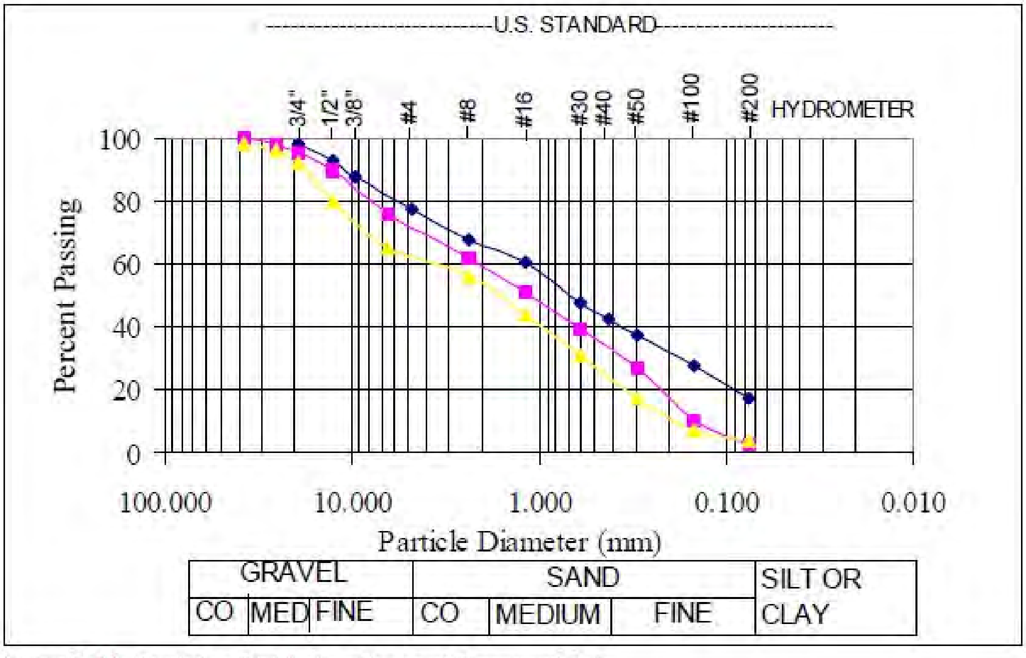


Figure 6–11: Gradation Distribution Range of Recovered Ash

The only other compounds detected that were within one order of magnitude of the category 2 criteria were antimony, barium, chromium and sulfate. The remaining elements were either non-detectable or were several orders of magnitude below the category 2 criteria.

The first 10,000 tons of recovered ash was used as a sub-base material under pavements. This practice has continued due to the excellent sub-base and base performance of the interlocking angular shaped recovered ash particles for this application. This is an application meeting NR538.10 (5) category 4 standards. However the recovered ash test results meet most of the NR 538 category 2 requirements.

In February 2001, Wisconsin DNR and We Energies entered into an agreement in which an ash sampling and testing procedure was specified. In order to determine the chemical consistency of the coal combustion materials recovered from the landfill, the ash was excavated, processed, and stored in a designated area in the landfill in no larger than 50,000 cubic yard piles. A representative sample was obtained per each 10,000 tons of reclaimed material for testing using guidelines presented in ASTM D-2234. A minimum of five discrete samples of at least 25 pounds each were collected from different locations on the storage pile. These discrete samples were composited, mixed, and volume reduced by manual riffling to develop the analysis sample. Testing was performed to measure category 2 parameters (described in ch. NR 538, Wis. Adm. Code), as well as boron as an additional leachable parameter, for use as sand/gravel/and crushed stone replacement materials. These recovered materials were used in category 4 or 5 applications (described in ch. NR 538, Wis. Adm. Code).

Reburning of Coal Ash (U.S. Patent # 5,992,336) (65)

If coal ash has a significant amount of unburned carbon, it cannot be utilized directly in applications such as concrete and concrete products. According to ASTM C-618, an ash must have a LOI value no higher than 6% for use in concrete. An upper limit of 3% is more realistic. Higher LOI ash cannot be used because of color problems and concerns with the use of admixtures especially for durability under freezing and thawing conditions.

We Energies is utilizing an innovative technique, reburning of coal ash, to treat high carbon coal ash using existing capital installations, and particularly the existing pulverized coal boilers. Coal ash, either fly ash or bottom ash or a mixture of both, is added in a fine particle condition to the furnace of a pulverized coal boiler in a small proportion to the pulverized coal fed to the furnace. The ash is burned with the pulverized coal. The proportion of coal ash is preferably in the range of 1% – 3.5%, by weight of the pulverized coal.

The high carbon coal ash generally results from burning bituminous coal while sub-bituminous coal will typically result in a low carbon ash with an LOI of less than 1%. The high LOI fly ash and bottom ash formed from a pulverized coal furnace burning bituminous coal can be rendered into a usable fly ash and bottom ash having very low LOI such as produced in a pulverized coal furnace using subbituminous coals. This can be achieved by adding the high LOI coal ashes to the coal stream which normally produces low LOI coal ashes.

The bottom ash and fly ash may be handled separately. The bottom ash typically has a larger particle size and may require grinding to reduce it to the size of the pulverized coal stream. The preferred approach for handling of the bottom ash is to add it to the store of coal prior to the coal being ground.

For instance in original tests conducted in 1996, bottom ash having an LOI of 37.9% and a moisture content of 60.0% was added to loaded coal cars using a front end loader. The bottom ash was added at a ratio of 5% of the coal prior to unloading in a rotary car unloader. The coal cars were then unloaded in a normal manner and the coal was transported by a conveyor system to one of five coal silos. The bottom ash and coal mixture was then milled and injected into the boiler with the fuel stream during normal operation in the furnace along with coal from the other four silos and mills that did not contain bottom ash. Thus, the actual ratio of bottom ash to coal transported for combustion was 1% of the overall fuel being burned. The addition of the 1% of bottom ash was not significant from an operational viewpoint. There was no discernable difference in emissions, and the bottom ash coal fuel blend had adequate fineness for combustion. The fly ash from the reburning of the bottom ash exhibited a LOI of between 0.2% and 0.4% and has a slightly reduced calcium oxide content. Bottom ash typically represents less than 20% of the coal ash.

High LOI fly ash can be introduced using four approaches: (1) introduced with the pulverized coal stream entering the pulverizer classifiers. This has the advantage of thorough mixing upstream of the burners and would require only a slight additional volume of air to transport the fly ash; (2) introduced with the pulverized coal stream at each burner location; (3) introduced with the secondary air flow stream as it enters the furnace. The secondary air flow with the fly ash provides sufficient mixing; (4) introduced through heat-resistant or stainless pipes into the furnace either above or adjacent to the existing burner level. Injection points through a waterwall could be used, although this may require modifications of the waterwalls in the boilers.

In the original tests conducted in 1996, a fly ash having an LOI of 26.5% and a moisture content of 0.3% was introduced into a coal pulverized furnace through injection pipes. The fly ash was stored in a horizontal silo from which it was pumped through stainless steel pipes extending through the furnace wall immediately above two coal burners. The hose was connected to a reducer splitter where the 5” diameter hose was reduced to two 2” diameter hoses. The fly ash was pumped at a rate of approximately 1% –2% of the coal flow into the furnace. The addition of the fly ash did not affect combustion. The resulting fly ash from the reburning had an LOI of between 0.2% and 0.5% based upon samples taken at intervals over four days. Reburning of high carbon bituminous coal ash in both sub-bituminous and bituminous pulverized fuel furnaces has now been performed at We Energies Pleasant Prairie and Elm Road Power Plants in Wisconsin and Presque Isle Power Plant in upper Michigan with excellent results.

We Energies Bottom Ash as Fine Aggregate in Concrete Masonry Products

Natural volcanic combustion products have been used in the manufacture of masonry products since ancient times. Several decades ago cinders, a combustion product of lump coal combustion, were used as a lightweight aggregate in the manufacture of masonry blocks. However, not much technical data was available on these products. Today, fly ash and bottom ash have been extensively investigated to determine performance.

We Energies has investigated the suitability of its bottom ash and fly ash in the manufacture of concrete bricks, blocks and paving stones. The following data is from research conducted at the Center for By-Products Utilization (CBU) of the University of Wisconsin-Milwaukee for We Energies at two local manufacturing plants (66).

Concrete masonry products can be manufactured either by the wet-cast process or the dry-cast process. Several mixes were designed at the CBU for the manufacture of concrete bricks, blocks and paving stones using the dry-cast method. Actual manufacture of the dry-cast test products was performed at Best Block Company in Racine, Wisconsin, using standard manufacturing equipment.

Tables 6-6 – 6-8 show the mixture design data for bricks, blocks and paving stones using the dry-cast method. Tables 6-9 – 6-11 show the compressive strength data for the above-mentioned products. The three mixtures for each product have varying amounts of fly ash and bottom ash. Each of the three products also has a control mixture with no fly ash and no bottom ash.

Table 6-6: Dry-Cast Concrete Brick Mixtures Using OCPP Bottom Ash and Fly Ash

Mix No.	BR-1	BR-2	BR-3	BR-4
Field Mix Designation	1	3	8	10
Fly Ash, [A/(C+A)](%)	0	29	29	41
Bottom Ash, [BA/S+BA)](%)	0	0	23	33
Cement, C (lb/yd^3)	345	260	245	215
Fly Ash, A (lb/yd^3)	0	110	100	150
Net Water, W (lb/yd^3)	145	160	190	260
[W/(C+A)]	0.43	0.43	0.55	0.72
SSD Fine Aggregate, S (lb/yd^3)	2335	2365	1655	1455
SSD Bottom Ash, BA (lb/yd^3)	0	0	490	705
SSD ⅜" Crushed Limestone Aggregate (lb/yd^3)	795	805	750	750
Moisture Content of Mixture, (%)	5.6	5.9	7.8	10.1
Unit Weight (lb/ft^3)	134.0	137.0	127.0	131.0
Test Batch Yield (yd^3)	0.60	0.60	0.60	0.60

The dry-cast concrete brick mixture BR-1 (control mix) had a 56-day strength that was lower than that of BR-2, a similar mix containing fly ash. Twenty-five percent cement was replaced with fly ash at a 1 – 1.3 replacement ratio. The exact proportions can be seen in Table 6-6.

Brick mixtures BR-3 and BR-4 containing bottom ash and fly ash showed lower compressive strengths at the 56-day age. The compressive strengths obtained were all above 3,000 psi. This level of strength is good for most applications. Similar strength patterns are also seen for blocks and paving stones.

Long-term behaviors of these masonry products were also studied at CBU, and this data showed that concrete bricks, blocks and paving stones with reasonable strength and good durability can be made using fly ash and bottom ash.

Table 6-7: Dry-Cast Concrete Block Mixtures

Mix No.	BL-1	BL-2	BL-3	BL-4
Field Mix Designation	13	14	16	18
Fly Ash, [A/(C+A) (%)	0	30	29	40
Bottom Ash, [BA/(S+BA)] (%)	0	0	23	33
Cement, C (lb/yd^3)	345	265	245	215
Fly Ash, A (lb/yd^3)	0	110	100	150
Net Water, W (lb/yd^3)	161	160	190	260
[W/(C+A)]	0.36	0.43	0.54	0.71
SSD Fine Aggregate, S (lb/yd^3)	2300	2355	1775	1430
SSD Bottom Ash, BA (lb/yd^3)	0	0	495	715
SSD ⅜" Crushed Limestone Aggregate (lb/yd^3)	795	815	755	765
Moisture Content of Mixture, (%)	5.9	5.9	6.5	10.1
Unit Weight (lb/ft^3)	137	137	127	131
Test Batch Yield (yd^3)	0.60	0.60	0.60	0.60

Table 6-8: Dry-Cast Concrete Paving Stone Mixtures

Mix No.	PS-1	PS-2	PS-3	PS-4
Field Mix Designation	2	4	6	11
Fly Ash, [A/(C+A)] (%)	0	18	18	30
Bottom Ash, [BA/(S+BA)] (%)	0	0	24	33
Cement, C (lb/yd^3)	650	560	510	425
Fly Ash, A (lb/yd^3)	0	125	115	180
Net Water, W (lb/yd^3)	16	180	195	190
[W/(C+A)]	0.25	0.26	0.31	0.31
SSD Fine Aggregate, S (lb/yd^3)	2205	2235	1540	1255
SSD Bottom Ash, BA (lb/yd^3)	0	0	475	605
SSD ⅜" Crushed Limestone Aggregate, (lb/yd^3)	750	760	695	650
Moisture Content of Mixture, (%)	5.7	6.1	7.6	8.0
Unit Weight (lb/ft^3)	139	143	131	122
Test Batch Yield (yd^3)	0.62	0.61	0.66	0.70

Table 6-9: Compressive Strength of Dry-Cast Concrete Bricks

Mixture No.	Field Mix No.	Fly Ash %	Bottom Ash %	Compressive Strength (psi)					
				5-Day		28-Day		56-Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.
BR-1	1	0	0	3255	3660	4005	4530	4480	4750
				3830		4345		4730	
				3895		4485		4735	
				--		4525		5055	
				--		4850		--	
				--		4935		--	
BR-2	3	29	0	2740	3360	3855	4650	490	5300
				3365		4645		5025	
				3970		4659		5220	
				--		4780		5550	
				-		4880		5785	
				--		5065		--	
BR-3	8	29	23	2260	2360	2530	2740	2600	3210
				2360		2610		3285	
				2460		2705		3305	
				--		2810		3375	
				--		2880		3480	
				--		2930		--	
BR-4	10	41	33	1690	1870	2835	3130	2650	3490
				1770		3130		3570	
				2140		3175		3635	
				--		3190		3700	
				--		3225		3910	
				--		3230		--	

ASTM C90 requirement for compressive strength is 1900 psi minimum average of 3 units and 1700 psi minimum individual brick.

Table 6-10
Compressive Strength of Dry-Cast Concrete Blocks

Mixture No.	Field Mix No.	Fly Ash	Bottom Ash %	Compressive Strength (psi) based on average net area							
				7 Day		14 Day		28 Day		91 Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
BL-1	13	0	0	2605	2780	2825	3150	2850	3290	3240	3350
				2775		3290		3415		3360	
				2955		3345		3610		3460	
BL-2	14	30	0	2830	2990	2805	2880	3405	3690	4200	4240
				3055		2880		3545		4215	
				3080		2950		4115		4300	
BL-3	16	29	23	2075	2150	2875	2960	3030	3100	3130	3260
				2190		2875		3110		3225	
				2195		3125		3150		3435	
BL-4	18	40	33	1315	1410	1790	1810	2040	2220	2075	2340
				1405		1805		2220		2260	
				1520		1825		2390		2695	

ASTM C90 requirement for compressive strength is 1900 psi minimum average of 3 units and 1700 psi minimum individual brick.

Table 6-11: Compressive Strength of Dry-Cast Concrete Paving Stones

Mixture No.	Field Mix No.	Fly Ash %	Bottom Ash %	Compressive Strength (psi)									
				5-Day		8-Day		28-Day		56-Day		91-Day	
				Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.	Act.	Avg.
PS-1	2	0	0	3820	5550	7100	7610	4460	4900	5515	7040	7050	7595
				5805		7630		4855		5745		7495	
				7025		8095		4950		7515		8235	
				--		--		5020		8075		--	
				--		--		5040		8365		--	
				--		--		5085		--		--	
PS-2	4	18	0	7745	7800	7020	7410	5640	6880	7120	8020	7700	7790
				7770		7265		5645		7895		7735	
				7880		7950		6645		8075		7790	
				--		--		6655		8985		7920	
				--		--		8195		--		8385	
				--		--		8520		--		--	
PS-3	6	18	24	3250	3840	3575	3870	5005	5310	5390	5740	5420	6050
				3935		3750		5015		5660		5775	
				4065		4295		5080		5725		6030	
				--		--		5565		5935		6035	
				--		--		5865		5975		6975	
PS-4	11	30	33	2080	2270	2945	2760	2865	3190	2820	3290	3435	3690
				2440		2815		3080		3245		3545	
				2295		2520		3155		3285		3675	
				--		--		3215		3350		3875	
				--		--		3385		3765		3925	
				--		--		3445		--		--	

We Energies Bottom Ash as Fine Aggregate in "Eco-Pad" (In-Situ Mixed Concrete Pavement) (67)

The scope of this research was to identify the mixture proportions and develop a high recycled content in-situ mixed concrete for a 3.5 acre outdoor storage pad for bottom ash and synthetic gypsum produced at We Energies' Pleasant Prairie Power Plant (PPPP) as shown in Figure 6-12. The storage pad was constructed in the fall of 2004 at PPPP, located in Kenosha County, Wisconsin. Development of the "eco-pad" allowed the usage of an alternative paving material and also development of an economic and environmentally friendly construction process.

The "eco-pad" is a concrete mixture that includes recycled concrete for coarse aggregate, bottom ash for fine aggregate, cementitious materials (Class C fly ash and either Portland cement or slag cement yielding a 93% or 100% recycled content, respectively) and water for obtaining the optimum moisture density of materials. The class C fly ash and bottom ash used in this project were produced at We Energies PPPP and is a by-product of Powder River Basin, Wyoming sub-bituminous coal combustion. The 1½-inch topsize recycled concrete was supplied from a crushed and screened stockpile managed by an asphaltic concrete producer in Racine County, Wisconsin. The Portland (Type I/II) cement was used in conjunction with Class C fly ash on the western half of the site and slag cement in conjunction with Class C fly ash was used on the eastern half. During construction in the late Fall season, the temperature was progressively getting colder and a shortage of Portland cement led to substituting with slag cement. The chemical composition of the cementitious material is

Figure 6-12: Eco-Pad construction at Pleasant Prairie power plant.

shown in Tables 6-12. The end result was an 8-inch thick concrete pavement on a 12-inch bottom ash base.

Table 6-12: Chemical Composition of the Cementitious Materials Used in the "Eco-pad" Pavement

Compounds (%)	Class C Fly Ash	Portland Cement (Type I/II)	Slag Cement
SiO_2	40.3	20.7	35.7
Al_2O_3	18.9	4.8	10.0
Fe_2O_3	5.2	2.7	0.6
$SiO_2 + Al_2O_3 + Fe_2O_3$	64.5	28.2	46.3
CaO	21.6	65.4	38.6
MgO	3.8	2.5	11.2
SO_3	1.9	2.4	2.4
LOI	0.4	1.6	--
Na_2O	1.8	--	0.4
K_2O	1.2	--	0.4
Available Alkalis (as equivalent Na_2O%)	1.3	0.5	--

Laboratory Testing

Prior to the placement of the in-situ mixed concrete pavement on the field site, a laboratory mix analysis was performed to determine the mixture proportions. The cementitious material (Class C fly ash and Portland cement mixture) and aggregate materials (recycled concrete and bottom ash) were evaluated for moisture content using ASTM D-2216, grainsize analysis (ASTM D-422), moisture density relationship by Modified Proctor method (ATM D-1557, except that the 5 lift requirement was replaced with 3 lifts), and to simulate the conditions of roller compacted concrete, the compressive strength analysis used was per ASTM D-1633 (Compressive Strength of Molded Soil-Cement Cylinders) and a 4-inch diameter split mold was used to facilitate the removal of each specimen with minimal disturbance to the samples. Upon completion, the specimens were sealed in plastic bags and curing was accelerated for seven days at 100ºF (per ASTM C-593) to approximate conditions of a 28-day cure period. After curing the samples were capped with a gypsum cap and the compressive strength was determined using a constant drive calibrated load frame. The tested specimen had a height to diameter ratio of 1.5:1 rather than the conventional ratio of 2:1 for a relative measure of the compressive strength.

The preliminary mixture proportion testing was performed in two phases. Initially, samples of the proposed recycled concrete (coarse aggregate) and the bottom ash (fine aggregate) were tested to determine their optimum blend for grainsize distribution and density. The second phase consisted of mixing the selected aggregate blend with varying amounts of the blended cementitious binder material for determination of the mixture's optimum density and strength characteristics.

Laboratory Results

The grainsize analysis of the proposed recycled aggregate indicated that the coarse aggregate is described as a poorly to well-graded crushed concrete with about 48-67% gravel, 31-45% sand, and 2.6-6.6% silt/clay sized particles. The fine aggregate is described as a bottom ash with about 4-6% gravel, 77-85% sand, and 13-17% silt/clay sized particles. The dry loose unit weight of the coarse and fine aggregates resulted in 99 pcf to 105 pcf and 65 pcf, respectively. The grainsize analysis test results are shown in Table 6-13.

Generally, the results of the coarse/fine aggregate blends 50/50, 60/40, 70/30, and 80/20 indicated a poorly graded aggregate with about 35-54% gravel, 41-57% sand, and 5-8% silt/clay sized particles. As shown in Table 6-13, the compacted unit weights of the blends ranged from 102.8 pcf to 109.1 pcf with the 60/40 and 70/30 blends producing the higher densities. Based on the blended aggregate testing the 60/40 blend was selected for moisture density and moisture strength relationship testing with 12%, 15% and 18% (50% Portland cement/50% Class C Fly Ash) cementitious content. A blend of 50% Portland cement and 50% Class C fly ash (denoted as 50PC/50FA), by mass, was selected due to excellent experience on numerous construction projects and to reduce the number of variables on this project. The test results shown in Table 6-14 indicate that using an 18% 50PC/50FA cementitious content with a 60/40 aggregate material had the highest compressive strength. However, since the difference between 15% and the 18% mixtures was less than 5 psi, the 15% 50PC/50FA cementitious content of 60/40 aggregate material was selected for economic and environmental benefits.

Additional testing was performed with varying aggregate blends when a second sample of recycled concrete showed a denser gradation. The aggregate blends of 50/50, 60/40 and 70/30 recycled concrete/bottom ash were mixed with a constant 15% content of 50PC/50FA to determine their moisture-density and moisture-strength relationship, as shown in Table 6-14. The 70/30 aggregate blend with 15% blended cementitious content produced the higher strength and density. This was due to the material's denser graded nature which allowed for a more compact arrangement of particles yielding a higher density and potentially higher strength.

Table 6-13: Summary of Aggregate Trial Blending Tests

Grainsize Analysis, mm [in or sieve#]	Fine Aggregate		Coarse Aggregate			Aggregate[1] Trial Blending Tests				Aggregate[2] Trial Blending Tests		
	BA[1]	BA[2]	RC[1]	RC[2]	RC (field)	50/50	60/40	70/30	80/20	50/50	60/40	70/30
38.1 [1½]	–	–	100	–	–	100	100	100	100	–	–	–
25.4 [1]	–	–	95.7	100	100	97.6	97.4	97.0	96.6	100	100	100
19.05 [¾]	100	100	85.0	94.2	94.2	92.5	91.0	89.5	88.0	96.7	96.0	95.4
12.7 [½]	99.0	98.5	65.2	79.1	79.1	82.1	78.7	75.3	72.0	87.0	84.7	82.4
9.5 [⅜]	98.1	96.7	54.6	69.4	69.4	76.4	72.0	67.7	63.3	81.4	78.3	75.3
4.76 [#4]	95.6	94.0	33.5	51.8	51.8	64.6	58.3	52.1	45.9	71.2	66.6	62.1
2.0 [#10]	92.3	91.2	20.3	35.8	35.8	56.3	49.1	41.9	74.7	64.2	58.7	53.3
0.84[#20]	83.5	83.8	12.1	24.2	24.2	47.8	40.7	33.5	26.4	55.9	50.3	44.7
0.42 [#40]	67.0	70.1	7.5	17.1	17.1	37.3	31.3	25.4	19.4	45.4	40.4	35.3
0.147 [#100]	26.7	36.1	3.5	8.7	8.7	15.1	12.8	10.5	8.1	22.8	20.1	17.4
0.074 [#200]	12.6	16.7	2.6	6.6	6.6	7.6	6.6	5.6	4.6	11.7	10.6	9.6
Unit Weight (Loose), kg/m³ [pcf]	1041.3 [65]	1041.3 [65]	1586.0 [99]	1682.1 [105]	–	–	–	–	–	–	–	–
Unit Weight (Compacted), kg/m³ [pcf]	–	–	–	–	–	1646.9 [102.8]	1744.6 [108.9]	1747.8 [109.1]	1733.4 [108.2]	–	–	–

[1] First set of Bottom Ash and Recycled Concrete samples

[2] Second set of Bottom Ash and Recycled Concrete samples

Table 6-14: Summary of Moisture Density/Strength Tests of RC/BA Aggregate Blend with Percent Cement Content

	Mixture ID	Moisture – Density Relationship		Moisture – Strength Relationship	
		Optimum Moisture %	Maximum Dry Density, kg/m^3 [pcf]	Optimum Moisture %	Maximum Strength, MPa [psi]
First set of RC/BA concrete samples	60/40 RC/BA @ 12% 50PC/50FA	15.5	1762.2 [110.0]	16.6	11.3 [1640]
	60/40 RC/BA @ 15% 50PC/50FA	16.5	1762.2 [110.0]	16.6	12.5 [1820]
	60/40 RC/BA @ 18% 50PC/50FA	14.5	1778.2 [111.0]	14.2	12.6 [1825]
Second set of RC/BA concrete samples	50/50 RC/BA @ 15% 50PC/50FA	13.5	1770.0 [110.5]	12.6	10.1 [1460]
	60/40 RC/BA @ 15% 50PC/50FA	12.5	1842.0 [115.0]	12.4	13.0 [1880]
	70/30 RC/BA @ 15% 50PC/50FA	10.5	1922 [120.0]	11.2	13.2 [1920]

Eco-Pad Construction Overview

A 12-inch thick compacted bottom ash base grade was established for the Eco-pad pavement of which 3-inches will later be incorporated into the concrete by in-situ mixing and 9-inches remains as the base. The in-situ mixing phase consisted of placing 5-inches of crushed recycled concrete across the proposed pavement area with dump trucks and using a road grader to create a uniform layer. The recycled concrete and bottom ash were then pre-mixed with a Wirtgen WR2500 asphalt reclaimer/ pulverizer set an 8 inch depth.

Lafarge pre-blended 50% Portland cement and 50% Class C fly ash was supplied from their bulk terminal in Milwaukee, Wisconsin. The 50PC/50FA blend of cementitious material was delivered to the jobsite via bulk pneumatic tanker trucks. The cementitious material was pneumatically conveyed to the vane spreader. The dry cementitious materials were placed with a vane spreader over the previously mixed aggregates. The 50PC/50FA blend was spread at a rate of 110 pounds per square yard. This rate was based on a 15% dry unit weight basis of the maximum dry density of the laboratory blended mixture.

Moisture conditioning was not required on this project due to relatively wet site conditions due to a rainy period prior to mixing. After mixing from the second pass of the pulverizer, the aggregate and cementitious materials mixture was compacted with a large vibratory sheepsfoot compactor, graded, and final rolling was accomplished with a smooth drum roller in the static mode. A target mixture moisture content of 10.5% for optimum strength was recommended along with directions to minimize the delay period from mixing of the cementitious materials to compaction. Compaction of the in-situ mixture was specified at 95% of the maximum dry density as determined by the Modified Proctor method. Saw cuts on a 20 foot grid followed the next day. A curing compound was applied following installation of the saw cuts and finally the elastomeric joint filler was applied to seal the saw cut joints.

Weather conditions during the in-situ mixing were challenging during construction. Due to a regional cement shortage, construction was delayed into late October and early November when temperatures were cold in Wisconsin. This was complicated by a rainy period that made obtaining optimum moisture content for compaction a challenge at the beginning of the project. A bottle neck in construction operation was the rate at which the cementitious material could be blended at the terminal and delivered to the project. An operating issue at the cement terminal also threatened to delay the project because cement could not be unloaded. However, ground granulated slag cement was available at the terminal and was substituted for Portland cement, thus adding another interesting dimension to this project. A call to the Slag Cement Association indicated that they were not aware of a prior use of a 50/50 fly ash/slag cement blend without Portland cement on a large construction project. The slag cement and Class C fly ash binder pavement combined with the recycled aggregates provided a 100% recycled material content in approximately two thirds of the pavement area.

Field Testing

The construction of the Eco-Pad test pavement was performed in three stages. The initial stage consisted of performing a grainsize analysis on samples of the field blended aggregates. A laboratory mixture analysis of the field aggregate blend with 15% of the blended cementitious material was also performed to establish laboratory moisture-density and moisture-strength relationships.

The second stage of the testing was performed during the field mixing of the blended aggregate and cementitious materials. Using the nuclear gauge method (ASTM D-2922), a field density test was performed during the compaction phase to assess the in-situ moisture content and percent compaction. Additionally, samples of the in-situ mixed concrete were obtained and compacted in the field by the Modified Proctor method. The field molded specimens were delivered to the laboratory and cured for a period of 7 to 365 days to assess the compressive strength development of the mixture.

The final phase of the testing included obtaining in-situ core specimens after approximately one and two years to assess the in-place strength of the pavement. The cores were obtained with a rotary type drill with a diamond impregnated core barrel in general accordance with ASTM D-42. Samples were subsequently air dried for 7 days, capped with a gypsum capping compound and compressive strengths were determined in accordance with ASTM C-39.

Field Test Results

Evaluation of the in-situ recycled concrete mixture constructed in the Eco-Pad pavement was based on the 5-inch thick recycled concrete and a 3-inch thick bottom ash aggregate blend and 15% blended cementitious materials (50PC/50FA) at the western side of the Eco-pad or 15% blended 50% slag cement and 50% fly ash, denoted as 50SC/50FA, at the eastern side of the Eco-Pad.

The grainsize analysis of the individual bottom ash and recycled concrete samples used on-site indicated gradations similar to the results obtained in the laboratory testing phase and this also held true for the field blended aggregate samples. The 5-inch recycled concrete and 3-inch thick bottom ash volumetric field blend has shown similarity to the 70/30 blend, by mass, prepared for the laboratory mixture analysis.

Results of the moisture density relationship testing indicated a higher maximum dry density at about the same optimum moisture content as in the preliminary laboratory mix proportioning phase. This is likely due to a well-graded sample resulting in a more densely compacted mixture. The higher result in the compressive strength may also be due to the higher density characteristics and lower optimum moisture contents. Subsequently, two additional samples of the previously sampled and combined field blended aggregate were mixed in the lab, one with 15% PC/FA and the other with 15% SC/FA cementitious blend to further assess the moisture-density and moisture-strength relationships. Results of the tests on the PC/FA blend showed similar results to those of the PC/FA blend of the first aggregate field blend mixture. Results of the SC/FA cementitious blend also provided results that were similar to those of the first aggregate field blend mixture. Results of the SC/FA cementitious blend resulted with similar moisture density relationships but with lower strengths, 1600 psi vs. 2225 psi and 2700 psi. This is likely due to the fact that the slag cement contained less CaO and also generally develops its strength at a slower rate than Portland cement. Results are shown in Table 6-15.

The second phase of the field testing included performing field moisture and density testing during the placement and compaction phase of the construction. In summary, the field blended aggregate had moisture contents initially of 14 to 19 percent, which was above the recommended optimum target of 10.5 percent. However, during the mixing process the moisture contents were generally found to range from 10 to 16 percent based on the in-place field density testing. The field density testing also indicated an in-place compaction ranging from 92 to 99 percent with an average compaction of 96.5 percent of the Modified Proctor density.

Table 6-15: Laboratory Summary of Moisture Density/Strength Tests on Field Blended Aggregate Samples

Mixture ID	**Moisture – Density Relationship**		**Moisture – Strength Relationship**	
	Optimum Moisture %	Maximum Dry Density, kg/m^3 [pcf]	Optimum Moisture %	Maximum Strength, MPa [psi]
Field Sample 1 @ 15% 50PC/50FA	10.5	1986.5 [124.0]	10.3	18.6 [2700]
Field Sample 2 @ 15% 50PC/50FA	10.0	1986.5 [124.0]	10.6	15.3 [2225]
Field Sample 2 @ 15% 50SC/50FA	11.0	1954.4 [122.0]	10.3	13.2 [1600]

Results of the field molded compressive strength specimens are summarized in Table 6-16. In summary, the field molded samples of the PC/FA cementitious blend indicated compressive strengths (2440 psi at 28 days and 2525 psi at 56 days) are similar to those of the laboratory mixtures with the field blend aggregates (2225 psi and 2700 psi) and somewhat higher than the mixtures with the laboratory blended aggregates (1880 psi and 1920 psi). The field molded samples with the SC/FA cementitious blend indicated compressive strengths on the order of 195 psi and 175 psi at 28 days which turned out to be much less than the laboratory mixture which yielded a strength of 1600 psi using the accelerated core method. This is probably due to the much lower curing temperatures of the field samples and the fact that slag cement generally develops strength at a slower rate at lower temperatures. The 365- day test results indicated compressive strengths on the order of 4325 psi and 2565 psi for the PC/FA and SC/FA mixtures, respectively.

The final phase of the field testing included obtaining field core samples from the eco-pad pavement section after one and two years of field curing. Results of the core strength tests indicated an average compressive strength of 3150 psi and 1852 psi after one year and 2960 psi and 2266 psi after two years for the PC/FA and SC/FA mixtures. In comparing these results to the molded field samples, it must be recognized that the molded specimens have a height to diameter ratio of 2. Therefore, the molded samples will yield a somewhat higher strength value. Correcting the shorter molded samples with a correction factor of 0.91 as suggested in ASTM C-42, the molded samples would indicate strengths of 3930 psi and 2334 psi, respectively. The test results for the field molded and cored samples are summarized in Table 6-16.

Table 6-16: Summary of Field Molded and Core Specimens Compressive Strength Test Results

Sample No.	**FS – 1**	**FS – 2**	**FS – 3**
Sample Date	11-04-04	11-05-04	11-08-04
Cementitious Blend	PC/FA	SC/FA	SC/FA
Moisture Content, (%)	13.6	14.9	13.1
Dry Density, kg/m^3 [pcf]	1941 – 1956 [121.2 – 122.1]	1919 – 1948 [119.8 – 121.6]	1933– 1954 [120.7 – 122.0]
Compaction, (%)	99 – 100	96 – 98	97 – 98
Compressive Strength, MPa [psi]			
7-day (air)	11.1 [1620]	1.3 [185]	1.0 [145]
28-day (air)	16.8 [2440]	1.3 [195]	1.2 [175]
56-day (air)	17.4 [2525]	1.8 [265]	1.7 [240]
180-day (air)	22.6 [3280]	6.8 [985]	6.2 [900]
365-day (air)	29.9 [4325]	18.4 [2675]	16.9 [2455]
365-day (corrected)[1]	27.1 [3930]	16.8 [2435]	15.4 [2235]
Field Core specimens			
1-year (air)	21.7 [3150]	13.6 [1970]	12.0 [1735]
2-year (air)	20.4 [2960]	13.7 [1983]	17.6 [2550]

[1] The molded field samples have a height to diameter ratio of 1.5:1 compared to the length to diameter ratio of 2:1 for the field core samples. The 1.5:1 H/D samples result in higher strength than would be achieved with the 2:1 H/D core samples. A correction factor of 0.91 was therefore applied to obtain a corrected strength value on the molded 365-day sample for comparison purposes.

Summary

Based on the data recorded in this project, the following general conclusion is drawn:

(1) When 70% crushed recycled concrete and 30% bottom ash are blended and mixed with a 15% blended (50PC/50FA) cementitious material by mass, in-situ mixed with an asphalt reclaimer/pulverizer, moisture conditioned and compacted, a compressive strength on the order of 3100 psi in one year was attainable.

(2) When the aggregate blend is mixed using slag cement in lieu of Portland cement in the cementitious material blend, a compressive strength on the order of 1700 to 2000 psi in one year and 2000 to 2500 psi in 2 years was

attainable.

(3) After 2 years of service, the concrete is not showing any significant distress due to freezing and thawing, except for some scaling near the storm water outlet that had excessive moisture contents during construction. There are no indications of structural failure despite high compressive loads from trucks, loaders and cranes that have used the pad. Typically, the Eco-Pad was covered with at least 2 feet of stockpiled bottom ash over the winter months, thus providing some freeze thaw protection. Saw cutting may not be necessary if random cracking can be tolerated.

(4) Future research and demonstration should explore in-situ mixed concrete using recycled concrete, bottom ash, Class C fly ash, and both Portland cement or slag cement to develop strength at a faster rate.

“Eco-pad” at Menomonee Falls Service Center

A second “eco-pad” pavement was constructed in the Fall of 2011 at Menomonee Falls Service Center (MFSC), located in Menomonee Falls, Wisconsin. The pavement was developed on an area of approximately 100 ft. by 165 ft. and was mixed in-situ with over a 90 percent recycled material content consisting of recycled concrete, bottom ash and cementitious Class C fly ash combined with Portland cement. The purpose of the MFSC “eco-pad” pavement was for support of heavy construction equipment (cable spools and transformers) and long term durability. Other locations at the MFSC have concrete slabs to serve the same purpose but were not as cost effective or environmentally friendly as an “eco-pad”.

A 9-inch thick uniform compacted bottom ash base grade was established for the “eco-pad” pavement of which 3 inches was later incorporated into the concrete by in-situ mixing and 6 inches remained as the base. A perimeter soil berm with a height of 6 inches and width of 12 inches was graded around the pavement area to contain cementitious powders placed with a vane spreader during the in-situ mixing operations. The in-situ mixing phase consisted of placing 5 inches of crushed recycled concrete across the proposed pavement area with dump trucks and using a road grader to create a uniform layer. The recycled concrete and bottom ash was pre-mixed to a depth of 8 inches with an asphalt reclaimer by making one pass over the pavement area.

The cementitious materials were pre-blended by Lafarge in a 50/50 blend of Portland cement and Class C fly ash and placed dry at a rate of 134 lbs/yd^2 with a vane feeder truck over the previously mixed aggregate blend. Then with a second pass, the pavement area was re-mixed with a pavement recycler. After mixing, the aggregate and cementitious materials mixture was compacted with a large vibratory sheepsfoot compactor (minimum of 3 passes), graded, and final rolling was accomplished with a smooth drum roller in the static mode. A target mixture moisture content of 9 to 13% (± 2%) for optimum strength (3000 psi) was required. The compaction of the in-situ mixture was specified at 95 percent of the maximum dry density as determined by the modified Proctor method. Following the final rolling, compaction, and sealing; the next day, control joints were sawed into the pavement at 20 foot grids. An additional application of sealer was applied to control joints following saw cutting and surface washing. Finally, the pavement surface was undisturbed for a minimum of 7 days, where no vehicle or equipment traffic was allowed on the surface during that period.

Field Testing and Results

As mentioned in the first "eco-pad" pavement section, there is a three-stage analysis. The initial stage consisted of performing a grainsize analysis on samples of the field blended aggregates. A laboratory mixture analysis of the 34/66 blend of bottom ash and crushed recycled concrete treated with 20% of the blended cementitious material was also performed to establish laboratory moisture-density and moisture-strength relationship. The test results are shown in Table 6-17. Results of the moisture density relationship testing indicated a higher maximum dry density (130 lb/ft^3) than expected (110 lb/ft^3) with a lower optimum moisture content (9%).

Table 6-17: The Laboratory Results of the BA/RC (34/66) Blend With 20% Cementitious Material

Testing Description	Results
Maximum Dry Density (lbs/ft^3)	130.0
Optimum Moisture Content	9.0%
Specific Gravity	2.7
Grain Size Distribution	
Sieve	**Percent**
> ¾"	10
> $^3/_8$"	28
> #4	45
< #200	7.7

The second stage of the testing was performed during the field mixing of the blended aggregate and cementitious materials. Using the nuclear gauge method, a field density test was performed during the compaction phase to assess the in-situ moisture content and percent compaction. Additionally, samples of the in-situ mixed concrete were obtained (sample size of 4 inch x 4.6 inch) and compacted in the field by the Modified Proctor method. The field molded specimens were delivered to the laboratory and cured for a period of 7 to 56 days to assess the compressive strength development of the mixture complying with the compaction method, ASTM D-1557. The results are shown in Table 6-18. In summary, by 7-days, the mixture in the cylinders had reached above the optimum strength and both the 28-day and 56-day compressive strengths were over 4,000 psi with the low water-to-cementitious ratio.

The final phase of the testing is to obtain in-situ core specimens which will be taken during Spring of 2012 (after one year of field curing) for testing of compressive strength.

Table 6-18: MFSC Eco-Pad Compressive Strength Data

Test Age (Days)	Average Moisture Content (%)	Average Dry Density (pcf)	Average Compressive Strength (psi)
7	7.3	127.1	3662
28	6.0	126.7	4449
56	5.8	127.6	4919

Figure 6-13: Eco-pad at Menomonee Falls Service Center

A) Bottom ash placed and compacted for a strong paving base.

B) After placing, bottom ash is mixed with recycled concrete and pre-mixed Class C fly ash + Portland cement and the full mix is compacted.

C) Water is added during mixing to the Eco-Pad mix and the paving hardens just like a conventional concrete pad.

Chapter 7

Natural Mined Gypsum and Commercial Applications of We Energies FGD Gypsum

Introduction

Natural Gypsum (68)
During the Paleozoic Era, 600 million years ago when salt water oceans covered most of the earth, gypsum deposits were formed. Gypsum is a non-metallic mineral, found in rock form and among the most plentiful minerals in the world. It is composed of 79.1% calcium sulfate and 20.9% water, by weight. It has the chemical formula $CaSO_4 \cdot 2H_2O$. In its absolute pure form, gypsum is white. However, gypsum normally contains impurities (such as clay and other minerals and in some cases soluble salts) whose presence makes the rock appear gray, brown, pink, or sometimes almost black.

Gypsum has been known and used from the earliest times. The ancient Assyrians called this rock, Alabaster, and it was used for sculpturing. Five thousand years ago, the Egyptians had learned to make plaster from gypsum and they used it to line the walls of palaces and tombs. It can also be found inside the great Pyramids, still standing unchanged after fifty centuries. The ancient Greeks named this mineral, “Gypsos”, and now it is known in English, as “Gypsum”. They described Gypsos as a material that does not burn. In later years, this unique property of gypsum made it very valuable. In the late 1700s, a French chemist Lavoisier analyzed the chemistry of gypsum. He and the other chemists then ground up gypsum into powder and heated it (calcined) until most of its water content was evaporated. When water was added to the resulting white powder, it formed a pliable, plastic mass known as Plaster of Paris. With such development, the material allowed molding to any desired shape, after which it would harden and retain that shape. Gypsum is the only natural substance that can be restored to its original rock-like state by the addition of water alone.

Based on the fact that gypsum can be calcined when exposed to heat treatment at low temperatures, there were vast increases in utilization of natural gypsum. Some of the modern applications include use as a setting time regulator for Portland cement, as fertilizer, and for soil amelioration. Benjamin Franklin was one of the first individuals to introduce it in the United States, when he used ground raw gypsum on his farm soils and called it land plaster. The largest volume use of gypsum today goes into wallboard manufacturing. In 1894, Augustine Sackett invented the principle of a panel "sandwich" made up of a gypsum core with sheets of cardboard stuck to each side. These gypsum "boards" were formed by sandwiching a core of wet plaster between two sheets of heavy paper. When the core sets and dries out, the sandwich becomes a strong, rigid, fireproof building material to be used as wallboards in construction.

Using natural mined gypsum in the applications identified above involves multiple processing and handling steps. The first stage consists of the preparation of the raw gypsum (rock form) which covers such steps as mining, transporting, and storage, drying, crushing, and grinding. The second stage involves the calcination of this material using a variety of equipment, such as kilns. Before moving to the second stage the natural gypsum needs to meet the requirements of the calcination unit, which includes control of the moisture content and particle size distribution. Usually, the gypsum rock consists of relatively large pieces containing up to 4% free moisture content.

We Energies FGD Gypsum

We Energies began operating a state-of-the-art air quality control system at Pleasant Prairie Power Plant (PPPP) in 2006, at Oak Creek Expansion Generating Units (OCXP) in 2010 and at the Oak Creek Power Plant (OCPP) in 2012. One of the systems, the flue gas desulfurization (FGD) system uses limestone and water in a slurry to wet scrub over 95 percent of the sulfur out of the plant's combustion gases. The chemical reaction between the limestone slurry and sulfur in the flue gas with the addition of oxygen produces calcium sulfate, also known as FGD gypsum, as a by-product.

As mentioned in chapter 3, FGD gypsum is similar to natural mined gypsum in overall composition, and hence can be used in many of the same manufactured products as mined gypsum. However, there are differences between the two which can either restrict or enhance the use of FGD gypsum in place of mined gypsum. For example, FGD gypsum has a higher moisture content which combined with fine grain size can affect handling and processing at existing manufacturing facilities designed for mined rock gypsum. On the other hand, FGD gypsum requires less grinding than rock gypsum due to its finer grain size. Most new plants for producing wallboard are designed to accommodate FGD gypsum, either solely or in combination with natural gypsum. Chlorides, ash, iron and manganese compounds in FGD gypsum can cause issues such as surface crystallization that can affect paper adherence and color variation that makes it undesirable for some products and applications (69).

In 2007, We Energies began marketing FGD gypsum, produced at PPPP, to produce wallboard building materials for construction use. Soon after, local farmers were interested in applying FGD gypsum to their fields to improve their soils, minimize surface water runoff, and increase crop production. After receiving approval from the Wisconsin Department of Natural Resources and a license from the Wisconsin Department of Agriculture in 2008, We Energies began actively marketing the FGD gypsum for agricultural use as a soil amendment to increase field productivity. Gypsum became a local source for amending soils for southeast Wisconsin famers and a lower-cost alternative when compared to out-of-state sources of mined gypsum. Figure 7-1 shows the growth in agricultural use at We Energies since 2008 and Table 7-1 shows a break-down of We Energies FGD gypsum utilization compared to national utilization.

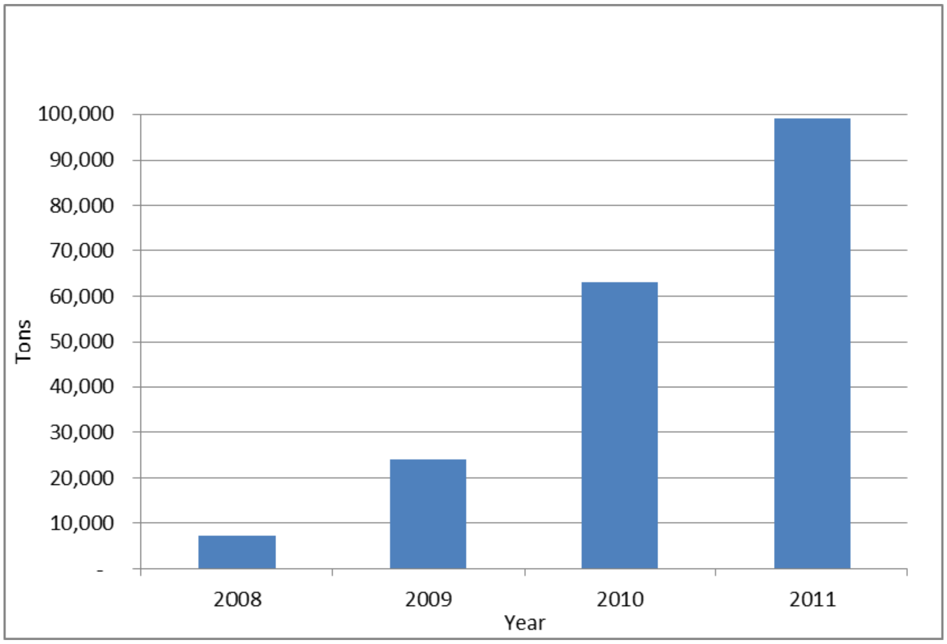


Figure: 7-1: We Energies FGD gypsum utilization growth in agriculture.

Table 7-1: FGD Gypsum Utilization

	ACAA National (2010)	We Energies (2011)	We Energies (2012)
Produced	22,000,000 tons	311,000 tons	Est. 300,000 tons
Concrete products	21,045 tons (0.2%)	--	TBD
Blended Cement	1,135,211 tons (10.6%)	--	TBD
Structural Fills/ Embankements	454,430 tons (4.2%)	--	TBD
Mining	835,536 tons (7.8%)	--	TBD
Wallboard	7,661,527 tons (71.5%)	154,000 tons	TBD
Agriculture	481,827 tons (4.5%)	99,000 tons	TBD
Miscellaneous/Other	123,562 tons (1.2%)	60,000 tons (incl. 2010 stockpile)	TBD

Note: ACAA National utilization is 10,713,138 tons (2010)

FGD Gypsum Use in Wallboard Manufacturing

While wallboard has traditionally been manufactured with mined gypsum, the use of FGD gypsum has become increasingly popular due to economic, environmental and the proximity of wallboard manufacture to power plant sources. For states like Wisconsin and Illinois, which do not have gypsum mines, FGD gypsum provides an attractive local alternative to importing mined gypsum from other states such as Iowa or Michigan.

On June 21, 2010, the EPA proposed national rules to ensure the safe disposal and management of coal combustion residuals from coal-fired power plants. The proposed rules primarily address disposal but also mention good utilization practices such as gypsum use in wallboard manufacturing. According to the EPA, making wallboard with FGD gypsum is safe and environmentally friendly. Notably, the EPA's own award-winning building in Arlington, Virginia is made using wallboard containing FGD gypsum[1].

The production of FGD gypsum is a controlled, engineered process designed for quality and consistency. By complying with the environmental regulations, the installation of wet scrubbers on coal-fired power plants reduces sulfur dioxide air emissions, and has resulted in an increase in production of FGD gypsum materials. Prior to using mined FGD gypsum in

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[1] http://www.epa.gov/epawaste/conserve/rrr/imr/pdfs/recy-bldg.pdf

wallboard manufacturing, the gypsum is calcined. This refers to the removal of one and a half waters of hydration, resulting in calcium sulfate hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$). When water is mixed with the powdered hemihydrate, it rehydrates, recrystallizes, and hardens. There are two board types of hemihydrates (beta and alpha), which depend on the calcination process used. Beta hemihydrate is formed by heating the gypsum under atmospheric pressure conditions; and alpha hemihydrate is formed by heating the gypsum under induced pressure. Beta hemihydrate is commonly referred to as “Plaster of Paris” or “stucco”, which is commonly used in standard wallboard. Alpha hemihydrate is referred to as gypsum cement, which is more expensive to produce and is utilized in flooring and high strength materials. After calcining, slurry of beta hemihydrate, foam and other additives are blended in a mixer. Set retarders may be added to the mixer to prevent premature hardening of the plaster. The slurry is then placed between two continuously moving sheets, one above and one below, and allowed to harden, forming the board. Once the material hardens, gypsum crystals form and bond to the cardboard. After hardening, the still-wet boards are sent to a dryer, where additional moisture is removed, for about 45 minutes. After drying, the boards are cut to lengths typically ranging from 8 to 14 feet. Table 7-2 shows the general specifications for FGD gypsum used in wallboard which may vary by manufacturer and the product being produced (69) and Figures 7-2a and 7-2b show a typical FGD gypsum wallboard process.

Table 7-2: General Specification for FGD Gypsum Utilization in Wallboard

Property	Specifications
Purity of $CaSO_4 \cdot 2H_2O$ (min.)	92% - 97%
Fly Ash (max.)	1.0%
SiO_2 (max.)	1.0%
$CaSO_3$ (max.)	0.5% - 1.0%
Free Moisture (max.)	9% - 15%
Particle Size (average)	9 -70 µm
Chloride (max.)	100 – 400 ppm
Sodium (max.)	25 – 250 ppm
Total Water Soluble Salts (max.)	325 – 500 ppm
Blaine Surface Area (max.)	3000 – 3500 cm^2/g
pH	6 – 8

The following general guidelines are followed with respect to FGD gypsum characteristics to meet product specifications (70):

a. **Gypsum Purity**
High purity in FGD gypsum (> 95% calcium sulfate) is desired by the manufacturer because lower weight board can be produced.

Also, higher purity reduces the potential for deleterious effects on the wallboard. In 2010, We Energies FGD gypsum had a combined average of 97.5% purity from its two power plant sources (PPPP and OCXP).

Purity can be determined by several test methods including Differential Scanning Calorimetry/Thermal Gravimetry (DSC/TGA), X-Ray Fluorescence Spectroscopy (XRF) and SO_3 analysis.

b. **Free Moisture**

The free moisture in FGD gypsum supplied by We Energies is approximately 8% compared to mined gypsum with 0% to 3% moisture. Sometimes wallboard manufacturers will blend FGD gypsum with mined gypsum depending on the thermal drying capacity of the system. The high moisture gypsum has the tendency to stick and build up on the conveying equipment. Hence, the high moisture reduces the usage of FGD gypsum and also its value.

Free moisture of mined and FGD gypsum materials are determined using a simple oven weight loss method per ASTM C-471.

c. **Impurities**

The type and quantity of impurities can have an impact on qualifying the FGD gypsum for uses and include:

I. *Residual carbonates:* Unreacted limestone ($Ca/MgCO_3$) is the predominant impurity found in many FGD gypsum sources. Since limestone remains chemically inert during the board conversion process, there is no interference. However, increased wear on processing equipment results from encountering higher amounts of hard limestone (Mohs value 3 - 4) compared to gypsum (Mohs value 1.6 – 2).

   Limestone quantity can be determined through XRF oxide analysis of calcium and magnesium in conjunction with CO_2 analysis by coulometric titrimetry. Alternatively, CO_2 can be quantified through Differential Scanning Calorimetry (DSC) scans.

II. *Fly ash:* The concern arises in the chemical variability associated with the burning of different coal sources. It can affect the paper to core bonding and cause increased wear on process equipment as it contains silica and iron. Another concern with fly ash are certain trace elements in raising question from some sources on industrial hygiene issues.

Fly ash can be detected using a scanning electron microscope (SEM). By using image analysis, an estimate of the amount of fly ash present can be established. Fly ash can also be calculated by determining the mass balance around the scrubber and dust collection system.

III. *Silica (SiO_2):* Silicon dioxide is an impurity found in clay, fly ash, or quartz which can raise a concern from an industrial hygiene perspective. It becomes an issue when high quantities of respirable silica of 0 to 4 microns are present. Additionally, low amounts (1-2%) of crystalline silica/quartz with Mohs value of 7 can cause wear on gypsum processing equipment.

Silica can be quantified using XRF. X-ray diffraction (XRD) is used to identify whether the SiO_2 present is amorphous or crystalline in nature. In addition, ASTM C-471 describes a wet chemistry method to determine SiO_2 and insoluble matter.

IV. *Calcium Sulfite ($CaSO_3 \cdot ½H_2O$):* This is an unwanted impurity in FGD gypsum as it can cause cake washing and dewatering problems. Usually materials rich in calcium sulfite are landfilled.

Thermal analysis and XRF will detect sulfite above 0.1%. Titration procedures are also considered in determining sulfite.

V. *Soluble Salts:* Soluble salt impurities affect the physical properties of gypsum wallboard. Salts go into solution when calcined gypsum is mixed with water and other additives in the board mixer. During the drying process in the kiln, the salts migrate to the paper and core interface, which interrupts the paper and core bond. Since salts are very hydroscopic and cause moisture to deposit in the critical bond area of the board, the salts can cause detachment between the board paper and the core. The four soluble salt ions typically monitored are magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+) and chloride (Cl^-).

Soluble salt analysis for FGD gypsum sample is determined on mathematical reconstruction based on the theoretical solubility of the ions.

VI. *Trace Elements:* Due to industrial hygiene concerns, the trace elements and the pH of the FGD gypsum are evaluated. Trace elements are unwanted impurities that are found in limestone minerals, fly ash, and can also increase process equipment wear. We Energies FGD gypsum pH ranged from 7.6 to 8.2 in 2010.

Studies have been performed (71) to determine whether trace quantities of mercury were being released into the atmosphere as part of gypsum used as a feedstock for wallboard production. Another question was to evaluate the potential for leaching in groundwater when wallboard is disposed in municipal landfills. As per the Ontario Hydro method, the measured mercury loss mass rates from the FGD gypsum feedstock ranged from 0.01 to 0.2 pounds of mercury per million square feet of wallboard produced. On the other hand, according to TCLP methodology, the wallboard did not produce measurable mercury concentrations as a leachate (<0.25µg/L). The TCLP maximum concentration allowed for mercury is 200µg/L.

Trace elements can be determined through several methods including Atomic Absorption/Emission (AA) with a graphite furnace option, wet chemistry methods, Inductive Coupled Plasma (ICP) and XRF.

VII. *Organic Impurities:* In the board conversion process, organic impurities can affect the gypsum rehydration step. It can easily cause the rehydration time to lengthen and cause the board line to slow down and reduce production. Also, organic impurities can affect the crystal growth and reduce the strength development of the gypsum core.

Organic impurities can be identified through several methods: coulometric titrimetry, Infrared spectroscopy (IR), Nuclear Magnetic Resonance (NMR) and High Performance Liquid Chromatography (HPLC).

d. Physical Properties

Even though mined gypsum and FGD gypsum are chemically equivalent, they are physically different in particle size and shape. Hence, this factor has to be accounted for when blended together.

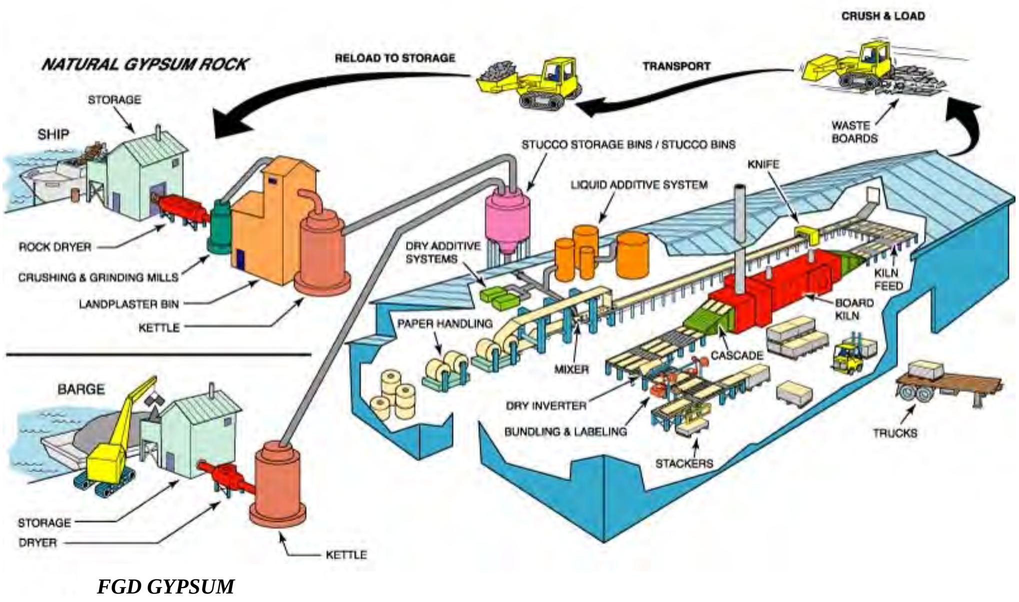

Figure 7-2a: Process of manufacturing wallboard using both Natural and FGD Gypsum. Illustration used from United States Gypsum Company.

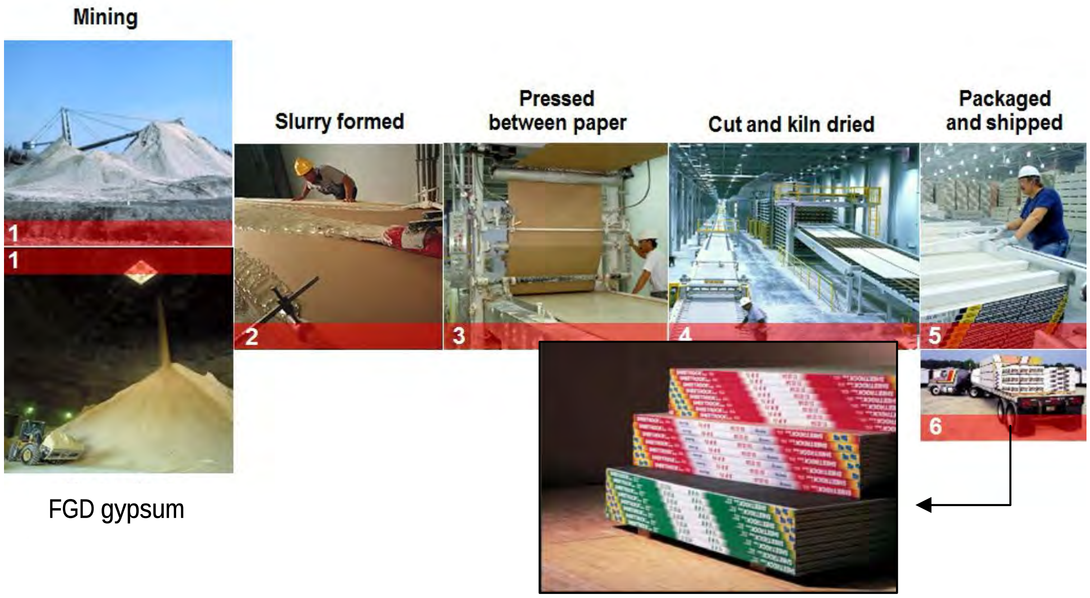

Figure 7-2b: Photographs of process of wallboard manufacturing steps using FGD Gypsum. Illustration used from National Gypsum Company.

FGD Gypsum Use in Portland Cement[2]

Portland cement is a mixture of compounds formulated by burning limestone and clay together at high temperatures ranging from 1400ºC to 1600ºC. Portland cement is utilized throughout the construction industry in a variety of applications, one of which is as an ingredient in the production of concrete. Portland cement consists of five major compounds: Tricalcium silicate (50%), Dicalcium silicate (25%), Tricalcium aluminate (10%), Tetracalcium aluminoferrite (10%) and Gypsum (5%). When water is added to cement, each of these compounds undergoes hydration resulting in the final hardened product. Uncalcined FGD gypsum (as a replacement to mineral gypsum) is used as an additive to Portland cement to serve as a set retardant in the mixture. Figure 7-3 shows a simple flow diagram of Portland cement production.

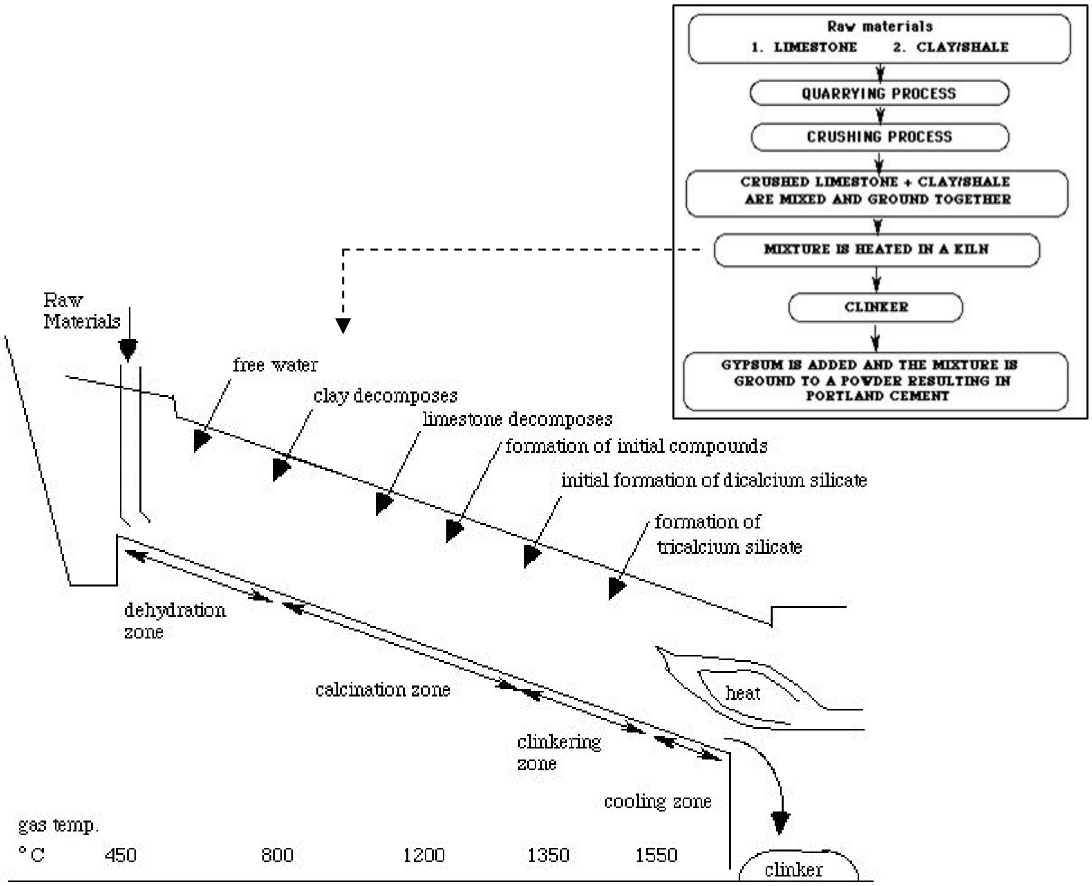

Figure 7-3: A flow diagram of Portland Cement production with full-blown schematic diagram of the rotary kiln. Diagram provided by University of Illinois (Materials Science and Engineering).

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[2] http://matse1.matse.illinois.edu/concrete/prin.html

FGD Gypsum Use in Agriculture

For many centuries, gypsum has been used in agriculture as a soil amendment, conditioner and fertilizer. Due to its chemical make-up, it provides soluble sources of calcium and sulfur, supplying needed nutrients and improving plant growth. Without the use of gypsum, soil compaction prevents root penetration, aeration and water infiltration. Also, the loss of soil permeability causes saturation of the soil with salt or other elements that can be harmful to plant growth and health. Some of the physical benefits of utilizing gypsum include promoting clay flocculation for air and water movement, correcting for subsoil acidity by decreasing the toxic soluble aluminum, enhancement of root penetration and assisting in reclaiming sodic soils.

In 2007, the Electric Power Research Institute, the Ohio State University and various other electric companies in the United States initiated a research project using FGD gypsum in agricultural applications to evaluate the effect on soils chemical and environmental properties for comparison to natural gypsum used in agricultural applications (72). In 2009, We Energies joined this network to help acquire additional scientific information to demonstrate the benefits of the FGD gypsum. The company gained regulatory approval for land application of FGD gypsum from the Wisconsin Department of Natural Resources (DNR) in 2008 and the Illinois Environmental Protection Agency (IL EPA) in 2010. We Energies marketer of agricultural gypsum also obtained regulatory approval for use in Indiana.

We Energies collected samples of commercial sulfur containing fertilizers and soil amendments from three sources, mined gypsum (“Top Grow” brand by ASC Mineral Processing, which is a Pelletized Gypsum), and sulfur fertilizer (“Hi Yield” brand used for soil treatment - Aluminum Sulfate and Ammonium Sulfate) for comparison to PPPP FGD gypsum and performed analyses of the chemical content and leaching characteristics in accordance with the ASTM standards specified in Wisconsin NR 538 requirements for the beneficial use of industrial by-products. The results are shown on Tables 7-3 and 7-4 respectively. This information was used to support We Energies exemption request to allow beneficial use to proceed in Wisconsin. As shown in Table 7-4, it is important to note that sulfate is the primary leachate component and its useful presence in FGD by-products, FGD gypsum can be sought as a valuable source for farmers to treat soils as an alternative to mined gypsum. The results show that the mined gypsum sample exceeded the Category 1 bulk chemical guidelines for As (0.76 ppm) and Be (0.052 ppm). Further, the mined gypsum sample exceeded the Category 1 leachate guidelines for Cr, Fe, Pb, and Mn. As for both Aluminum sulfate and Ammonium sulfate, they also exceeded numerous Category 1 leachate guidelines. Category 1 leaching guidelines were exceeded for the PPPP FGD gypsum parameters fluoride and manganese. Thus, FGD gypsum has been exempted and licensed for use in agriculture in Wisconsin. Lastly, the very low volume filter cake produced by the FGD wastewater treatment process was also tested and found to be unsuitable for use in agriculture.

Farmers began adopting We Energies gypsum materials as they learned about the local source availability and the benefits of using a more concentrated form of FGD gypsum (>95%) thus providing more calcium sulfate per ton than mined gypsum. Due to the nature of the production process of FGD gypsum, it yields a consistent fine and uniform particle size, which not only provides rapid release of the calcium and sulfur into the soil, but can be easily applied with conventional lime spreading equipment. Wisconsin farmers now have the advantage of obtaining the material at a lower cost since the FGD gypsum is produced in southeast Wisconsin. Approvals for agricultural use of We Energies FGD gypsum have also been obtained for several counties in Illinois and Indiana.

Table 7-3: Chemical Contents of Mined Gypsum, Soil Fertilizers and We Energies FGD Gypsum and Filter Cake

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	Pelletized Gypsum TopGrow Brand	Ammonium Sulfate Hi Yield Brand	Aluminum Sulfate Hi Yield Brand	P4 FGD Gypsum	P4 Gypsum from Belt	P4 FGD 0-1 WWT Filter Cake	P4 FGD 0-2 WWT Filter Cake
Total Aluminum	ppm			1100	50	82000	-	-	-	-
Total Antimony	ppm	6.3		0.055	0.15	<0.011	0.27	0.28	2.8	2.4
Total Arsenic	ppm	0.042	21	**0.76**	<0.12	<0.12	**0.46**	**0.25**	**2.8**	**2.9**
Total Barium	ppm	1100		32	<0.25	1.6	14	15	74	64
Total Beryllium	ppm	0.014	7	**0.052**	<0.039	**0.44**	<0.037	<0.037	0.16	0.15
Total Boron	ppm	1400		8.6	<0.18	<0.18	1.9	2.3	160	150
Total Cadmium	ppm	7.8		0.14	0.051	<0.011	0.02	0.039	0.38	0.36
Hexavalent Chromium	ppm	14.5		<0.68	<0.68	<0.66	<0.60	<0.60	4.5	4.6
Total Cobalt	ppm			0.63	0.034	0.13	-	-	-	-
Total Copper	ppm			0.7	0.067	0.4	-	-	-	-
Total Lead	ppm	50		<0.0089	<0.0089	0.1	0.51	0.59	7.1	6.8
Total Molybdenum	ppm	78		1	0.26	0.09	0.35	0.52	5.4	5.5
Total Nickel	ppm	310		3.4	<0.12	0.45	2.1	3.1	39	38
Total Selenium	ppm	78		0.46	0.25	0.13	3.3	2.8	48	52
Total Silver	ppm	9400		<0.030	<0.030	<0.030	<0.028	<0.029	0.12	0.11
Total Strontium	ppm	9400		3600	0.21	0.94	120	120	55	60
Total Thallium	ppm	1.3		0.057	<0.0032	<0.0032	0.019	0.022	0.42	0.35
Total Vanadium	ppm	110		<0.048	<0.048	1.8	1.6	1.8	21	21
Total Zinc	ppm	4700		9	1.6	13	1.6	8.9	49	51
Total Mercury	ppm	4.7		0.003	0.002	0.039	1.1	1	**18**	**19**

Table 7-4: ASTM D-3987 Leachate Test Results of Mined Gypsum, Soil Fertilizers and We Energies FGD Gypsum and Filter Cake

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 & 3 Standard	NR538 Category 4 Standard	Extraction Blank	Pelletized Gypsum ASTM Extract	Ammonium Sulfate ASTM Extract	Aluminum Sulfate ASTM Extract	P4 FGD Gypsum ASTM Extract	P4 Gypsum from Belt ASTM Extract	P4 FGD 0-1 WWT Filter Cake ASTM Extract	P4 FGD 0-2 WWT Filter Cake ASTM Extract
Dissolved Aluminum	mg/l	1.5			0.00078	0.75	0.016	**3500**	0.33	0.24	<0.0015	0.0042
Dissolved Antimony	mg/l	0.0012	0.012		0.0000084	0.00058	<0.00024	**0.028**	0.00022	0.00026	<0.000043	0.0007
Dissolved Arsenic	mg/l	0.005	0.05		<0.000053	<0.0026	<0.0026	<0.026	0.0012	0.0011	0.0022	0.004
Dissolved Barium	mg/l	0.4	4		<0.00011	0.083	<0.0055	<0.055	0.072	0.11	0.047	0.045
Dissolved Beryllium	mg/l	0.0004	0.004		<0.000017	<0.00085	<0.00085	**0.02**	<0.00017	<0.00017	<0.00017	<0.00017
Dissolved Boron	mg/l	0.19	1.9	4.8	0.0074	0.083	0.0087	**0.2**	0.014	0.01	0.11	**1**
Dissolved Cadmium	mg/l	0.0005	0.005	0.025	<0.0000050	0.00034	0.00026	<0.0025	0.00025	0.00021	0.000099	<0.00005
Chloride	mg/l	125	1250		<0.012	8.9	<0.60	66	0.71	0.73	48	48
Dissolved Chromium	mg/l	0.01	0.1	0.5	<0.000063	**0.012**	**0.012**	<0.032	<0.00063	<0.00063	0.004	0.0039
Dissolved Copper	mg/l	0.13	1.3		0.000046	0.0054	0.0019	0.019	0.00083	0.0004	0.064	0.018
Dissolved Cyanide	mg/l	0.04	0.4		<0.0060	0.032	<0.0060	<0.0060	<0.0094	<0.0094	0.017	<0.0094
Dissolved Fluoride	mg/l	0.8	8		<0.012	<0.060	**1.3**	**3.4**	**5.5**	**5.7**	**8.2**	**10**
Dissolved Iron	mg/l	0.15	1.5		<0.0050	**1.7**	**0.29**	<2.5	<0.050	<0.050	<0.000050	<0.000050
Dissolved Lead	mg/l	0.0015	0.015		0.00009	**0.021**	0.00028	**0.0021**	0.00042	0.0004	<0.000039	<0.000039
Dissolved Manganese	mg/l	0.025	0.25		0.000021	**0.5**	**0.03**	**0.062**	**0.1**	**0.027**	<0.00076	<0.00075
Mercury	mg/l	0.0002	0.002		<0.000012	<0.000012	<0.000012	<0.000012	0.0000018	0.0000062	0.0000088	<0.0000055
Dissolved Molybdenum	mg/l	0.05			0.000031	0.0061	0.0079	0.016	0.00067	0.0016	0.044	0.015
Dissolved Nickel	mg/l	0.02	0.2		<0.000014	0.014	0.017	**0.038**	0.003	0.0023	**0.028**	0.0065
Nitrate-Nitrite as N	mg/l	2	20		0.08	0.68	**4.3**	**3.4**	0.2	<0.020	**6.8**	**7.5**
Dissolved Phenolics	mg/l	1.2	12		<0.0038	0.033	<0.0038	<0.0038	<0.0056	<0.0056	0.0096	<0.0056
Dissolved Selenium	mg/l	0.01	0.1	0.25	<0.000093	<0.0046	0.0049	<0.046	0.0067	0.0062	**0.097**	**0.17**
Dissolved Silver	mg/l	0.01	0.1	0.25	<0.000013	<0.00065	<0.00065	<0.0065	0.0002	0.00016	0.00036	0.00054
Sulfate	mg/l	125	1250	2500	<0.10	**1750**	**35300**	**24900**	**1470**	**1450**	**1460**	**1500**
Dissolved Thallium	mg/l	0.0004	0.004		0.0000038	0.00012	0.000092	**0.0019**	0.00015	0.00013	<0.000014	<0.000014
Dissolved Zinc	mg/l	2.5	25		0.00035	0.022	0.02	0.6	0.0029	0.0024	0.0095	0.0031

Benefits of Using Gypsum for Agricultural Purposes (73)

Figure 7-4: Soil Structural Difference – Control (left) and Gypsum (Right). Diagram provided by Agricultural Research Service [3].

Source of Plant Nutrients:
The composition of pure gypsum ($CaSO_4{\cdot}2H_2O$) is 79% calcium sulfate ($CaSO_4$) and 21% water (H_2O). It consists of 23.3% calcium (Ca) and 18.6% sulfur (S) and provides an excellent source of soluble plant nutrients in the soil (Figure 7-4) [3]. Calcium is an essential component of plant cell wall structures providing strength in the plant. It plays the role of counteracting the effects of alkali salts and organic acids within a plant. Sulfur is an essential plant food for production of protein, promoting activity and development of enzymes and vitamins. It improves root growth and seed production.

Source of Improving Soil's Chemical and Physical Properties:
Farmers with various crops face sulfur deficiencies due to a combination of factors. These factors include "increased crop yields that result in more sulfur removal from soil, reduced sulfur inputs contained as by-products in other nutrient fertilizers, and decreased sulfur deposition from the atmosphere" (72). Hence, gypsum is used as a sulfur fertilizer. Sulfate in the gypsum is the most favorable form for the plant roots to absorb sulfur to enhance crop production and increase resistance to environmental stress and pests.

Gypsum is also used as a calcium fertilizer to help improve the soil's physical properties. Without adequate calcium, the biochemical uptake mechanism would fail. Soils that are Ca-deficient in the humid regions have the tendency to disperse and form a stable suspension of particles in water. In other words, highly hydrated ions, such as Na^+ or Mg^{2+} repel the clay particles causing soil erosion. Thereby, adding the gypsum allows an amendment for sodic soil reclamation. This means, the Ca^{2+} that is provided by the gypsum is exchanging with Na^+ and Mg^{2+}, leading to clay flocculation in the soil. Clay flocculation is the "coagulation of the individual clay particles into micro-aggregates" (73), thus improving the soil structure for root growth and air and water movement as shown in Figure 7-5. The flocculation also prevents crusting of soil and aids in rapid seed emergence for no-till field crops. The crust formation is a result of rain or sprinkler irrigation on unstable soil.

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[3] http://library.acaa-usa.org/5-FGD_Gypsum_Influences_on_Soil_Surface_Sealing_Crusting_Infiltration_and_Runoff.pdf

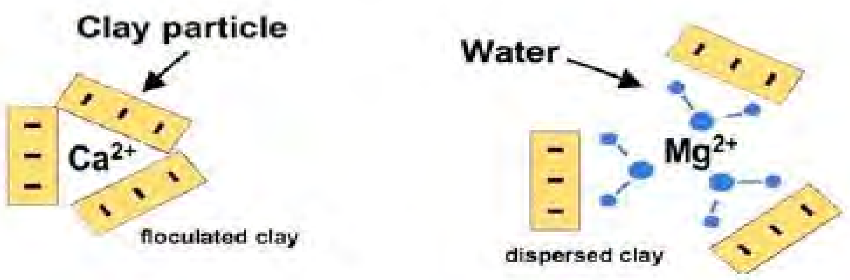

Figure 7-5: Flocculation effect where soluble electrolyte, Ca^{2+} from the FGD gypsum overcoming the dispersion effects of highly hydrated ions, Mg^{2+} and promoting structural development.

Plants growing in acid soils can be chemically detrimental as they can be prone to high concentrations of soluble aluminum. "Subsoil acidity prevents root exploitation of nutrients and water in the subsoil horizons" (73). Even though the soil has low pH, the presence of high levels of exchangeable aluminum (Al^{3+}) makes it very toxic to most plant roots. Gypsum being a neutral salt and not a limiting agent, does not change the soil's pH but rather enhances the root tolerance from acid subsoil. The addition of the FGD gypsum "can ameliorate the phytotoxic conditions arising from excess soluble aluminum in acid soils by reacting with Al^{3+}, thus removing it from the soil solution and reducing its toxic effect on the plant roots" (73). This leads to an increase in calcium supply to lower depths for root uptake of water and nutrition from the subsoil layers as shown in Figure 7-6. Gypsum utilization can also improve the water-use efficiency of crops that are grown in dry areas or during times of drought.

$$CaSO_4 + Al^{3+} \rightarrow Al(SO_4)^{+} + Ca^{2+}$$

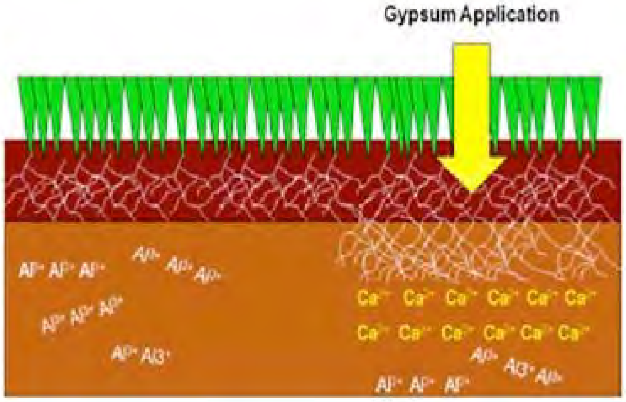

Figure 7-6: FGD gypsum ($CaSO_4$) forming soluble complex with Al^{3+} and reducing the soil toxicity with exposure to Ca^{2+} for root uptake.

The application of FGD gypsum has been shown to improve surface water infiltration rates and percolation by inhibiting and delaying surface seal formation. This also reduces soil erosion by flocculated clay particles which inhibit the soil to move offsite.

Phosphorus is an essential macronutrient required by the plants, to transfer energy from one reaction to drive another reaction within cells. Having adequate phosphorous available to the plants stimulates early plant growth and accelerates maturity. However, many soils are highly enriched with soluble phosphorus when manures or fertilizer phosphorous are heavily applied without proper soil testing. It gets very critical when eroded sediment are easily transported by storm water towards streams, ponds and wetlands as phosphorus is carried along with the sediment from the agricultural field causing eutrophication. "Eutrophication is defined as excessive nutrients in a lake or other body of water" (73). Hence, with the FGD gypsum application, the soluble calcium binds with the soluble reactive phosphate (SRP) forming an insoluble calcium phosphate precipitate (shown in Figure 7-7) improving the water quality with decreased runoffs.

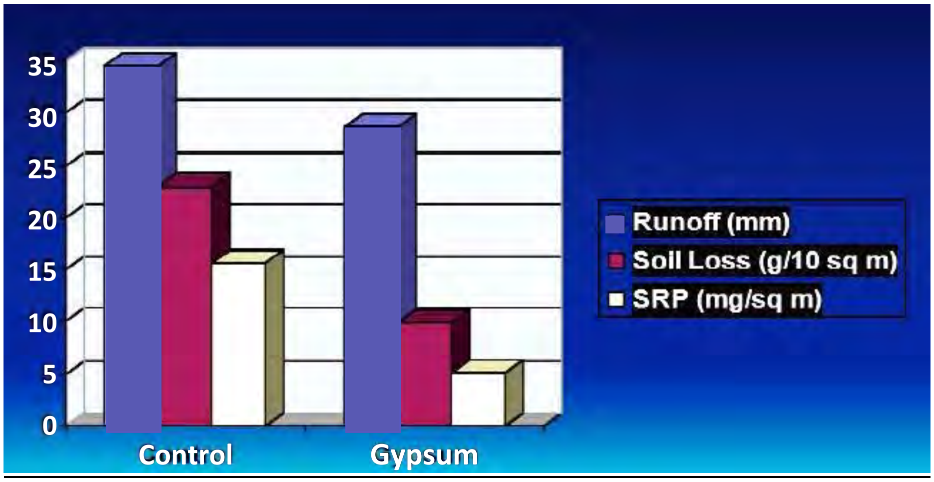

Figure 7-7: Effect of FGD gypsum on Erosion. Illustration provided by Agricultural Research Service.

In summary, gypsum can provide many physical and chemical benefits to soil in addition to nutritional benefits.

1. Improves soil structure with flocculation effect for root growth and air and water movement
2. Prevents crusting of soil and aids in seed emergence
3. Improves infiltration rates and hydraulic conductivity of soils to have adequate drainage
4. Reduces erosion losses of soils and nutrients and phosphorus concentration in surface water runoff
5. Corrects for subsoil acidity and aluminum toxicity.

Chapter 8

Fly Ash Stabilized Cold In-Place and Full Depth Reclamation of Recycled Asphalt Pavements, Stabilized Soils, and Stabilized Coal Ash

Introduction

We Energies conducted studies in cooperation with Bloom Consultants, LLC and the Center for Highway and Traffic Engineering at Marquette University in Milwaukee, Wisconsin to evaluate the potential application of fly ash in asphalt pavement construction. In a typical cold in-place recycled (CIR) application, existing hot mix asphalt (HMA) layers are pulverized, graded, compacted and used as a base layer for a new hot mix asphalt surface. In most CIR applications, the existing HMA layers are pulverized to the full thickness, and in some cases through the top 2" or 3" or the entire depth of aggregate base. The CIR material is sprayed with water to get the desired moisture content. The material is graded and then compacted with vibrating steel drums and pneumatic tired rollers.

In recent years, stabilizers have been added into the CIR materials to improve the structural capacity of the CIR layers. In these studies self-cementing Class C fly ash was used to bond with CIR materials and the long-term performance of the final pavement section is being monitored.

In addition, Class C fly ash was used by We Energies to stabilize a coal ash fill surface to construct a commercial office building parking lot on top of the coal ash fill area.

We Energies also conducted a study that demonstrated the use of industrial by-products (Class C fly ash, bottom ash and cement kiln dust) with the recycling process known as full depth reclamation (FDR) of asphalt pavements. "FDR is a process of pulverizing a predetermined amount of flexible pavement that is structurally deficient, blending it with chemical additives and water and compacting it in place to construct a new stabilized base course" [1]. This process was developed for road reconstruction with longer life than the traditional roads and uses fewer resources, making it more sustainable and economical.

Case Study I: Highland Avenue, Mequon

A 1.5 mile long section of West Highland Avenue, between Wauwatosa Avenue and Farmdale Road, was resurfaced in 1997. The existing pavement had a 5½" thick asphaltic surface with an aggregate base varying in thickness from 7" – 18". This stretch of road is a two-lane cross section with an average annual daily traffic (AADT) of 1150. The pavement was constructed over a natural cohesive soil subgrade material.

A 1.5 mile length of the pavement was re-surfaced, two 800 ft. long test sections were stabilized with a fly ash binder and an asphalt emulsion binder respectively. The project was undertaken in August of 1997. The existing HMA surface was pulverized to a total depth of 8" then graded and compacted using standard procedures.

The 800 ft. asphalt emulsion stabilized test section was constructed by repulverizing the upper 4" of the CIR base, and incorporating emulsified asphalt at a rate of 1½ gal/yd^2. The base was then graded and compacted. The 800-ft. length of fly ash stabilized section was constructed by applying 35 lbs/yd^2 of Pleasant Prairie ASTM C-618, Class C fly ash over the pulverized CIR base and repulverizing the top 5" of CIR base. The pulverized layer was shaped with the grader and moistened with surface applied water, at the rate of 8 gal/yd^2. The stabilized base was graded and compacted similar to the other test section.

The asphalt emulsion stabilized test section received a 3½" HMA surface, and the fly ash stabilized test section received a 4" HMA surface. The remaining portion of the pavement received a 4" HMA surface without repulverization of the base. Due to the lack of established procedures and equipment to transfer fly ash from the supply tank to the spreader truck and in spreading fly ash, some delays and dusting problems occurred. This problem has now been solved by using a vein feeder spreader for the fly ash and by addition of water to the reclaimer mixing chamber.

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[1] Wolfe, W., Butalia, T.S., and Walker, H., "Full-Depth Reclamation of Asphalt Pavements Using Lime-Activated Class F Fly Ash: Structural Monitoring Aspects", The Ohio State University, Departement of Civil and Enviornmental engineering and Geodectic Science, 2009.

Figure 8-1: Fly ash being placed uniformly on the pulverized pavement.

Figure 8-2: Pavement being repulverized after fly ash application.

Pavement Performance

Representative sections, 500 ft. each in length, were selected from the asphalt emulsion stabilized, fly ash stabilized and control sections. Visual inspections performed on these three sections did not show any surface distress (i.e., cracking, rutting or raveling). Nondestructive deflection testing using the Marquette Falling Weight Deflectometer (FWD) was conducted prior to the construction, after initial pulverization, after one year, and after six years of service to establish structural integrity of each test section. This data was used to back calculate in-situ subgrade resilient moduli and the structural number of the pavement (74).

The preconstruction and post pulverization structural number (SN) results (back calculated) indicate general agreement between section uniformity of the upper pavement layers. The post construction testing and back calculation of SN shows that the fly ash stabilized section gave an 8.6% increase in SN (2.53 vs. 2.33) when compared to the control section. Also the fly ash stabilized section gave a 4.6% increase in SN (2.53 vs. 2.42) compared to the asphalt stabilized section, after making adjustments for the difference in thickness of the HMA surface.

Using the back-calculated SN values of the pavement sections, the structural coefficients of the stabilized and unstabilized CIR base material were calculated. The structural coefficient was found to be 0.11 for the untreated CIR base layer, 0.13 for the asphalt emulsion stabilized layer and 0.15 for the fly ash stabilized base layer.

Based on the 1993 edition of the AASHTO Guide for Design of Pavement, an estimate of the allowable number of 18,000 lb. equivalent single axle loads (ESALs) was determined. In this calculation, a design reliability of 85%, an overall standard deviation of 0.35 and a design serviceability loss due to traffic of 2.0 were used. Figure 8-3 shows the allowable ESALs vs. SN (structural number) for the range of subgrade resilient moduli exhibited within the test sections. By holding the subgrade resilient modulus constant and adjusting the asphalt layer coefficient to 0.44, the structural numbers were recalculated. The revised values of SN are as follows:

Control section = 2.65

Emulsion stabilized section = 2.74

Fly ash stabilized section = 2.85

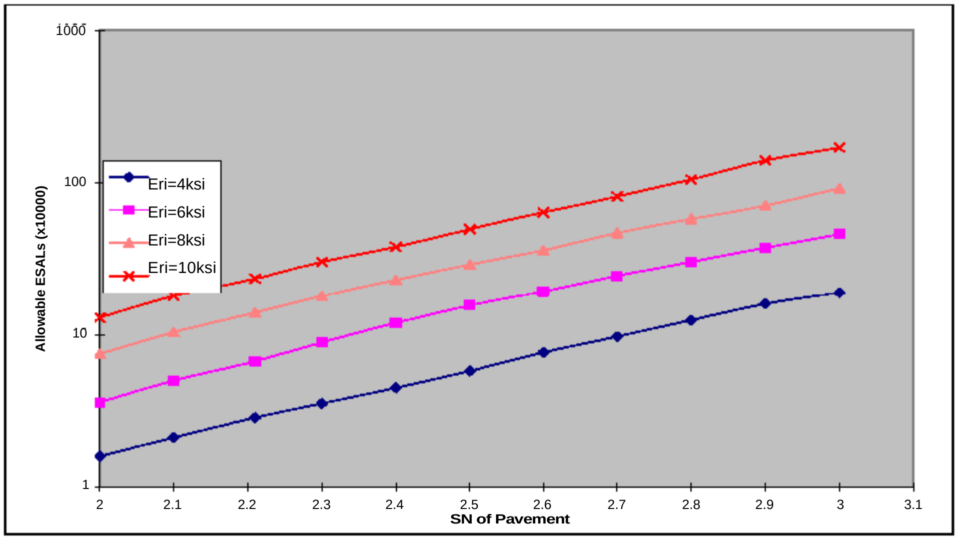


Figure 8-3: Allowable Traffic Estimates

The allowable traffic estimate based on the revised SN provided a more meaningful comparison. Based on the revised SN, the fly ash test section provided a 58% increase in allowable traffic compared to the control section and a 28% increase in allowable traffic compared to the asphalt emulsion test section. Long term testing of the pavement is required to understand its behavior. However from the studies completed to date, the fly ash stabilized CIR section appears to have good potential.

Falling Weight Deflectometer tests were conducted again in October 2003, approximately six years after construction, within the control section, the emulsion stabilized section, and the fly ash stabilized section. Surface deflections were used to back calculate subgrade and pavement parameters including the flexural rigidity of the upper pavement layers and the effective structural number of the pavement (75).

Figure 8-4 provides a summary of the back calculated effective structural number (Sneff.) As shown, the Sneff of the fly ash stabilized section is greater than comparable control or emulsion stabilized sections with the exception of the westbound emulsion stabilized section with a stronger subgrade.

In general, after six years of service the structural integrity of fly ash stabilized section of Highland Road appeared to be equal or better than both the control and emulsion stabilized sections. From a condition standpoint, all sections are performing well with no observed surface cracking.

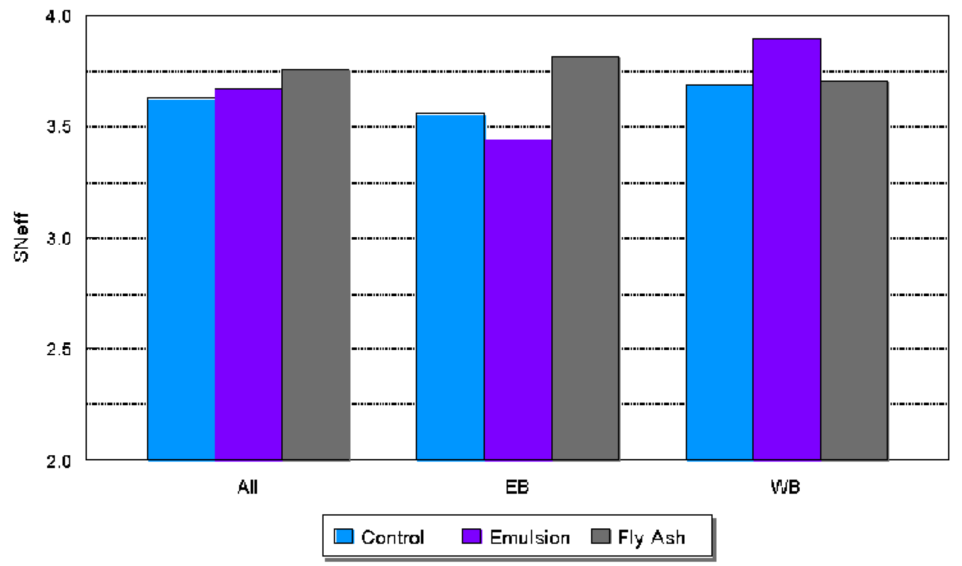


Figure 8-4: Comparison of Effective Structural Numbers (Sneff.) (75)

Case Study II: CTH JK, Waukesha

County Trunk Highway JK is located in Waukesha County, Wisconsin and the project segment runs between County Trunk Highway KF and County Trunk Highway K, with a project length of 3,310 ft. It is a two-lane road with an average daily traffic (ADT) count of 5,050 vehicles in year 2000 and a projected ADT of 8,080 in design year 2021. The existing pavement structure consisted of approximately a 5” asphalt concrete surface layer and a 7” granular base course.

The project scope included construction of a reinforced concrete pipe culvert. The contractor completed this task prior to starting the paving. The base course of the pavement section at the culvert for a length of approximately 50 feet was constructed using crushed aggregate, instead of fly ash stabilized CIR materials. Prior to construction of the road, undercutting was performed at places where severe pavement distresses existed. The pavement was excavated to a depth of 2 feet underneath the existing base course and was filled with breaker run stone. Initial pulverization started on October 9, 2001. The existing HMA pavement was first pulverized to a depth of 5”. After spraying water on the surface of pulverized materials, the pavement was repulverized to a depth of 12” and was graded and compacted by a Sheep’s Foot Roller.

Fly ash was placed on October 11, 2001. Fly ash was transferred from the supply tanker to the vein feeder spreader truck through a hose, which significantly reduced dusting. The vein feeder spreader truck applied the fly ash at an application rate of 8% by weight. The feed gates from the spreader truck provided a six ft. wide surface application. Water was sprayed to obtain the water content of the stabilized CIR materials to the desired 5.0% moisture content. The fly ash and moisture contents were controlled by an operator, based on field experience. The mixing operation commenced immediately after distribution of fly ash over a length of approximately 100 feet and was completed within one hour, using the pulverizer. Compaction of the mixture began immediately after mixing and was completed within one hour following spreading of fly ash. The compaction of the base course included 6 passes of the Sheep's Foot Roller followed by 2 passes of the Vibratory Drum Compactor.

A laboratory mix analysis to evaluate the stabilization potential of recycled pavement material with Class C fly ash was conducted. A field sample of existing asphalt pavement and underlying aggregate bases was obtained from CTH JK. The results of the grain size analysis on the CIR material indicated a sand and gravel mixture with trace fines. The analysis showed that the sample contained 68% gravel (larger than #4 sieve), 26% sand (between #4 and #200 sieves) and 6% silt (between #200 sieve and a size of 0.005 mm) and clay (between 0.005 and 0.001 mm) size particles. Evaluation of fly ash stabilized CIR material was performed at two fly ash contents, 6% and 8% by dry weight of total mix. Laboratory analysis of the fly ash stabilized materials was in accordance with ASTM C-593, where the Moisture-Density (ASTM D-1557) and Moisture-Strength (ASTM D-1633) relationship of specimens compacted in a 4" diameter mold was obtained. Results of the moisture density relationship test on the recycled asphalt pavement indicated a maximum dry density of 141.7 pcf at an optimum moisture level of 5.0%. In addition, moisture density relationship tests on the recycled asphalt pavement material with 6% and 8% fly ash added indicated a maximum dry density of 142.3 pcf and 142.9 pcf at an optimum moisture content of 5.5%, respectively. A maximum unconfined compressive strength of 250 psi and 380 psi at an optimum moisture content of 5% were also obtained after seven days curing, respectively.

Pavement Performance

Pavement performance of CTH JK was evaluated using the FWD test in each year between October 2001 and 2008. The results of the testing indicate that the strength of fly ash stabilized CIR recycled asphalt base course developed significantly and the modulus increased from 179.7 ksi in 2001, to 267.91 ksi in 2002, and to 328.82 ksi in 2003. The layer coefficient of fly ash stabilized CIR recycled asphalt base course was 0.23 at time of FWD testing in 2002 and 0.245 in 2003, compared to 0.16 in 2001. No cracking and rutting was identified in the pavement distress survey. Compared to the pavement of CTH VV with untreated CIR recycled asphalt base course, the structural capacity of fly ash stabilized CIR recycled asphalt base course in CTH JK, with a layer coefficient of 0.245, is appreciably higher than that of untreated CIR recycled asphalt base course, with a layer coefficient of 0.13 (76). Figure 8-5 shows the structural number of CTH JK pavement for the first three years.

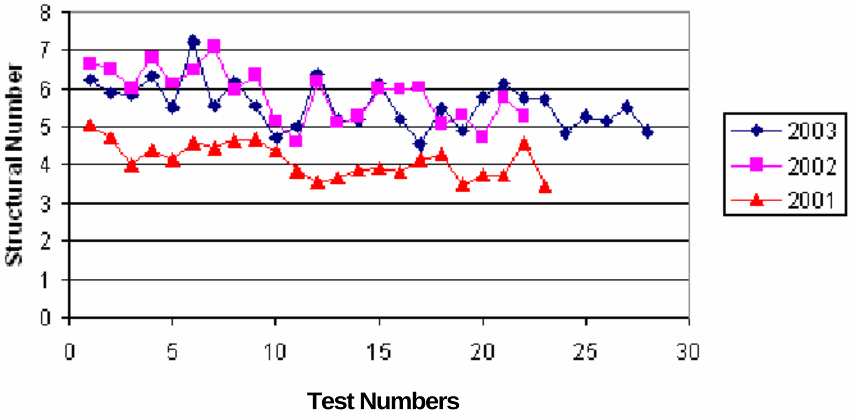


Figure 8-5: Structural Numbers of Pavement in CTH JK

In 2004, a few additional transverse cracks were observed, as well as some longitudinal cracks in the traffic wheel paths. In 2005, the longitudinal cracks were more severe, when compared to the 2004 survey. The surveys performed in 2007 and 2008 showed alligator cracking becoming an issue in some locations. However, a crack sealing operation was conducted in 2010 to address those cracking issues. In general, cracking in the pavement represents the most severe threat to this pavement, either due to fatigue represented by alligator cracking, or thermal distress due to weather conditions. Rutting does not present a challenge to this section of CTH JK, as measured in the field.

The most recent visual distress survey was conducted in October 2010 to evaluate the physical condition and distress of the pavement. The visual distress survey determined the type, size, location and degree of severity of distresses present at the time of the inspection. The subsequent evaluation of those distresses included comparing the current survey information with the results observed in previously conducted inspections.

The pavement received a crack sealing treatment in 2010. This report establishes the gains in the pavement physical properties due to the crack sealing treatment. In 2007, this study started collecting visual survey data complying with ASTM D-6433 (Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys). Based on the reports for the years before 2007, it can be assumed that the pavement condition was fair as of 2005. Table 8-1 was prepared to compare the Pavement Condition Index (PCI) calculated according to the procedure, ASTM D-6433. PCI is a numerical rating of the pavement condition that ranges from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition. The PCI value is then translated into a verbal rating that ranges from "Excellent" to "Failed".

Table 8-1: Intensity of Distresses in the Pavement

Year	Level	1. Alligator Cracking	2. Block Cracking	3. Bumps and Sags	4. Depression	5. Edge Cracking	6. Lane/Shoulder Drop off	7. Longitudinal & Transverse Cracking	8. Patching and Utility Cut Patching	9. Pothole	10. Rutting	PCI	PCI Rating
2007	Low	7.8%		0.2%				5.7%			0.6%	47	Poor
	Medium	0.5%						14.1%			0.1%		
	High												
2008	Low	11.6%	0.4%		0.1%	1.1%	7.3%	6.6%	0.1%	0.03%	0.6%	38	Very Poor
	Medium	3.1%						22.3%		0.01%	0.1%		
	High							0.3%					
2010	Low	3.9%	0.3%	0.2%	0.1%	6.8%	8.6%	42.9%	0.02%	0.04%	0.6%	57	Fair
	Medium	2.3%	0.3%			0.3%	1.9%	0.4%		0.01%	0.1%		
	High						0.3%	0.5%					

Table 8-1 shows that the longitudinal and transverse cracking is the dominant mode of cracking followed by the alligator cracking. For the longitudinal and transverse cracking, the table shows that in 2007 medium severity cracking exhibited an intensity of 14.1%. This value increased to 22.3% by 2008. After the cracking sealing treatment, this value dropped significantly to 0.4%. The table also shows that the rutting severity did not change since 2007. The average rut depth also did not change since 2007.

Figure 8-6 shows the PCI rating as determined using the ASTM D-6433 standard. It is important to note that the PCI value and the corresponding rating represent a collective quality of the pavement physical characteristics. The pavement is assumed to have a PCI score of 100. Then a deduct value is determined based on the intensity and severity of the recorded distresses.

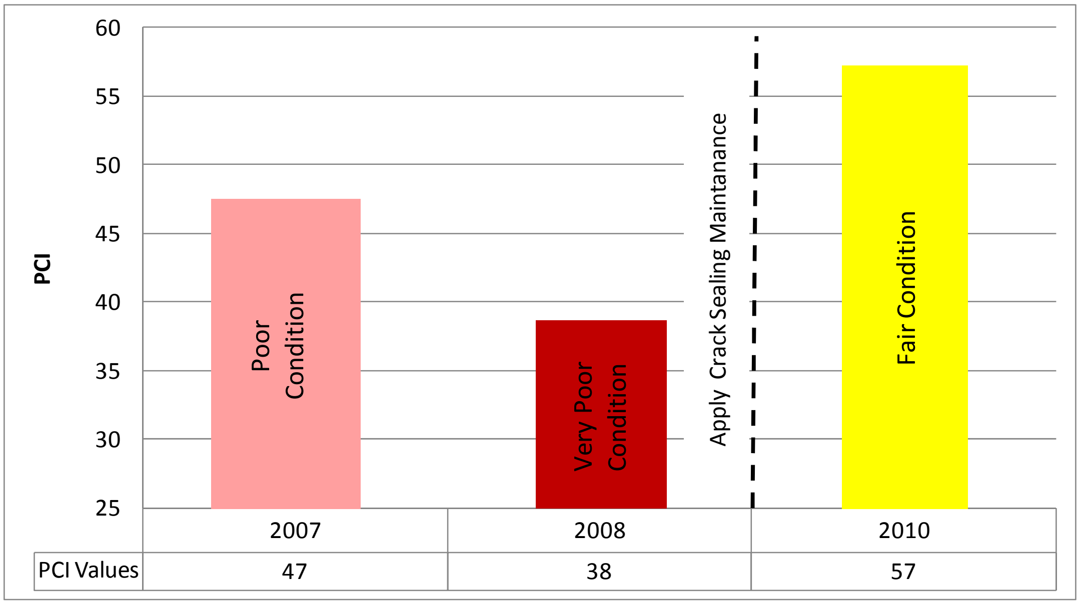


Figure 8-6: PCI rating for CTH JK since 2007

Figure 8-6 shows that the condition of the pavement was degrading since the pavement is rated poor in 2007 and very poor in 2008. The visual survey in 2010 was conducted after crack sealing maintenance was applied to the pavement. This upgraded the pavement condition to “Fair”. This big jump in the PCI value reflects the severity of the cracking experienced by the pavement. Alligator cracking observed in pavement is an indicator of fatigue failure, and longitudinal and transverse cracking are typically related to either thermal stresses or construction practices.

The rutting and alligator distresses are structurally-related distresses. These distresses are caused by the pavement deflecting under the given traffic loads. This deflection might be due to deformation in the surface layer, or deformation in the pavement system of base and surface layers. The FWD is capable of determining the weak points in the pavement through back calculating of the layers modulus.

It is important to note that the average rut depth measured for this pavement section since 2002 is within the low severity range according to the ASTM D-6433. However, the rut depth recently showed a significant increase. The following plot (Figure 8-7) shows the progression of the rut depth measured since 2002.

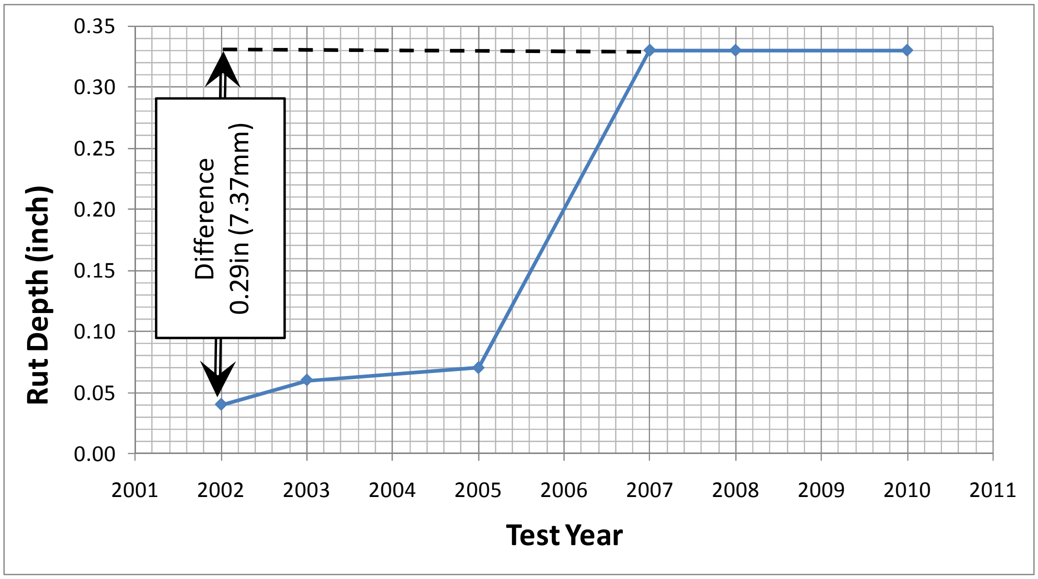


Figure 8-7: Rut depth progression since 2002.

The plot shows that between the years 2005 and 2007, the rut depth jumped by 0.26 inch (6.6mm). This represents about 79% of the total accumulated rut depth occurring in just two years. The average rut depth has not changed since 2007, which is recorded at 0.33in (8.82mm). According to the ASTM standard, a rut depth less than 0.5 inch is considered low severity. This indicates that the pavement structure is able to resist the accumulation of severe levels of permanent deformation.

The results of this pavement condition survey are providing an improved rating due to the recent maintenance treatment. It is important to note that this improvement in the rating is due to the mechanism by which the PCI rating is conducted, where the severity of some of the cracks were downgraded to a low severity level as a result of the crack sealing. Yet, this does not mean that the cracks decreased in opening size, or the pavement resistance to traffic loads improved. The best way to evaluate the pavement structural capacity is to conduct testing using the FWD to calculate the layer modulus and structure number. Once this is conducted, the information can be incorporated in the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) to conduct further analysis and predict pavement performance in the coming years.

Case Study III: Commercial Office Building Parking Lot

The surface parking lot is located at 3600 S. Lake Drive, St. Francis, Wisconsin. The lot area contained a capped coal ash fill. The coal ash was placed there more than 30 years ago by We Energies. The Class F fly ash and bottom ash were by-products from the former Lakeside Power Plant operation. Due to the large quantity of coal ash, the cost to remove, transport and dispose of the coal ash is prohibitive. Therefore, it was decided to build the parking lot on the existing coal ash fill. Because the coal ash fill did not contain any Class C fly ash, the coal ash was graded and stabilized with Class C fly ash to a depth of 12”. Upon compaction, a 5” asphalt pavement was placed directly on top of the compacted self-cementing fly ash mixture, without the need to use crushed aggregate base course. For the parking lot ramp, a 12” Class C fly ash stabilized sandy clay was used as sub-base directly underneath the asphalt pavement. The construction was done in August 2002.

A significant cost savings of approximately $400,000 was achieved by avoiding the costs associated with removal and hauling of the existing coal ash off site and the need to import crushed aggregate for base course. The life expectancy of the parking lot using Class C fly ash stabilization is expected to be equal to or better than the standard practice of using a crushed aggregate base course material. Figure 8-8 shows the parking lot. The parking lot has been inspected regularly since installation and has performed very well, showing little sign of distress over the years. The last pavement inspection was made in April 2012.

Figure 8-8: Commercial office building parking lot.

Case Study IV: PIPP Haul Road Pavement, Marquette, Michigan (77)

A 3.6 mile length of the landfill access roadway at Presque Isle Power Plant (PIPP) in the Town of Marquette, Michigan, is used by PIPP operations and a portion is used by an iron mine to access its coal and limestone stockpiles. This Marquette haul road was rebuilt during October 2006 using the full depth reclamation (FDR) process. The existing two-lane road was approximately 26 feet in width, with a narrow shoulder in each direction. This road had an asphaltic pavement section and two unpaved gravel sections, which had been exposed to 30 years of extreme weather conditions and heavy wheel loading of plant equipment that often exceeded 195,000 pound gross weight loads. Over time, the paved areas had potholes and widespread cracking and rutting, and the base was degrading. The unpaved sections had potholes, severe rutting, and was slippery during wet weather conditions and dusty during dry periods. The paved section was designed with 3.5 in to 4.0 in of asphalt and 6 in to 10 in of stabilized base course on top of granular subgrade. The objectives of this project were to reduce hauling and maintenance costs, improve safety, improve storm water management and dust control, conserve natural resources, and demonstrate the economics and structural performance of using CCP in road construction.

For this project, We Energies used substantial amounts of CCP for the full depth reclamation of a deteriorating paved roadway and in-situ stabilization of an unpaved roadway at PIPP. The base course layer was stabilized with the introduction of coal combustion by-products from PIPP that included cementitious fly ash (FAC) meeting ASTM C-618 Class C, granular bottom ash (BA), and cement kiln dust (CKD), which is produced by Lafarge North America located in Alpena, Michigan. In addition, reclaimed asphalt material (RAM) and recycled gravel material (RGM) were also used in some sections to improve the base course layer. Eleven mix compositions of BA, FAC and CKD were used and evaluated in this project as shown in Table 8-2.

Table 8-2: Tested Road Base Composition

Road Base Mix No.	Mix Composition	Original Road Surface	Type of Base	Road Base Treatment Width, ft (m)	Depth of Stabilization, in. (cm)	Asphalt Thickness, in. (cm)
1	25% BA (7-9) + RGM	Gravel	U	28 (8.5)	8 (20.3)	4.0 (10.2)
2	25% BA (7-9) + RAM	Paved	U	28 (8.5)	6 (15.2)	4.0 (10.2)
3	25% BA (1-6) + 11% FAC + RAM	Paved	S	14 (4.3)	8 (20.3)	3.5 (8.9)
5	25% BA (1-6) + 11% FAC + RGM	Gravel	S	14 (4.3)	10 (25.4)	3.5 (8.9)
6	25% BA (7-9) + 11% FAC + RAM	Paved	S	14 (4.3)	8 (20.3)	3.5 (8.9)
7	25% BA (1-6) + 11% CKD + RAM	Paved	S	14 (4.3)	8 (20.3)	3.5 (8.9)
8	11% FAC + RAM	Paved	S	14 (4.3)	8 (20.3)	3.5 (8.9)
9	11% FAC + RGM	Gravel	S	14 (4.3)	8 (20.3)	3.5 (8.9)
10	25% BA (1-6) + 11% FAC + RGM	Gravel	S	14 (4.3)	8 (20.3)	3.5 (8.9)
11	RGM	Gravel	U	14 (4.3)	8 (20.3)	4.0 (10.2)

Note: Road base mix 4 was not part of this study.

U: Unstabilized and S: Stabilized

Soil stabilization was essential for the new asphaltic concrete pavement to support the heavily loaded trucks that haul materials to the power plant's landfill and to a nearby mining operation. As the cementitious fly ash binder is mixed with RAM or RGM and compacted, it improves the dry density by filling in the voids which, controls the shrink-swell properties by cementing the soil grains together much like Portland cement bonds aggregates together. "By bonding the soil grains together, soil particle movements are restricted and instead solidify into a dense monolith which improves the structural properties of the treated base or sub-base material by spreading the loads over a greater area." (77). CCP and CKD were both used in stabilizing the base coarse and pulverized with asphaltic pavement.

The pavement system was designed using the AASHTO method of flexible pavement design with a structural number of 4.2. To decrease the cost and thickness of the asphaltic concrete, the team targeted a compressive strength of 300 psi (2.1MPa) based on the past project test results of full-depth reclamation. Prior to construction, samples of the gravel and asphaltic concrete from the existing structures were taken to determine the maximum dry density and optimum moisture for the different mixture combinations. Based on the lab results, the target moisture range and binder content of FAC and CKD were established for each stabilized base mixture.

Typically in-situ stabilized full depth reclamation projects would have two pass processes. The initial pass, using the pulverizer machine, pulverizes the asphaltic concrete and mixes it with the road base and added water. Then the composite is shaped and graded. The cementitious binder is then placed over the prepared material and a second pass with the pulverizer machine mixes both the materials. However, to reduce the costs, the project team decided to mix all the materials with a single pass process. BA from PIPP units 1-6 and 7-9 was an agglomerated ash that was used as a sandy aggregate within the structural pavement. BA was loaded from a stockpile at the landfill and hauled via a live bottom dump truck and placed to a thickness of 4" at the predetermined locations on the existing road sections. Dry FAC was loaded from the PIPP storage silo directly into the vane spreader truck. The vane spreader truck spread the fly ash at an application rate of 110 lbs/yd^2 (540 kg/m^2) which is approximately 11% by mass of the total stabilized base. The CKD was pneumatically conveyed from a bulk tanker truck to the vane spreader truck at a similar application rate as FAC. The distributer bar on the vane spreader truck was maintained at the lowest position to minimize the drop height of the cementitious powders and to minimize the amount of fugitive dust during the placement period.

After the placement of BA and the cementitious binder (FAC or CKD) on the existing paved and gravel road sections, the materials were pulverized in-situ to a total depth of 6 -10 in. (15.2 – 25.4 cm). The depths were adjusted at some road sections due to the presence of large rocks that would break cutting teeth on the pulverizer machine. A water truck followed the pulverizer and increased the moisture in the mix when needed. The base was immediately compacted with a vibratory sheepsfoot compactor with five to eight passes to achieve 95% of the proctor density. The material was then fine graded and the road crown was shaped using the swell in volume of the mixed materials. Due to high traffic flow, the fly ash stabilized and non-stabilized sections were surfaced with 3.5 in. (9 cm) and 4 in. (10 cm) of HMA (MDOT 13A) surface, respectively. The stabilized base extended one-foot (30 cm) beyond the edge of the pavement to facilitate distribution of wheel loads and protect the HMA pavement from shear failure. The base was stabilized to a width of 28 ft (8.5 m), while paving to a width of 26 ft (7.9 m).

Pavement Performance

Field samples of RAM and RGM, combined with FAC, CKD and BA, were obtained from various designated test sections. Laboratory mix analysis, proctor numbers, optimum moisture contents and compressive strengths were provided by local testing firms. The physical properties of the stabilized base course layers with the combination of different by-products are shown in Table 8-3. The moisture-density relationship was determined using the Proctor test method for each composite material in accordance with ASTM D-698 Method C. Moisture content was monitored during the construction with a nuclear density meter. The nuclear density tests resulted in a compaction range varying from 89.6% to 98.8% of the maximum dry density while the moisture content ranged from 7.7% to 14.9%. Generally, a lower water-to-cementitious material ratio yields higher compressive strength but not necessarily the highest density. The objective of soil stabilization is to optimize the moisture that will yield the highest density and highest compressive strength.

Table 8-3: Summary of the Field Measurements of Physical Properties of Stabilized Base Course Layers

Mixture / Composition	Moisture Content Range (%)	Dry Density (pcf) % Compaction Range	Compressive Strength Range (psi)
25%BA(1-6) + 11%FAC + RAM	8.9% - 14.9%	$\frac{116.5}{89.6\%} - \frac{128.4}{98.8\%}$	3 days 250 – 310 7 days 290 – 310 28 days 260 – 290 56 days 300 – 320
25%BA(1-6) + 11%FAC + RGM	7.7% - 9.1%	$\frac{122.5}{94.5\%} - \frac{125.4}{96.5\%}$	3 days 290 – 320 7 days 240 – 340 28 days 290 – 330 56 days 310 – 400
25%BA(1-6) + 11%CKD + RAM	10.5% - 11.5%	$\frac{124.8}{96.0\%} - \frac{127.1}{97.7\%}$	3 days 150 – 190 7 days 240 – 280 28 days 410 – 540 56 days 510 – 580
11% FAC + RAM	8.1% - 8.3%	$\frac{126.8}{96.9\%} - \frac{128.2}{98.6\%}$	3 days 450 – 480 7 days 450 – 460 28 days 360 – 490 56 days 390 – 460

Note: 145 psi = 1 MPa

The field samples of fresh stabilized base material were compacted into 4 in. (10 cm) diameter by 4 in. (10 cm) high cylinders using the ASTM D-698 Method C, wrapped in plastic and cured at room temperature in the laboratory. All the field samples had compressive strength exceeding the target strength of 300 psi (2.1 MPa) within 56 days and were over 90% of the target within 7 days. The results demonstrated that the FA mixture had the highest initial compressive strength, but at 28 days the BA+CKD mixture surpassed the FA mixture, having the highest compressive strength as shown on Table 8-3 and Figure 8-9. Overall, the composite mixtures for the stabilized base acquired good compaction and early strength development which allowed truck traffic at reduced speeds on the stabilized base after 24 hours of curing thus minimizing disruption to the plant and mining company operations. The early traffic loading did not have any apparent detrimental effects on the base. Within 48 hours, HMA (MDOT 13 A) was laid on top of the stabilized base.

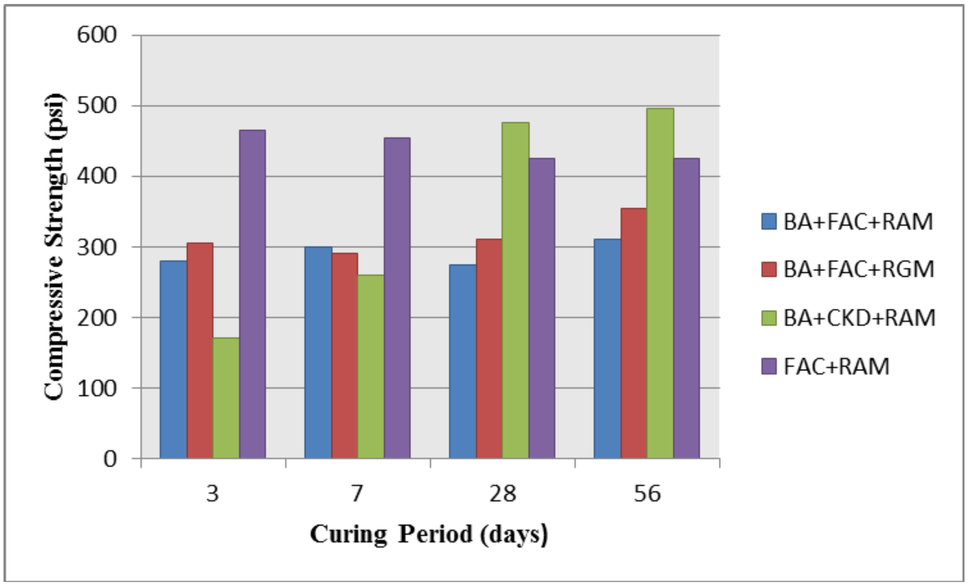


Figure 8-9: Average compressive strength at 3, 7, 28 and 56 days curing period for different composite mixtures. **Note:** 145 psi = 1 MPa

Figure 8-10 shows the reconstructed Marquette haul road after 3½ years of service. To determine the performance and the structural capacity of the Marquette haul road under traffic, distress identification surveys and FWD testing were conducted on all the test sections approximately 3½ years after reconstruction and four winter seasons. None of the sections exhibited rutting (using straight edge assessment) despite load differences from loaded dump trucks (westbound) going to the landfill and coming back (eastbound) empty, but this may become distinctive as the road ages. Reflective transverse cracking was generally observed in stabilized base areas that had a resilient modulus exceeding 300,000 psi (2,070 MPa). The cores at the cracks indicate that it is not a structural failure of the base material. Longitudinal cracks were generally observed at the center line of the road between differing base mixtures.

Longitudinal cracks were observed within the lanes at hilly areas where there are switch back curves, at intersections, and in the area where there is a higher frequency of heavy truck traffic from mining operations. The cracks were filled with sealer after the third winter season. It is evident that some extension cracks propagated after the fourth winter season. Table 8-4 shows the distress survey and resilient moduli test results.

Ten auger borings were completed with a truck mounted drill rig along the haul road in areas near the midpoint of the test sections or areas suspected of having shallow bedrock. Thicknesses of the pavement layers were measured. Bedrock depths exceeded 15 ft (4.6 m) except for borings within test sections EB6, WB3a, EB10a and WB5 which had an 11 ft (3.3 m) depth, and approximately 13.5 ft (4.1 m) in depth at sections EB2, WB2, and WB8. The flight auger soil samples were classified visually in general conformance with the Unified Soil Classification System (USCS).

A silt layer was observed at each boring location except in the area of EB10b. The depth to the saturated silt was recorded. The thickness of the silt layer ranged from 2 ft (0.6 m) thick to 12 ft (3.7 m) thick. Most of the test sections that had longitudinal and transverse cracking had saturated silt within 3 ft (0.9 m) of the pavement surface. The Marquette area typically has frost penetrating over 6 ft (1.8 m) under paved roads. Plant personnel observed heaving conditions in the areas of the shallow silt layer. No heaving was observed at the time of the distress condition survey and the FWD testing, and there was no observable frost remaining in the soil. It is very likely that the frost heave contributed substantially to the transverse and longitudinal cracking.

Figure 8-10: Reclaimed haul road with a HMA surface. (A) after one year, and (B) after four winter seasons.

FWD testing was performed by Engineering & Research International, Inc. (ERI). ERI performed FWD tests at a total of 241 points. A KUAB FWD was used in the test with a two-mass falling weight system to create a smoother rise of the force pulse on pavements with both stiff and soft subgrade. Deflections were measured by nine sensors. The test points were selected based on the sections length and with an intention to reduce the standard deviation of the test results. The FWD test points were equally spaced within the test sections except where cracks were encountered. A FWD survey was conducted in the eastbound and westbound lanes.

An elastic layer analysis was performed to back calculate the pavement layer moduli from the FWD test results by employing the ELMOD 6 software. The pavement temperature during the FWD test was recorded to be 45°F (7.2°C). The back calculated elastic moduli values for asphaltic concrete were corrected to a standard temperature of 70°F (21°C). The layer moduli were back calculated by assuming a three-layer pavement system. The three-layer system consisted of an asphalt bound layer, the base layer, and the subgrade layer. Iterations of the back calculations were performed to yield the lowest combination of standard deviations for the three layers. The bedrock depth did not influence the calculations. Figure 8-11 shows the average pavement layer modulus for the eighteen test sections. Based on the FWD test results, shown in both Table 8-4 and Figure 8-11, the subgrade layer in section EB 8 shows the comparably higher modulus of 25,553 psi (176 MPa) and EB 11 show the comparably lower modulus of 8,847 psi (61 MPa) within the project limit. As for the stabilized base course layer, section EB 6 shows the comparably higher modulus of 486,907 psi (3,357 MPa) and WB1 shows comparably the lower modulus of 41,397 psi (285 MPa). Finally, the asphalt concrete layer in section EB 3b and WB 3b show the comparably higher modulus of 485,480 psi (3,347 MPa) and EB 9a shows the comparably lower modulus of 133,434 psi (920 MPa).

The results (Table 8-4) show that FAC and CKD blended with RAM, RGM and BA improved the stiffness of the base in sections where they were used. The westbound lanes (loaded truck traffic) had moduli that were about 25% to 60% lower than the eastbound lanes (unloaded traffic). The unstabilized BA+RAM base had a higher than expected resilient modulus that warrants additional study. All the test sections had moduli values that were significantly higher than the conventional gravel base (EB11) except for WB1 as shown in Figure 8-12. It should be noted that WB1 did not exhibit any cracking or rutting.

Overall, the utilization of BA, FAC, CKD with the full depth reclamation process for soil stabilization demonstrated important benefits for the road construction industry. The construction of a stabilized base material (with a one pass process) attained high early strength development with minimal impact on traffic while also performing well for over 3½ years of service.

A typical cost for full depth reclamation ranges from $3.00 to $4.25 per square yard. The variation of the cost depends on the depth of pulverization, the amount of binders used, utilization of one or two pulverization passes, water truck requirements, the thickness of asphalt concrete being utilized without compromising the structural performance and finally the location of the road construction. Figure 8-13 shows a brief overview of the environmental benefits in utilizing full depth reclamation versus a new base.

TABLE 8-4: Distress Condition Survey and Mean Layer Modulus, April 2010

Section	Mix	Depth to saturated silt (ft)	Section Length (ft)	Distress Condition	Mean Layer modulus (psi)		
					AC	Base	Subgrade
EB7	BA+CKD+RAM	2.7	6441	Some LC, frequent TC	335,381	357,266	20,131
EB6	BA+FAC+RAM	2.0	859	Frequent LC and TC	431,252	486,907	20,000
WB 3a	BA+FAC+RAM	2.0	1825	Frequent LC and TC	333,595	314,095	18,398
WB 3b	BA+FAC+RAM	2.7	700	Some LC and frequent TC	485,480	224,444	18,664
EB 10a	BA+FAC+RGM	2.5	600	Some LC	172,479	135,685	9,431
EB 10b	BA+FAC+RGM	NS	1900	Some LC	469,378	106,332	13,027
WB 5	BA+FAC+RGM	2.7	1095	Some LC	292,330	81,043	11,405
EB 3b	BA+RAM	NA	2875	Some LC and frequent TC	485,480	224,444	18,664
EB 2	BA+RAM	4.4	100	No distress observed	207,782	258,994	18,334
EB 3a	BA+RAM	NA	100	Frequent LC and TC	306,440	247,554	14,077
WB 2	BA+RAM	4.4	1600	No distress observed	219,822	190,502	24,837
EB 1	BA+RGM	5.0	520	No distress observed	243,319	110,247	12,932
WB 1	BA+RGM	MUS	6441	No distress observed	339,070	41,397	21,898
EB 8	FAC+RAM	3.0	859	Frequent LC and TC	346,876	368,532	25,553
WB 8	FAC+RAM	5.0	2700	Frequent LC and TC	272,259	179,866	15,511
EB 9a	FAC+RGM	NA	2525	Some LC	133,434	106,080	10,979
EB 9b	FAC+RGM	NA	5000	Minor LC at center line	380,189	75,469	12,161
EB 11	RGM	NA	400	Some LC	216,426	53,509	8,847

Note: 145 psi = 1 MPa

Abbreviations

LC – Longitudinal cracking
TC – Transverse cracking
NA – No available information
NS – No silt layer
MUS – Moist unsaturated silt layer

BA – Bottom Ash
FAC – Class C Fly Ash
CKD – Cement Kiln Dust
RAM – Reclaimed Asphaltic Material
RGM – Recycled Gravel Material

AC – Asphalt

EB – East Bound
WB – West Bound

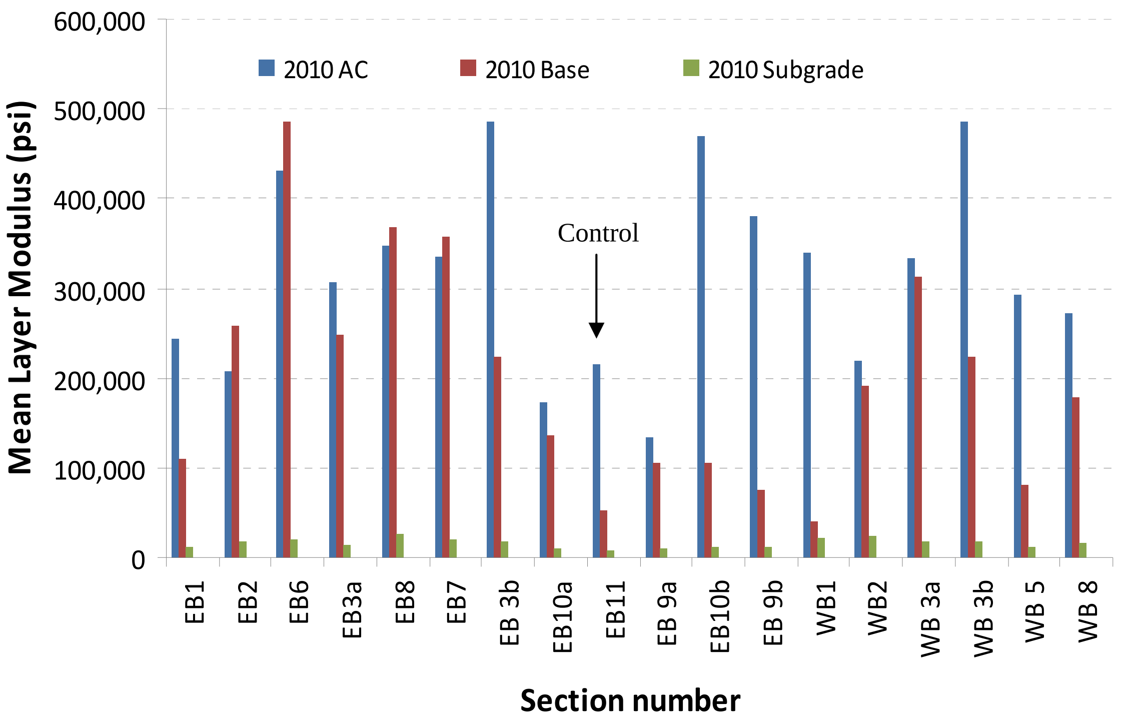


Figure 8-11: The Falling Weight Deflectometer (FWD) test results for the 18 test sections for the individual layer. See Table 8-4 for mixture composition for the individual section number.

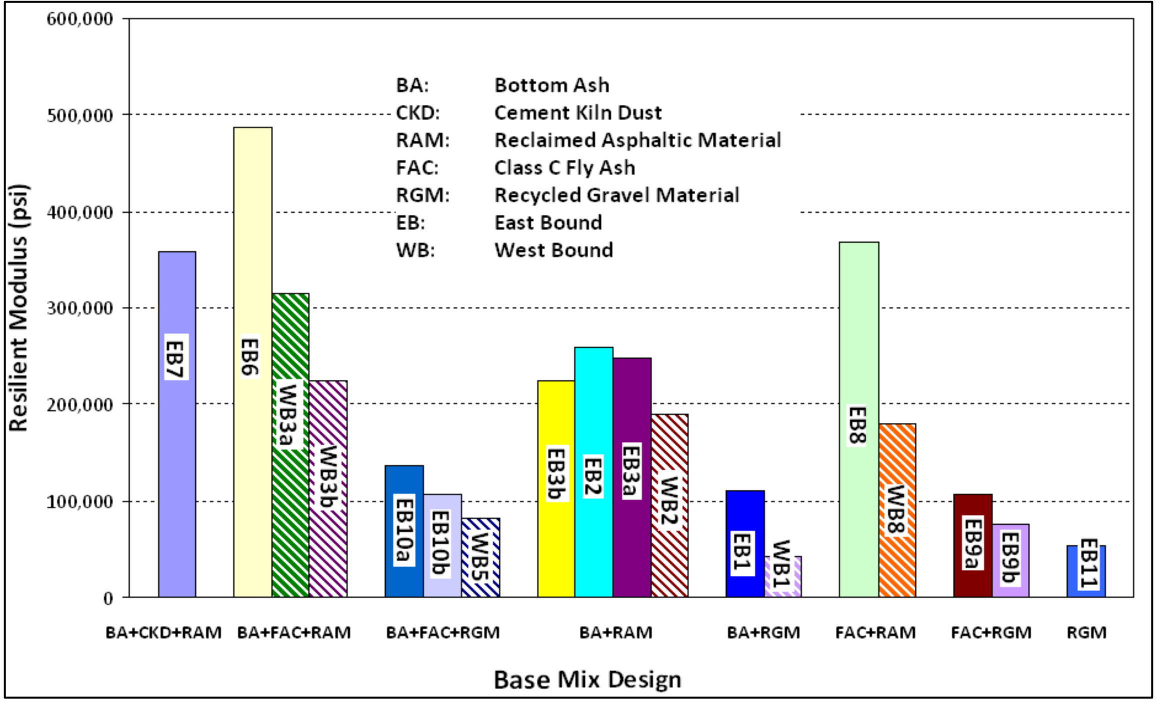


Figure 8-12: The FWD – Base layer test results for the 18 test sections.

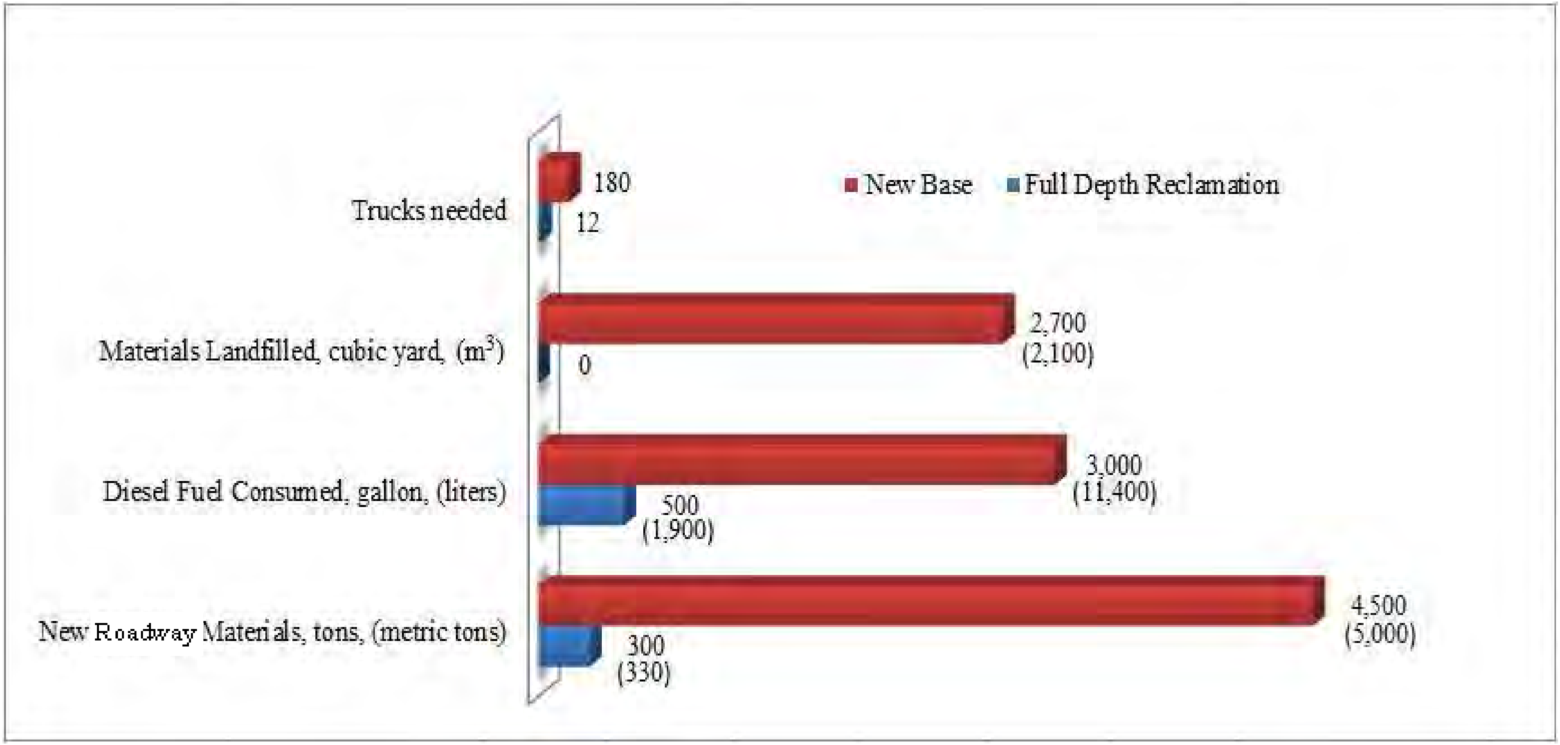


Figure 8-13: The environmental benefits of full depth reclamation (in-place asphalt recycling with self-cementing fly ash) vs. new base by comparing the use of energy and materials.

Note: The above statistics are based on 1 mile (1.6 km) of 24 foot (7.3 m) – width of 2-lane road, 6-inch (150 mm) base.

Chapter 9

Fly Ash Metal Matrix Composites

Introduction

Metal matrix composites (MMCs) are engineered materials formed by the combination of two or more materials, at least one of which is a metal, to obtain enhanced properties. MMCs tend to have higher strength/density and stiffness/density ratios, compared to monolithic metals. They also tend to perform better at higher temperatures, compared to polymer matrix composites.

Though MMCs have been in existence since the 1960s, their commercial applications have been limited due to their higher cost and lack of proper understanding. More developed MMCs, especially cast aluminum-fly ash composites, have shown the potential of being cost effective, ultra light composites, with significant applications (78). Such composites, if properly developed, can be applied for use in automotive components, machine parts and related industries.

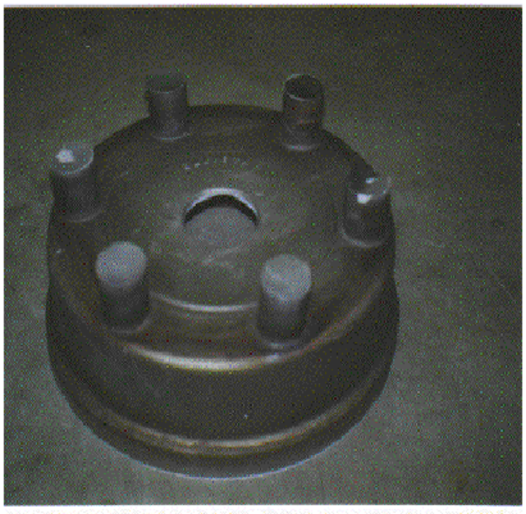


Figure 9-1: Brake drum cast with aluminum ash alloy material in Manitowoc, Wisconsin

Aluminum and magnesium are lightweight materials, when compared to iron and steel. However, they do not have the strength requirements necessary for several applications. Metal matrix composites manufactured by dispersing coal fly ash in common aluminum alloys improve mechanical properties such as hardness and abrasion resistance.

Processed fly ash is estimated to cost about $0.10 per pound (including the cost of mixing the ash into the aluminum melt). Aluminum alloy 380 costs approximately $0.70 per pound. An alloy blend containing 40% fly ash would cost about $0.50 per pound, compared to $2.40 to $2.60 per pound for similar conventional aluminum-silicon carbide composites (79).

Preparation of Ash Alloy Metal Matrix Composites

Ash alloy metal matrix composites can be prepared using various techniques. The following methods were studied at the University of Wisconsin-Milwaukee to prepare ash alloys using We Energies fly ash.

- Stir Casting
- Powder Metallurgy
- Pressure Infiltration

Stir Casting

Aluminum-silicon alloys (A356.2 and Al 6061) were used in this work which was conducted at the University of Wisconsin-Milwaukee. In the stir casting process, the alloy is melted at a controlled temperature and the desired quantity of fly ash is added to the molten aluminum alloy. The molten alloy is stirred continuously to create a vortex to force the slightly lighter particles into the melt. Stirring continues to disperse the fly ash particles as uniformly as possible in a short time.

The matrix is then transferred into a preheated and precoated transfer ladle. The material is stirred again and then poured into preheated permanent molds. It is then cooled, cut to shape, and surface cleaned.

Photomicrographs of aluminum alloy (A356.2), with a 10% volume of precipitator fly ash showed that fly ash particles tend to segregate along the aluminum dendrite boundary due to particle pushing. Fly ash particles tend to float to the top of the cast ingots due to their lower density. However, the distribution is reasonably uniform except for the top layer.

Powder Metallurgy

Commercially pure aluminum (99.9%) and We Energies fly ash were used in this work. Oven-dried at 110°C, aluminum and fly ash powders were well-blended by using a rotating drum. The amount of fly ash varied from 5 to 10 percent by weight in the mixtures.

Aluminum fly ash samples were compacted at different pressures (20,000 psi to 60,000 psi) using a uniaxial hydraulic press (80). Aluminum and aluminum fly ash compacts were sealed in a transparent silica tube under pure nitrogen and sintered at 625°C and 645°C for 2.5 and 6 hours at both temperatures.

The green density of the aluminum fly ash powder compacts increased with the increase in compacting pressure and decrease in fly ash content. Fly ash particles did not change shape significantly even when sintered at 625°C for 2.5 hours.

The morphology of aluminum powders changes during compaction due to plastic deformation. When the quantity of fly ash in the composite increased above 10% by weight, the hardness significantly decreased, and thus it was concluded that powder metallurgy did not seem very promising for producing ash alloy composite parts.

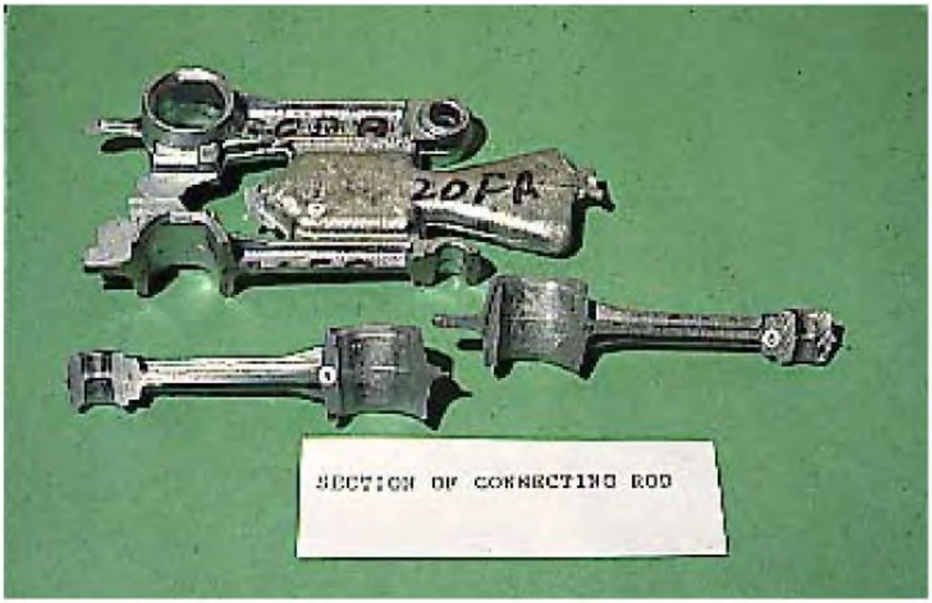


Figure 9-2: Connecting rods produced at the University of Wisconsin-Milwaukee with aluminum ash alloy material.

Pressure Infiltration

Commercial aluminum-silicon alloy (A356.2) and We Energies fly ash were used in this study. Preforms were prepared by mixing cenospheres and precipitator ash with MAP (mono-aluminum phosphate). The slurry was poured into a mold, dried at 204°C for 24 hours and then cured at 815°C for five hours. The preforms were placed in a graphite die followed by preheating at 815°C for two hours. The aluminum alloy was poured into the die at 840°C. A pressure of 1,500 to 2,500 psi was applied on top of the molten alloy for a period of 10 minutes.

When higher percentages of fly ash are used in ash alloy materials, the pressure infiltration casting technique is preferred. The distribution of fly ash particles is uniform in the pressure-infiltrated casting. The volume percentage of fly ash in the composite can be controlled by controlling the porosity in the fly ash preform, which can be controlled by adjusting the quantity of foaming agent in the preform. The pressure infiltration method gave better castings than the other techniques developed earlier.

Properties of Ash Alloy

In order to determine the suitability of fly ash composites in the manufacture of various automobile and other components, abrasive wear behavior and forging characteristics of composites containing We Energies fly ash were also studied at the University of Wisconsin-Milwaukee.

Abrasive Wear Behavior

Standard Al - 7Si casting alloy (A356) and We Energies fly ash were used in wear tests in the laboratory. Composites were prepared in the lab by stir casting containing 3% fly ash by volume, and composites were also prepared by the squeeze casting technique containing 56 % fly ash by volume. Wear tests were carried out on a FALEX machine. The details of the test procedure can be obtained from reference 80.

The study concluded that:

1. Fly ash improves the abrasive wear resistance of aluminum alloy. Specific abrasive wear rate of aluminum alloy with 3% fly ash composites was decreased with increasing load and increasing sliding velocity.
2. The aluminum alloy - 3% fly ash composite showed better resistance than the base alloy up to 24N.
3. Specific abrasive wear rates of the composite (aluminum alloy with 3% fly ash by volume) decreased with decreasing size of the abrading particles.
4. Friction coefficients of the above composites decreased with increasing time, load and size of the abrading particles.
5. Observation of wear surface and wear debris shows that fly ash particles in the composite tend to blunt the abrading SiC particles, thus reducing the extent of ploughing.

Forging Characteristics

The hot forging behaviors of Al 6061- fly ash composites were compared with that of the Al 6061 matrix alloys, Al 6061-20% (by volume) SiC and Al 6061 - 20% Al_2O_3 composites made by Duralcan and Comalco, respectively.

The Al 6061 - fly ash composites were made at the University of Wisconsin-Milwaukee using sieved precipitator fly ash particles obtained from We Energies and cenospheres from another source. The fly ash composites were made using the stir casting and squeeze casting techniques. Table 9-1 is a list of alloys and samples tested in the laboratory.

Table 9-1: Alloy Samples Tested in the Laboratory

No.	Type	Description
1.	Al 6061	Matrix alloy only
2.	Al 6061	20% SiC (14-20 um) Duralcan)
3.	Al 6061	20% SiC $A1_2O_3$ (14-20 um) (Comalco)
4.	Al 6061	5% Cenosphere fly ash (100 um)
5.	Al 6061	10% Cenosphere fly ash (100 um)
6.	Al 6061	10% Precipitator fly ash (44 - 75 um) squeeze cast
7.	Al 6061	20% Precipitator fly ash (44 - 75 um) squeeze cast
8.	Al 6061	30% Cenosphere fly ash (110 um) squeeze cast

Three-inch thick blocks were cut from the ingots and slightly turned to clean up imperfections. The blocks were then coated with either boron nitride or graphite paste to lubricate the ends.

The pieces were then forged in a 150-ton (1.34 MN) hydraulic press at a forging rate of 0.5 in/minute, under a vacuum of 13MPa (97508 torr). The forgings were made at The Ladish Co., Inc., in Milwaukee, Wisconsin. Table 9-2 lists the defects found in each forging.

The study at the University of Wisconsin-Milwaukee led to the following conclusions:

1. The A1 6061 fly ash composites containing 5% or 10% fly ash performed similar to the A1 matrix alloys containing no fly ash during forging.
2. All castings had porosity which affected forgeability.
3. The A1 6061 alloy containing 5% and 10% fly ash forged without cracking. Under similar conditions, A1 6061- 20% SiC and A1 6061- 20% A12O3 showed peripheral cracking. A1 6061- 20% fly ash composite showed some cracking. This may be due to non-uniform distribution of fly ash.
4. A1 6061- fly ash composites had significant segregations in the forgings due to segregations in the billets. Despite the non-uniformity in the microstructure, these composites can be forged.
5. The fly ash particles remained integrated to the alloy particles, showing good microstructure and no debonding. However, during forging some cenospheres collapsed leading to a layered structure of aluminum and collapsed cenospheres.

The University of Wisconsin-Milwaukee study suggests that We Energies fly ash can be used to make composites suitable for forging. However, additional work is being conducted to perfect this technology.

Table 9-2: Defects of Forging Samples Tested

Serial No.	Material	Forging Temperature F (C)	Initial Dimension Height/Dia. (mm)	Forged Thickness	Remarks
4199	Matrix alloy Al 6061	800 (427)	74.7/50.3	9.91	No cracking
4201		800 (427)			
4202	Duralcan Al 6061-20 Vol % SiC (14 - 20 µm)	800 (427)	69.9/50.5	10.9	All five forgings cracked quite severely under a strain greater than 80% forging strain
4203		800 (427)	72.6/50.5	10.7	
4205		800 (427)	72.6/50.3	11.2	
4206		800 (427)	74.4/50.5	11.4	
4211		800 (427)	68.1/50.3	11.4	
4207	Comalco Al 6061-20 Vol % Al_2O_1 (14 – 20 µm)	800 (427)	73.9/50.0	10.9	All four forgings cracked, more or less similarly o the Duralcan forgings
4208		800 (427)	73.7/50.0	10.7	
4209		800 (427)	81.2/50.5	11.7	
4210		800 (427)	68.8/50.5	11.4	
4189	UWM Al 6061-5 Vol % cenospheres fly ash (110 µm)	900 (482)	76.2/49.3	9.14	All three forgings are crack free
4190		900 (482)	73.7/50.3	9.14	
4198		800 (427)	76.2/50.0	10.2	
4186	UWM Al 6061-10 Vol % cenospheres fly ash (110 µm)	900 (482)	76.7/50.3	10.9	Both forgings are crack free
4188		900 (482)	75.9/50.0	9.65	
4194	UWM Al 6061-10 Vol % precipitator fly ash, squeeze cast (44 – 75 µm)	800 (427)	75.4/50.5	8.89	No transverse edge crack
4191	UWM Al 6061-20 Vol % precipitator fly ash, squeeze cast (44 – 75 µm)	900 (482)	45.7/50.5	11.9	A little cracking. However, the strain was about 75%

Cenospheres

Cenospheres are hollow, gas-filled glassy microspheres, which normally represent a small portion of fly ash. Cenospheres are formed when primarily CO_2 and N_2 fill the semi-molten material in a coal-fired boiler. Cenospheres are generally about 1-3% by weight of the total fly ash produced. They are generally gray to buff in color, inert, and primarily consist of silica and alumina. Cenospheres are hard and rigid, light, waterproof, and insulative. Due to their hollow structure, cenospheres have low density (e.g., some cenospheres have a density below 1 g/cm^3 and/or have a density as high as 2.9 g/cm^3 depending upon the degree of hollowness, the size and the wall thickness of cenospheres) as compared to solid fly ash particles with densities as high as 3.2 g/cm^3.

Cenospheres have valuable applications as fillers in the manufacture of paints, plastics, ceramics, adhesives, metal alloys, low density concrete, and lightweight composite materials such as syntactic foams. Cenospheres are also excellent thermal insulators, which is a direct result of their low density.

Cenospheres were harvested from fly ash by other electric power utilities utilizing wet separation methods in fly ash ponds. However, coal ash management regulations are currently under development by the United States Environmental Protection Agency that may eliminate wet handling and disposal methods, thus diminishing the supply of fly ash cenospheres to the market. This change has provided a potential economic opportunity for We Energies to develop processes for the separation of cenospheres using dry handling technologies. Furthermore, cenospheres in Class C fly ash (sub-bituminous coal) cannot be easily harvested using wet methods due to cementitious properties causing rapid solidification and hardening of the remaining fly ash. Therefore, dry separation methods would overcome this limitation on separating cenospheres from both bituminous and sub-bituminous based fly ash (U.S. Patent on “Separation of Cenospheres from Fly Ash”, 8,074,804 B2).

Identifying and Quantifying Cenospheres in Fly Ash (81)

We Energies has utilized methods using a stereomicroscope, polarized light microscopy and a Ferroscope to identify and semi-quantify cenospheres in fly ash samples.

In one method, fly ash samples were mounted on a slide with Fryquel, an organic liquid of known density and refractive index. Cenospheres were distinguished from the fly ash by their “bullseye” pattern (as shown in Figure 9-3), indicating a hollow particle. The quantification was based on volumetric optical classification rather than gravimetric measurements. This method allows for limited density separation of the fly ash particles on the slide and quantification of the density of the cenospheres particles with respect to the mounting fluid (Fryquel).

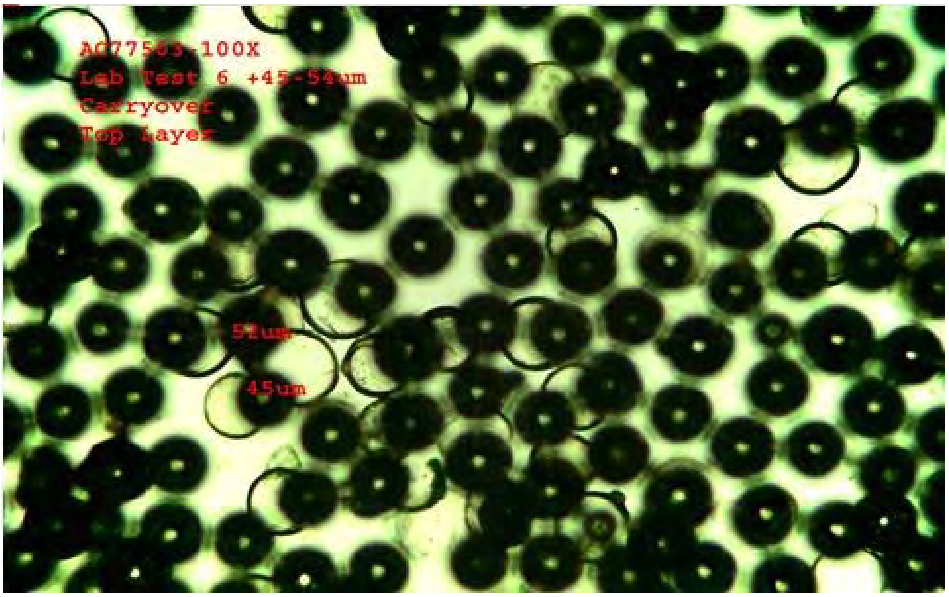


Figure 9-3: Using dry separation method, the “bullseye” pattern represents the cenospheres (hollow particle) in fly ash samples.

Sedimentation and centrifuging were also examined on a limited basis as an attempt to identify a simpler method to both separate and quantify the amount of cenospheres in a fly ash sample. Keep in mind that water cannot be used as a sedimentation fluid due to the reactivity of sub-bituminous fly ash (PPPP fly ash meets the Class C requirements of ASTM C-618) with water, as mentioned earlier. However, water was utilized successfully in centrifuge tests due to high dilution and the limited fly ash contact time. Other fluids were utilized in both sedimentation and centrifuging tests which included glycerin and synthetically derived heavy fluids.

Properties of Cenospheres in Pleasant Prairie Fly Ash

The observed particle size distribution of cenospheres in fly ash from PPPP is summarized in Table 9-3. The data shows that particle size distribution (measured in volume) can vary from sample to sample. The size range is based on the cenospheres alone. In other words, if 20% by volume of the 09/22/2008 sample shown on Table 9-3 contained cenospheres and 40% are in the 10-30 micron range, then the total fly ash sample contained 8% cenospheres in the 10-30 micron range.

Table 9-3: Particle Size Distribution of Cenospheres in PPPP Fly Ash

Particle Size Range (microns)	Sample Collected 09/22/2008 10-20% Cenospheres (by volume)	Sample Collected 09/06/2010 3-5% Cenospheres (by volume)
< 10	10%	2%
10 - 30	40%	90%
30 - 40	30%	5%
> 40	20%	5%

The cenospheres produced at other power plants are being marketed worldwide within the size ranges of 10 to 600 microns. Most of the size ranges being marketed are above 70 microns. As seen in Table 9-3, the cenospheres from PPPP fly ash are smaller than most of the cenospheres and have the highest concentration in the 10 to 30 micron size range. The larger size cenospheres are a reflection of the floatation separation method which limits collection to particles that float on water. Smaller hollow particles are less buoyant due to a smaller volume of encapsulated gases. The cenospheres in Class C fly ash are much smaller with diameters as small as one micron, which are anticipated to have greater utility and value.

The density of cenospheres was previously assumed to be less than 1 g/cm^3, because they have been only harvested by wet methods. Recent observations have shown cenospheres with particle densities greater than 1 g/cm^3, via transmission optical microscopy. The density of cenospheres in PPPP fly ash has been observed to vary from approximately 0.6 g/cm^3 to 2.9 g/cm^3, with density largely dependent upon the wall thickness of the particle.

The distribution of cenospheres in fly ash captured at various points within the electrostatic precipitators at PPPP was also evaluated. Fly ash captured in the inlet section of the precipitators had a greater percentage of cenospheres and a wider particle size distribution than fly ash and cenospheres captured in the outlet section of the precipitators. This suggests that fly ash from the inlet section of precipitators may be targeted to maximize cenospheres content and particle size distribution. However, such segregation of fly ash from inlet versus outlet hoppers may be impractical during routine power plant operation and the relatively small quantity of fly ash collected in the outlet hoppers.

Since little has been done in characterizing the variability of cenosphere size concentration and properties within PPPP fly ash and other power plants, We Energies concentrated on the fly ash cenospheres from PPPP. This way the variations in coal sources, combustion processes and NO_x control additives would be one less concern on the impact of the effectiveness of the dry separation technologies that are being evaluated for a large scale process. Also it is generally understood that reburning fly ash at PPPP enriches the concentration of cenospheres since the previously burned fly ash particles bloat when injected and fired in the furnace a second time.

Recovery of Cenospheres from Fly Ash (US Patent 8,074,804 B2) (82)

Cenospheres can be recovered from fly ash by several methods, all of which take advantage of cenospheres' low density property. Some of these methods include addition of fly ash to a pond of water, and skimming off cenospheres from the water surface, dry screening of fly ash into coarse and fine particles followed by addition of water to the coarse particles, skimming off cenospheres from the water surface, and drying and storage (U.S. Patent No. 4, 652, 433).

These processes do have disadvantages. For example, these methods only collect cenospheres with a density of less than 1.0 g/cm^3 as only cenospheres of these densities float on water. Also, the fly ash that is produced from burning subbituminous western coal includes significant amounts of calcium compounds. For example, fly ash may include 10% or more lime. High calcium fly ashes such as ASTM C-618 Class C fly ash have cementitious properties and therefore, when mixed with water can rapidly harden and the remainder cannot then be easily saved for other purposes such as for use as a cementitious material in the production of concrete. In the case of Class F fly ash, a dry method is also appropriate because it provides the advantage of not expending energy to dry the remainder after separation of cenospheres for other uses. Another disadvantage is that many cenospheres are entrapped in agglomerated and/or hardened masses before floatation occurs. These methods also do not allow the recovery of cenospheres of controlled sizes and densities. As a result, the properties of polymeric composites that include cenospheres cannot be optimized due to the lack of availability of cenospheres with narrowly controlled sizes and densities.

In the We Energies dry process to recover cenospheres from fly ash, size separation followed by the density separation (or vice versa) with methods such as air classification, dynamic air classification, conventional vibratory screening, ultrasonic screening, fluidized bed classification, or a combination of these methods are used.

Air Classification or Fluidized Density Separation

This process involves using a dynamic centrifuge to separate cenospheres from fly ash by density and separation into narrow size fractions. First, the ultrafine fractions of the particles are screened out (which have less cenospheres) using a Micron Air Jet Sieve with 38 or 45 microns sieve (73.40% or 85.68% passing, respectively). The coarser fraction can be classified by mechanical screening and air jetting using a Hosokawa Air

Classifier for narrow size ranges. The final classification screening would separate the hollow cenospheres from the fine solid fly ash particles. However, ultrafine fly ash contamination (ie., < 25 microns) was still observed retaining in the various sieve screens utilized to separate the fly ash into narrow size fractions due to agglomeration of the ultrafine fly ash by static charges induced during handling.

Density Classification

This process involves first separating fly ash in terms of density, followed by screening to separate the hollow from the solid particles with a further benefit of establishing narrow particle size ranges.

Use of Microscopy for Identification of Cenospheres

Cenosphere particles are identified by first spreading the particles on a layer of fluid. This is followed by viewing the particles under a light microscope. The particles having a central "bullseye" area are hollow (See Figure 9-3). The total number of particles in the sample are then counted. A ratio of the number of hollow particles to the number of all particles in the sample is then calculated to provide a percentage of cenospheres identified in the sample.

Using various methods of dry separation of cenospheres conducted at a lab-scale (detailed description of the methods in U.S. Patent 8,074,804 B2) resulted in a conclusion that a single step fluidized bed or other classification process is not likely to lead to the separation of cenospheres due to the overlap in size of solid and hollow particles of the same weight of fly ash, and the wide variation in density combined with a tendency to agglomerate. However, fluidized bed classification (density separation) after size separation into different narrow size fractions by screening did yield both solid fly ash and hollow cenospheres particles. The narrow size fraction recovered high volume percentages (above 90%) of cenospheres. Additionally, the usage of transmitted light and reflected light microscopy work, heavy media density separation, centrifugal and settling work quantified the size, weight or volume percentage and density of cenospheres during the different separation processes. With the heavy media density separation, the resulted cenospheres revealed higher densities of up to 2.9 g/cm^3 when compared to the usual density less of than 1.0 g/cm^3 as they were separated by floatation in water.

Applications of Cenospheres in Manufacturing Products

Cenospheres have been used for more than 30 years and were first used in the United States as an extender for plastic compounds, as they were found to be compatible with plastisols, thermoplastics, latex, polyester, epoxies, phenolic resins, and urethantes. Cenospheres are primarily used to reduce the weight of plastics, rubbers, resins, cements, extensively used as filler lubricants in oil drilling operations under high heat and high stress conditions, and also used in oil well cementing, mud putty and similar applications. The application of cenospheres in gypsum board jointing compounds, veneering plasters, stuccos, sealants, coatings and cast resins take advantage of reducing the material's weight, increasing filler loadings, providing better flow characteristics, less shrinkage and reduced water absorption.

Listed below are some of the various applications where cenospheres are extensively used:

Ceramics: Refractories, Castables, Tile, Fire Bricks, Aluminum Cement, Insulating Material and Coatings

Plastics: BMC, SMC, Injection Molding, Moulding, Extruding PVC Flooring, Film, Nylon, High density Polyethylene, Low Density Polyethylene, Polypropylene.

Construction: Specialty Cements, Mortars, Grouts, Stuccos, Roofing Material, Acoustical Panels, Coatings, Shotcrete, Gunite

Recreation: Marine Craft Floatation Devices, Bowling Balls, Surf Boards, Kayaks, Golf Equipment, Footwear, Lawn and Garden Décor.

Automotive: Composites, Undercoating, Tires, Engine Parts, Brake Pads, Trim Mouldings, Body Fillers, Plastics, Sound Proofing Materials.

Energy & Technology: Oil well Cements, Drilling Muds, Industrial Coatings, Grinding Materials, Aerospace Coatings & Composites, Explosives, Propeller Blades.

Concrete Countertops (new and growing application): Cenospheres being a lightweight aggregate and its variability in particle sizes, it can replace the normal-weight and size of the sand used in the concrete. For example, one pound of cenospheres is equivalent to the same absolute volume of about 3.8 pounds of sand. Additionally, it enhances the workability when these small spherical particles act like microscopic ball bearings in the concrete mixture and due to its spherical structural shape, the cenospheres improve the concrete's density and strength by providing better packing. Finally, cenospheres can be a bulk filler where they can be used in cement grout slurry to replace other ingredients. Therefore, not only the grout increases in volume with cenospheres, the fine aggregate gradation of the particles also helps to reduce shrinkage.

We Energies, along with the Electric Power Research Institute (EPRI) and several other agencies, have been funding research projects aimed at developing technology for manufacturing ash-alloy automobile components. Moreover with the invention of dry methods to separate the cenospheres from fly ash and provide both larger quantities and a wider variety of qualities; the future applications in composite materials look promising.

We Energies holds patents for manufacturing methods with ash-alloy (U.S Patent 5,897,943 and 5,711,362). The first step of one method is to prepare a solid, porous, reinforcing phase preform combined with an aqueous medium comprising a binder, such as sodium silicate and polyvinyl alcohol. The ratio of the reinforcing phase to aqueous medium ranges is from 1:1 to 3:1. The ratio of binder to water in the aqueous medium generally ranges from 1:1 to 1:9, more usually 1:1 to 1:2. Following introduction into the mold, the slurry produced by the combination of the aqueous medium and reinforcing phase is dried to produce a porous, reinforcing material preform at temperatures ranging from 194°F to 482°F for one hour or two. The molten metal is then infiltrated into the porous preform by pressure ranging from about 2000 to 2500 psi. After infiltration, the resultant metal matrix composite is cooled using air drying or low temperature.

Ash alloys containing a volume of over 40% hollow cenospheres are extremely light. It is possible to develop magnesium composites with the density of plastics by proper addition of cenospheres and the use of controlled processes.

The metal matrix composites are produced with an excess of 50% of reinforcing phase. The reinforcing phase is comprised of fly ash combined with an aqueous medium comprising a binder to produce slurry. The slurry is then dried to produce a solid, porous, reinforcing phase preform. Molten metal is then introduced into the preform, resulting in metal matrix composites.

For fly ash preforms, both cenosphere fly ash (density <1) and precipitator fly ash (density >1) were combined with monoaluminum phosphate solution (MAP solution) to produce a pourable slurry for the preparation of aluminum-fly ash metal matrix composites. The preparation used was the squeeze casting or pressure infiltration technique as mentioned above. From the resultant aluminum-fly ash composites, the fly ash was evenly distributed throughout the composite with a percentage of 60% fly ash.

When in preparation of lead-fly ash composites, 40% in volume, cenosphere fly ash was used and the resultant characteristics have shown that the hardness of the material significantly increased and decreased in density compared to a pure lead composite. The cenosphere's density is 0.48 g/cm^3 and lead density is 11.27 g/cm^3, and the observed density of lead-40 volume percent cenosphere composite was 7.75 g/cm^3.

Extended corrosion tests were conducted for a period of 470 days on lead-fly ash (cenospheres) composites to determine the applicability for use in batteries. 13 mm diameter rods of lead-fly ash specimens were immersed in the electrolyte to a depth of 7.5 mm. The anode specimens were immersed in 5M sulphuric acid and subjected to electrical potentials controlled to stimulate the condition of a lead-acid battery anode under stand-by conditions. All specimens were subjected to the same constant applied potential where the measurements were performed at ambient room temperature of 20ºC. The current readings for each cell were taken every 24 hours. Observed measurements of current densities of several lead samples and lead-fly ash composites showed close proximity to each other. It was concluded that there may be a little higher corrosion current in the fly ash composites in initial stages due to acid exposure of some surface fly ash particles, but, over time the corrosion current decreased. However, in long term exposure at room temperature, the anode corrosion behavior of lead-fly ash composites was as least equal to, if not better than, pure lead samples. This has shown a potential use in lead-lite batteries (US Patent 5,711,362).

Since the development of new methods of producing metal matrix composites involves reinforcing phase preforms (comprising of fly ash – cenospheres), the percentage of reinforcing material and metal in the composite can be readily controlled, the distribution of the reinforcing phase throughout the matrix can be controlled, the strength of the composite can be enhanced, and the shape of the composite can be readily controlled through the shape of the preform resulting in a wide range of potential applications.

Advantages of Using Ash Alloys

The significance of developing and marketing ash alloys can be fully understood only if we consider the overall benefit to various industries and to the environment. The process of developing an ash alloy matrix with excellent properties is very involved, expensive and lengthy. The following are a few of the benefits that hold promise in providing a significant impact on the community:

1. **Economics:** Ash alloys are at least 10-30% lower in cost than other alloys available in the market. Hence, foundries and auto part manufacturers can potentially realize significant savings that can be shared with consumers.
2. **Reduced Energy Consumption:** With a projected annual displacement of 225,000 tons of aluminum with ash, the savings in energy costs for aluminum production is about $156 million annually.
3. **Availability of Lightweight Material:** The U.S. auto industry has a goal to reduce vehicle weight. Ash alloys are significantly lighter when compared to steel.
4. **Improved Gas Mileage:** Due to the projected significant weight reductions, the gas mileage of U. S. vehicles will improve and the savings will be significant. The Department of Energy's Light-Weight Materials Program has predicted that a 25% weight reduction of current vehicles would result in a 13% (750,000 barrels/day) reduction in U.S. gas consumption.

5. **Avoided Ash Disposal Cost:** Electric utilities generate approximately 60 million tons of coal fly ash per year, which are landfilled. If fly ash can be sold as a metal matrix filler, utilities would avoid disposal costs and simultaneously generate revenue from the sale of ash. The anticipated market value of processed fly ash is $100/ton.
6. **Reduced Greenhouse Gases:** Greenhouse gases are produced during the two stages of aluminum production; bauxite processing and alumina reduction. Carbon dioxide (CO_2) and perfluorocarbons (PFCs) are generated in significant amounts during these processes. Decreasing the production of aluminum or other metals by fly ash substitution will significantly reduce the production of these gases. CO_2 emissions would also be reduced by approximately 101 million tons per year.
7. **U.S. Competitiveness:** The U.S. auto parts manufacturers are losing market share to overseas competitors who benefit from low-cost labor. The competitive edge of the United States is its research and development facilities and technical expertise. Development and commercial use of a superior ash alloy matrix at less than half the cost of conventional materials can boost the competitive edge of U.S. parts manufacturers.

These benefits are not limited to the automotive industry. The commercial applications of lighter weight materials, if adapted, can benefit foundries, manufacturers, transportation, construction, electrical and consumer goods industries.

Chapter 10

Environmental Considerations of We Energies Coal Combustion Products and Regulatory Requirements

Introduction

Fly ash and bottom ash consist primarily of residual inorganic components in coal that are not vaporized or emitted as volatile gases when coal is burned. The ash contains smaller amounts of other non-combustible constituents that are not inorganic such as small amounts of unburned coal. The most common mineral elements found in coal ash in the form of oxides are primarily silicon, aluminum, iron and calcium (60). During coal combustion, FGD residue is produced during the SO_x removal process from generated gases. Even though FGD residue does not contain significant quantities of heavy metals, mixing with fly ash can contribute trace elements such as boron, arsenic and selenium to the material making its utilization more challenging. We Energies has employed FGD systems after the fly ash is collected.

Oxidation takes place in the furnace due to the heat of combustion. Coal ash contains trace quantities (in the parts-per-million/billion range) of many other naturally occurring elements in their oxidized form. Coal ash composition and mineralogy, including trace element contents, vary primarily based on the source of coal and the combustion conditions.

The major chemical constituents of both fly ash and bottom ash obtained from the same power plant are essentially the same. However, the availability of minor and trace elements can vary between fly ash and bottom ash. The chemistry of coal ash is very similar to many naturally occurring soils and natural aggregates. The availability of trace elements from all of these materials is directly related to the particle size. Therefore, the leaching potential of fine fly ash is higher than sand to gravel size bottom ash due to the exponentially higher total surface area available in samples of the same mass.

After reviewing research work on the environmental and health risks associated with coal ash utilization, the U.S. EPA determined that coal ash is nonhazardous in 2000. Current Wisconsin and Michigan regulations require lined landfills with leachate collection, covers and a network of monitoring wells when either fly ash, bottom ash and/or FGD material (gypsum or filter cake) is placed in solid waste disposal sites or other non-contained applications to prevent trace elements from reaching drinking water sources. The use of a respirator is also recommended when handling dry fly ash, which is the same for other finely divided siliceous materials.

Precautions are generally taken to prevent ash from blowing or dusting during handling. We Energies material safety data sheets (MSDS) for coal ash and gypsum are included in Appendix A

The utilization of CCPs has several benefits. For example, the controlled emissions from a typical cement plant producing 245,000 tons of cement (which is similar to the quantity of We Energies fly ash used as a cementitious material) are 12,000 lbs. of HCl; 54 lbs. of Hg; 220 lbs. of HF; 171 lbs. of Pb; and 49 lbs. of Se. This is in addition to approximately one ton of CO_2 emissions for every ton of cement produced.

Hence, if the entire 245,000 tons of cement is replaced by Class C fly ash (produced anyway from coal combustion), we are reducing CO_2 emissions that would otherwise be released into the atmosphere by 490,000,000 pounds. About 11 million tons of greenhouse gas emissions were avoided by using coal ash to replace cement in 2010 alone (ACAA, December 13, 2011). This is a large step in reducing greenhouse gas emissions and preserving our virgin raw materials for future generations (sustainable development).

Chemical Elements in Coal Ash

Coal ash contains many of the naturally-occurring elements, most of them in trace quantities. Table 10-1 gives the list of commonly found elements in coal ash.

Table 10-1: Chemical Elements in Coal Ash

Group 1 (Major) 25% to 1%	Group 2 (Intermediate) 1% to 10 ppm	Group 3 (Minor) 50 to 5 ppm	Group 4 (Minor) 10 ppm to BDL	Group 5 (Usually Minor) 100 to 1 ppm
Silicon	Barium	Silver	Mercury	Carbon
Aluminum	Strontium	Arsenic	Chloride	Cesium
Iron	Manganese	Cadmium	Fluoride	Rubidium
Calcium	Boron	Chromium	Selenium	Germanium
Magnesium	Molybdenum	Copper	Beryllium	Tin
Sodium	Vanadium	Nickel	Antimony	Cobalt
Potassium	Sulfur	Lead	Uranium	Gold
Titanium	Phosphorus	Zinc	Thorium	Platinum

The type and quantity of trace elements in the ash primarily depends on the source of coal. The presence of trace elements in coal ash is a reason that good judgment is required for utilization especially when considering new applications. Many states have regulations that provide guidelines for safe utilization practices.

Leaching From Coal Ash Land Applications

We Energies fly ash, bottom ash and FGD material (FGD gypsum and filter cake) have been successfully used in several varieties of land applications. FGD gypsum is used for wallboard material for construction, cement manufacturing and as a soil amendment in agriculture. FGD filter cake can be used as an admixture for road base material but recently, it is being stored for future landfill construction applications. Bottom ash is commonly used as a replacement for conventional sand, gravel and crushed stone base material for roads, parking areas and building floor slabs, structural fill, backfill, in manufactured soils and recently as a fine aggregate for EcoPads. Fly ash is also sometimes used in the production of CLSM, for soil stabilization, cold in-place recycling (FDR) of asphalt pavements, and as a raw feed material for the production of Portland cement.

We Energies performs total elemental analysis by the Test Method for Evaluating Solid Waste Physical/Chemical Methods (SW-846) and Proton Induced X-ray Emission Spectroscopy (PIXE) methods and leaching tests of ash samples in accordance with the ASTM distilled water method (ASTM D-3987). These tests are used to assess the elemental composition and leaching potential of the ashes as well as to categorize each combustion product source for permitted applications under the State of Wisconsin rules.

The Wisconsin Department of Natural Resources (WDNR) adopted NR 538 in January, 1998, with the purpose of encouraging the beneficial use of industrial by-products. NR 538 also requires generators to provide certification information on their by-products to the WDNR. The results of the total elemental analysis by SW-846 and PIXE methods on We Energies fly ash, bottom ash and FGD material are shown in Tables 10-2, 10-4 and 10-6, respectively. The results of the ASTM D-3987 extraction analysis on We Energies fly ash, bottom ash and FGD material are shown in Tables 10-3, 10-5 and 10-7. NR 538 has defined limits for several categories of industrial by-products based on the concentration of certain specified parameters.

There are five categories in total with Category 1 having the lowest concentration of the listed parameters. Category 1 by-products also have the lowest level of regulatory requirements in terms of beneficial utilization. It can be seen from the following tables that the concentration of elements leaching from fly ash, bottom ash and FGD material is very low. We Energies fly ash, bottom ash and FGD materials contain only very limited quantities of the trace elements.

Most of these parameters meet the requirements set for Category 1 or Category 2 material. The WDNR can grant an exemption to be classified in a particular category if the concentration of one or two elements is slightly in excess of the set limits. However, this is done on a case-by-case basis. If no exemptions are granted, We Energies bottom ash is primarily a Category 2 material and FGD gypsum and fly ash are primarily Category 4 materials (with a few exceptions for both fly ash and bottom ash).

Table 10-2: NR 538 Fly Ash Analysis – Bulk Analysis Data Summary (2010)

Parameter	Units	NR 538 Category 1 Standard	NR 538 Category 2 Standard	VAPP Flyash AD30995	PIPP 5 & 6 Flyash AD30996	PIPP 7-9 Flyash AD03997	OCPP Flyash AD30998	PPPP Flyash AD30999	ERGS Flyash AD31000
Antimony	ppm	6.3		1.2	2	1.8	1.7	2.8	4.1
Arsenic	ppm	0.042	21	**4**	**7.9**	**17**	**11**	**21**	**83**
Barium	ppm	1100		810	**1400**	**6100**	**5800**	**4800**	**290**
Beryllium	ppm	0.014	7	**1.6**	**2.7**	**3.3**	**4.1**	**4.3**	**5.3**
Boron	ppm	1400		440	670	550	590	780	390
Cadmium	ppm	7.8		0.17	0.31	1.4	1	1.9	0.56
Chromium, Hexavalent	ppm	14.5		0.4	0.96	**24**	**19**	**25**	2.4
Lead	ppm	50		6.2	16	22	31	40	27
Mercury	ppm	4.7		0.11	0.24	0.0014	0.38	0.24	0.096
Molybdenum	ppm	78		3.8	6.2	8.5	7.8	12	11
Nickel	ppm	310		13	18	41	48	58	68
Thallium	ppm	1.3		0.22	0.44	0.81	0.5	0.55	**3.2**
Vanadium	ppm	110		39	63	**160**	**180**	**240**	**180**
Zinc	ppm	4700		17	38	96	120	110	88
Acenaphthene	ppm	900		0.0058	0.0091	<0.0023	<0.0023	<0.0023	<0.0024
Acenaphthylene	ppm	8.8		<0.0027	<0.0027	<0.0027	<0.0027	<0.0027	<0.0027
Anthracene	ppm	5000		<0.0039	<0.0039	<0.0039	<0.0039	<0.0039	<0.0039
Benzo(a)anthracene	ppm	0.088	44	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024
Benzo(a)pyrene	ppm	0.0088	4.4	<0.0027	<0.0027	<0.0027	<0.0027	<0.0027	<0.0028
Benzo(b)fluoranthene	ppm	0.088	44	<0.0029	<0.0029	<0.0029	<0.0029	<0.0029	<0.0029
Benzo(g,h,i)perylene	ppm	0.88		<0.0022	<0.0022	<0.0022	<0.0022	<0.0022	<0.0022
Benzo(k)fluoranthene	ppm	0.88		<0.0031	<0.0031	<0.0031	<0.0031	<0.0031	<0.0031
Chrysene	ppm	8.8		<0.0030	<0.0030	<0.0030	<0.0030	<0.0030	<0.0031
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0046	<0.0045	<0.0045	<0.0045	<0.0045	<0.0046
Fluoranthene	ppm	600		<0.0084	<0.0083	<0.0083	<0.0084	<0.0083	<0.0084
Fluorene	ppm	600		<0.0042	<0.0041	<0.0041	<0.0042	<0.0041	<0.0042
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024	<0.0024
Methylnaphthalene 1	ppm	8.8		<0.0026	<0.0025	<0.0025	<0.0026	<0.0025	<0.0026
Methylnaphthalene 2	ppm	8.8		<0.0026	<0.0025	<0.0025	<0.0026	<0.0025	<0.0026
Naphthalene	ppm	600		<0.0029	<0.0029	<0.0029	<0.0047	<0.0029	<0.0029
Phenanthrene	ppm	0.88		<0.0037	<0.0037	<0.0037	<0.0037	<0.0037	<0.0037
Pyrene	ppm	500		<0.0031	<0.0031	<0.0031	<0.0031	<0.0031	<0.0031
Total PAH's	ppm		100	0.0058	0.0091	<0.059	0.0047	<0.059	<0.060

NR 538 Table 1B exceedances are highlighted in ***bold*** type

Table 10-3: NR 538 Fly Ash Analysis – ASTM D-3987 Leachate Test Result Summary (2010)

Parameter	Units	NR538 Category1 Standard	NR538 Category 2&3 Standard	NR538 Category 4 Standard	Extraction Blank AD31337	VAPP Flyash AD31338	PIPP 5&6 Flyash AD31339	PIPP 7-9 Flyash AD31340	OCPP Flyash AD31341	PPPP Flyash AD31342	ERGS Flyash AD31343
Aluminum	mg/l	1.5			<0.0084	**5.5**	**16**	**56**	**29**	**72**	**10**
Antimony	mg/l	0.0012	0.012		<0.00030	**0.0029**	**0.0079**	**0.0012**	<0.00030	0.00058	**0.013**
Arsenic	mg/l	0.005	0.05		<0.00044	0.0016	0.0028	0.00092	<0.00044	<0.00044	**0.044**
Barium	mg/l	0.4	4		<0.00052	**1.4**	**1.4**	**1.5**	**42**	**9.1**	0.1
Beryllium	mg/l	0.0004	0.004		<0.000022	0.000041	<0.000022	<0.000022	0.00013	0.00005	0.000046
Boron	mg/l	0.19	1.9	4.8	<0.0016	**7**	**41**	0.11	**3.5**	**0.2**	**8.1**
Cadmium	mg/l	0.0005	0.005	0.025	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019
Chloride	mg/l	125			<0.025	1	2.3	3.1	0.13	<0.025	0.32
Chromium - Total	mg/l	0.01	0.1	0.5	0.00067	0.0083	**0.039**	**0.46**	0.00078	**0.15**	**0.047**
Copper	mg/l	0.13			<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	0.0018	<0.0013
Iron	mg/l	0.15			0.0027	0.006	0.0078	0.022	0.018	0.019	0.0087
Lead	mg/l	0.0015	0.015		<0.00024	<0.00024	<0.00024	<0.00024	0.00048	<0.00024	<0.00024
Manganese	mg/l	0.025	0.25		0.00022	0.00014	0.00014	0.00034	0.00044	0.00033	<0.000095
Mercury	mg/l	0.0002	0.002		<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072
Molybdenum	mg/l	0.05			<0.00090	**0.074**	**0.16**	**0.2**	0.0012	**0.13**	**0.31**
Nickel	mg/l	0.02			<0.0016	<0.0016	<0.0016	<0.0016	<0.0016	<0.0016	<0.0016
Nitrate-Nitrite as N	mg/l	2			<0.04	<0.04	<0.04	<0.04	0.04	0.05	<0.04
Selenium	mg/l	0.01	0.1	0.25	<0.0047	**0.081**	**0.13**	**0.046**	<0.0047	<0.0047	**0.033**
Silver	mg/l	0.01	0.1	0.25	<0.00043	<0.00043	0.00047	0.0021	**0.012**	0.0044	<0.00043
Sulfate	mg/l	125	1250	2500	<0.05	88	120	**260**	<0.05	11	**640**
Thallium	mg/l	0.0004	0.004		<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	**0.00069**
Vanadium	mg/l				<0.00051	0.018	0.051	0.081	<0.00051	0.0081	0.087
Zinc	mg/l	2.5			0.0021	<0.0021	<0.0021	<0.0021	0.0022	<0.0021	<0.0021

Note: A value highlighted in *bold* exceeds the NR 538 Category 1 Standard

Table 10-4: NR 538 Bottom Ash Analysis – Bulk Analysis Data Summary (2010)

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	MCPP Mixed Ash AD31001	VAPP Bottom Ash AD31002	PIPP 5-6 Bottom Ash AD31003	PIPP 7-9 Bottom Ash AD31004	OCPP 5&6 Bottom Ash AD31005	OCPP 7&8 Bottom Ash AD31006	P4 Bottom Ash AD31007	ERGS Bottom Ash AD31008	P4 Recovered Ash 07-02-10 AD31009	P4 Recovered Ash 08-02-10 AD31010	P4 Recovered Ash 08-11-10 AD31011	P4 Recovered Ash 08-19-10 AD31012	P4 Recovered Ash 08-25-10 AD31013
Antimony	ppm	6.3		1.2	0.27	0.26	0.38	0.55	0.41	0.44	0.21	0.5	0.55	0.58	0.48	0.5
Arsenic	ppm	0.042	21	**5.5**	**0.79**	**1.3**	**3.6**	**4**	**3.5**	**4.9**	**3.8**	**5.8**	**6.8**	**6.9**	**5.8**	**5.7**
Barium	ppm	1100		720	210	480	**3400**	**3500**	**3500**	**2700**	120	**3100**	**2800**	**3000**	**3100**	**2700**
Beryllium	ppm	0.014	7	**1.2**	**0.52**	**0.9**	**1.9**	**3**	**2.9**	**2.6**	**1.5**	**2.7**	**2.4**	**2.6**	**2.5**	**2.3**
Boron	ppm	1400		240	72	100	170	330	290	240	48	280	260	260	260	240
Cadmium	ppm	7.8		0.71	<0.021	0.22	0.4	0.27	0.16	0.36	<0.021	0.4	0.88	0.84	0.9	0.44
Chromium Hexavalent	ppm	14.5		0.56	<0.060	0.091	0.2	3.8	3.3	<1.2	0.21	<1.2	<1.2	<1.2	<1.2	<1.2
Lead	ppm	50		25	1.7	2.2	3.9	5.6	4.6	7.5	1.7	10	13	10	9.5	9
Mercury	ppm	4.7		0.061	0.001	0.0016	0.0017	0.0008	0.00068	0.0034	0.0005	0.013	0.026	0.017	0.017	0.036
Molybdenum	ppm	78		2.8	0.55	1.6	2.9	4	3.4	2.6	0.62	4.1	3.8	5.4	3.5	3.5
Nickel	ppm	310		9.1	3.9	6.3	21	27	28	35	26	42	40	40	39	36
Thallium	ppm	1.3		0.38	<0.026	0.029	0.16	<0.026	0.2	<0.026	0.032	0.15	0.26	0.53	0.28	0.38
Vanadium	ppm	110		21	10	18	87	**120**	110	100	40	**140**	110	**130**	**130**	100
Zinc	ppm	4700		42	7.2	13	24	36	50	36	15	65	60	57	51	46
Acenaphthene	ppm	900		0.0035	<0.0049	<0.0043	<0.0030	<0.0026	<0.0026	<0.0029	<0.0027	0.0037	0.0079	0.0041	0.0031	0.0102
Acenaphthylene	ppm	8.8		<0.0038	<0.0055	<0.0048	<0.0034	<0.0029	<0.0030	<0.0032	<0.0031	0.0032	0.0057	0.0032	0.0036	0.0052
Anthracene	ppm	5000		<0.0055	<0.0081	<0.0070	<0.0050	<0.0043	<0.0044	<0.0047	<0.0045	<0.0040	<0.0041	<0.0043	<0.0044	<0.0042
Benzo(a)anthracene	ppm	0.088	44	<0.0034	<0.0049	<0.0043	<0.0031	<0.0026	<0.0027	<0.0029	<0.0028	<0.0024	<0.0025	0.0084	0.012	0.0037
Benzo(a)pyrene	ppm	0.0088	4.4	<0.0039	<0.0057	<0.0050	<0.0035	<0.0030	<0.0031	<0.0033	<0.0032	<0.0028	<0.0029	**0.0089**	**0.0109**	<0.0030
Benzo(b)fluoranthene	ppm	0.088	44	<0.0041	<0.0060	<0.0052	<0.0037	<0.0032	<0.0032	0.0105	<0.0034	0.0089	<0.0030	0.0209	0.0248	0.0107
Benzo(g,h,i)perylene	ppm	0.88		<0.0031	<0.0046	<0.0040	<0.0028	<0.0024	<0.0025	<0.0027	<0.0026	<0.0022	<0.0023	0.0038	0.0056	0.0045
Benzo(k)fluoranthene	ppm	0.88		<0.0044	<0.0064	<0.0056	<0.0040	<0.0034	<0.0035	<0.0038	<0.0036	<0.0032	<0.0032	0.0059	0.006	<0.0034
Chrysene	ppm	8.8		<0.0043	<0.0063	<0.0055	<0.0039	<0.0033	<0.0034	<0.0037	<0.0035	<0.0031	<0.0032	0.0108	0.012	<0.0033
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0065	<0.0094	<0.0082	<0.0059	<0.0050	<0.0051	<0.0055	<0.0053	<0.0046	<0.0048	<0.0050	<0.0052	<0.0049
Fluoranthene	ppm	600		<0.0119	<0.0173	<0.0151	<0.0108	<0.0092	<0.0094	<0.0102	<0.0097	<0.0085	0.0087	0.0283	0.0286	0.0186
Fluorene	ppm	600		<0.0059	<0.0086	<0.0075	<0.0054	<0.0046	<0.0047	<0.0051	<0.0048	<0.0042	<0.0043	<0.0045	<0.0047	<0.0045
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.0034	<0.0049	<0.0043	<0.0031	<0.0026	<0.0027	<0.0029	<0.0026	<0.0024	<0.0025	0.004	0.0051	<0.0026
Methylnaphthalene 1	ppm	8.8		0.0468	<0.0053	<0.0046	0.0034	<0.0028	<0.0029	0.0051	<0.0030	0.0089	0.0171	0.0108	0.0123	0.0165
Methylnaphthalene 2	ppm	8.8		0.0667	<0.0053	<0.0046	<0.0033	<0.0028	<0.0029	0.004	<0.0030	0.0097	0.0131	0.0157	0.0183	0.0165
Naphthalene	ppm	600		0.0744	<0.0061	<0.0053	0.0162	<0.0032	0.0034	0.0133	<0.0034	0.0233	0.0221	0.0196	0.0303	0.0276
Phenanthrene	ppm	0.88		<0.0052	<0.0076	<0.0067	<0.0047	<0.0041	<0.0041	<0.0045	<0.0043	0.0077	0.0274	0.0226	0.0212	0.0236
Pyrene	ppm	500		<0.0044	<0.0063	<0.0055	<0.0039	<0.0034	<0.0034	<0.0037	<0.0036	0.0031	0.0063	0.0194	0.0195	0.0121
Total PAH's	ppm		100	0.191	<0.123	<0.108	0.0196	<0.065	0.0034	0.0329	<0.069	0.069	0.108	0.186	0.213	0.149

NR 538 Table 1B exceedances are highlighted in *bold* type

Table 10-5: NR 538 Bottom Ash Analysis – ASTM D-3987 Leachate Test Result Summary (2010)

	Units	NR538 Category1 Standard	NR538 Category 2&3 Standard	NR538 Category 4 Standard	MCPP Mixed Ash AD31345	VAPP Bottom Ash AD31346	PIPP 5-6 Bottom Ash AD31347	PIPP 7-9 Bottom Ash AD31348	OCPP 5&6 Bottom Ash AD31349	OCPP7&8 Bottom Ash AD31350	PPPP Bottom Ash AD31351	ERGS Bottom Ash AD31353	P4 Landfill Recovered Ash 7/2/2010 AD31354	P4 Landfill Recovered Ash 8/2/2010 AD31408	P4 Landfill Recovered Ash 8/11/2010 AD31409	P4 Landfill Recovered Ash 8/19/2010 AD31410	P4 Landfill Recovered Ash 8/25/2010 AD31411
Aluminum	mg/l	1.5			**3.5**	0.39	**1.6**	**10**	**29**	**30**	**4.8**	0.71	**2.6**	**13**	**12**	**13**	**15**
Antimony	mg/l	0.0012	0.012		**0.0093**	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	0.00095	0.00054	0.00048	**0.0013**
Arsenic	mg/l	0.005	0.05		**0.012**	0.002	0.0032	<0.00044	<0.00044	<0.00044	0.0015	**0.0085**	0.0014	0.00086	0.00076	0.00075	0.00058
Barium	mg/l	0.4	4		0.16	0.11	0.16	0.39	**0.97**	**1.4**	0.3	0.013	0.2	0.23	0.17	0.18	0.24
Beryllium	mg/l	0.0004	0.004		0.00005	0.000023	<0.000022	0.000066	0.000024	0.000032	0.000023	0.000033	0.000051	<0.000022	0.000035	0.000036	0.00004
Boron	mg/l	0.19	1.9	4.8	**2.7**	0.099	**0.4**	**0.53**	**0.34**	**0.41**	**0.53**	0.052	**1.1**	**1.9**	**1.4**	**1.2**	**2**
Cadmium	mg/l	0.0005	0.005	0.025	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019
Chloride	mg/l	125			1.1	1.5	0.58	0.5	<0.025	<0.025	0.79	0.26	0.21	0.3	0.43	0.55	0.29
Chromium - Total	mg/l	0.01	0.1	0.5	0.00099	0.00056	0.00087	0.0034	**0.056**	**0.055**	0.0035	0.00098	0.0045	**0.021**	0.0068	0.0056	**0.019**
Copper	mg/l	0.13			<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	<0.0013	0.0016	0.0015	0.002	0.0022
Iron	mg/l	0.15			0.0056	0.0043	0.0041	0.0037	0.0088	0.0095	0.0026	0.021	0.0022	0.004	0.0046	0.0071	0.0034
Lead	mg/l	0.0015	0.015		<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024
Manganese	mg/l	0.025	0.25		<0.000095	0.00021	<0.000095	<0.000095	<0.000095	<0.000095	<0.000095	0.00056	0.00029	<0.000095	0.000098	0.00012	<0.000095
Mercury	mg/l	0.0002	0.002		<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072	<0.0000072
Molybdenum	mg/l	0.05			0.043	0.0023	0.019	0.016	0.029	0.026	0.0053	0.0014	0.0069	0.017	0.017	0.017	0.015
Nickel	mg/l	0.02			<0.0016	<0.0016	0.0017	<0.0016	0.0018	<0.0016	<0.0016	<0.0016	<0.0016	<0.0016	<0.0016	0.0018	<0.0016
Nitrate-Nitrite as N	mg/l	2			<0.04	<0.04	0.07	0.14	<0.04	<0.04	0.06	0.07	<0.04	0.04	<0.04	<0.04	<0.04
Selenium	mg/l	0.01	0.1	0.25	0.0083	<0.0047	<0..0047	<0.0047	<0.0047	<0.0047	<0.0047	<0.0047	<0.0047	0.0079	0.0049	0.0048	0.006
Silver	mg/l	0.01	0.1	0.25	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043
Sulfate	mg/l	125	1250	2500	120	10	22	**190**	29	40	43	12	120	**220**	**200**	**46**	**310**
Thallium	mg/l	0.0004	0.004		<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010
Zinc	mg/l	2.5			<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021

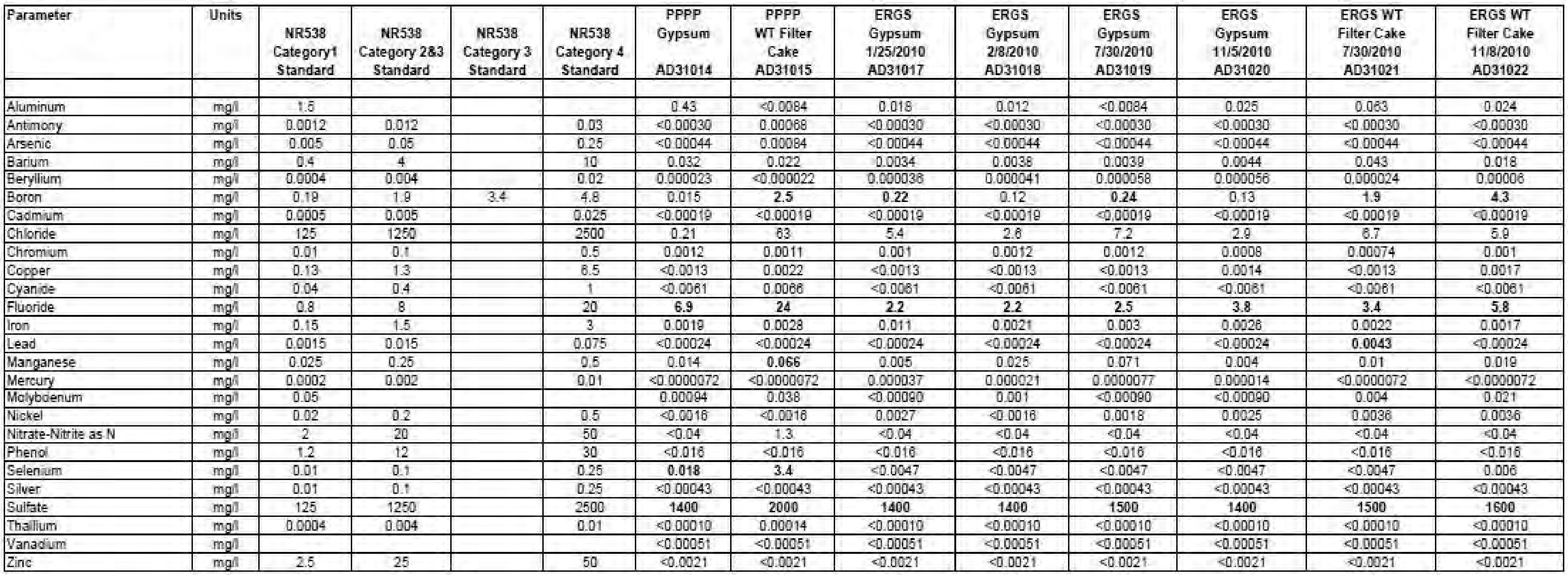
Note: A value highlighted in *bold* exceeds the NR 538 Category 1 Standard

Table 10-6: NR 538 FGD Materials Analysis – Bulk Analysis Data Summary (2010)

Parameter	Units	NR538 Category 1 Standard	NR538 Category 2 Standard	PPPP Gypsum AD31014	PPPP WT Filter Cake AD31015	ERGS Gypsum 1/25/2010 AD31017	ERGS Gypsum 2/8/2010 AD31018	ERGS Gypsum 7/30/2010 AD31019	ERGS Gypsum 11/5/2010 AD31020	ERGS WT Filter Cake 7/30/2010 AD31021	ERGS WT Filter Cake 11/8/2010 AD31022
Antimony	ppm	6.3		0.1	3.6	<0.074	<0.074	0.52	0.086	0.3	1.4
Arsenic	ppm	0.042	21	**0.33**	**11**	**0.64**	**0.61**	**0.6**	**0.61**	**5.2**	**18**
Barium	ppm	1100		7.4	220	1.3	1.2	1.5	1.4	45	40
Beryllium	ppm	0.014	7	**0.018**	**0.5**	**0.026**	**0.024**	**0.042**	**0.025**	**0.12**	**0.36**
Boron	ppm	1400		2.2	180	7.1	4.7	8.6	5	64	190
Cadmium	ppm	7.8		<0.021	0.5	0.1	0.18	0.48	<0.021	0.28	0.8
Chromium, Hexavalent	ppm	14.5		<0.06	<1.2	<0.60	<0.60	<0.60	0.25	1.2	8.8
Lead	ppm	50		0.32	22	0.25	0.24	0.89	0.3	2.4	11
Mercury	ppm	4.7		1.6	**140**	0.57	0.57	0.61	0.43	**5.1**	**13**
Molybdenum	ppm	78		<0.23	18	0.4	0.48	0.65	0.59	2.5	16
Nickel	ppm	310		1.3	120	1.4	1.3	2.2	1.4	16	74
Phenol	ppm	9400		0.08	0.022	0.034	0.065	0.019	0.21	<0.005	0.04
Selenium	ppm	78		8.5	**900**	1.6	2	3.2	1.6	15	74
Silver	ppm	9400		<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11
Strontium	ppm	9400		140	83	130	120	94	130	100	95
Thallium	ppm	1.3		<0.026	0.86	<0.026	<0.026	1	0.1	0.11	0.36
Vanadium	ppm	110		1.2	62	0.88	0.74	1.3	0.92	9.5	39
Zinc	ppm	4700		8	140	6.6	8	7.8	8.3	47	140
Acenaphthene	ppm	900		<0.0029	<0.0048	<0.0030	<0.0031	<0.0029	<0.0030	<0.0037	<0.0035
Acenaphthylene	ppm	8.8		<0.0032	<0.0054	<0.0034	<0.0035	<0.0033	<0.0034	<0.0042	<0.0040
Anthracene	ppm	5000		<0.0047	0.0084	<0.0050	<0.0052	<0.0049	<0.0050	<0.0061	<0.0059
Benzo(a)anthracene	ppm	0.088	44	<0.0029	0.0514	<0.0031	<0.0032	<0.0030	<0.0030	<0.0037	0.0091
Benzo(a)pyrene	ppm	0.0088	4.4	<0.0033	**0.0461**	<0.0035	<0.0036	<0.0034	<0.0035	<0.0043	0.008
Benzo(b)fluoranthene	ppm	0.088	44	0.0122	**0.112**	<0.0037	<0.0039	<0.0036	<0.0037	<0.0045	0.027
Benzo(g,h,i)perylene	ppm	0.88		<0.0027	0.0492	<0.0028	<0.0029	<0.0028	<0.0028	<0.0035	0.0112
Benzo(k)fluoranthene	ppm	0.88		<0.0038	0.0396	<0.0040	<0.0041	<0.0039	<0.0040	<0.0049	0.0084
Chrysene	ppm	8.8		<0.0037	0.102	<0.0039	<0.0040	<0.0038	<0.0039	<0.0048	0.0132
Dibenzo(a,h)anthracene	ppm	0.0088	4.4	<0.0055	**0.0103**	<0.0058	<0.0061	<0.0057	<0.0058	<0.0071	<0.0069
Fluoranthene	ppm	600		<0.0102	0.134	<0.0107	<0.0111	<0.0105	<0.0107	<0.0131	<0.0126
Fluorene	ppm	600		<0.0051	<0.0085	<0.0053	<0.0055	<0.0052	<0.0053	<0.0065	<0.0063
Indeno(1,2,3-cd)pyrene	ppm	0.088	44	<0.0029	0.0213	<0.0031	<0.0032	<0.0030	<0.0030	<0.0037	<0.0036
Methylnaphthalene 1	ppm	8.8		<0.0031	0.0156	<0.0033	<0.0034	<0.0032	<0.0033	0.0128	0.0115
Methylnaphthalene 2	ppm	8.8		<0.0031	0.0197	<0.0033	<0.0034	<0.0032	<0.0033	0.0174	0.0162
Naphthalene	ppm	600		<0.0036	0.0199	<0.0038	<0.0039	<0.0037	<0.0037	0.0228	0.0191
Phenanthrene	ppm	0.88		<0.0045	0.057	<0.0047	<0.0049	<0.0046	<0.0047	<0.0058	0.031
Pyrene	ppm	500		<0.0037	0.122	<0.0039	<0.0041	<0.0038	<0.0039	<0.0048	0.0226
Total PAH's	ppm		100	0.0122	0.808	<0.076	<0.079	<0.075	<0.078	0.053	0.177

NR 538 Table 1B exceedances are highlighted in *bold* type

Table 10-7: NR 538 FGD Materials Analysis – ASTM D-3987 Leachate Test Result Summary (2010)



Parameter	Units	NR538 Category1 Standard	NR538 Category 2&3 Standard	NR538 Category 3 Standard	NR538 Category 4 Standard	PPPP Gypsum AD31014	PPPP WT Filter Cake AD31015	ERGS Gypsum 1/25/2010 AD31017	ERGS Gypsum 2/8/2010 AD31018	ERGS Gypsum 7/30/2010 AD31019	ERGS Gypsum 11/5/2010 AD31020	ERGS WT Filter Cake 7/30/2010 AD31021	ERGS WT Filter Cake 11/8/2010 AD31022
Aluminum	mg/l	1.5				0.43	<0.0084	0.018	0.012	<0.0084	0.025	0.063	0.024
Antimony	mg/l	0.0012	0.012		0.03	<0.00030	0.00068	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030	<0.00030
Arsenic	mg/l	0.005	0.05		0.25	<0.00044	0.00084	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044	<0.00044
Barium	mg/l	0.4	4		10	0.032	0.022	0.0034	0.0038	0.0039	0.0044	0.043	0.018
Beryllium	mg/l	0.0004	0.004		0.02	0.000023	<0.000022	0.000038	0.000041	0.000058	0.000056	0.000024	0.00006
Boron	mg/l	0.19	1.9	3.4	4.8	0.015	**2.5**	**0.22**	0.12	**0.24**	0.13	**1.9**	**4.3**
Cadmium	mg/l	0.0005	0.005		0.025	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019	<0.00019
Chloride	mg/l	125	1250		2500	0.21	63	5.4	2.6	7.2	2.9	6.7	5.9
Chromium	mg/l	0.01	0.1		0.5	0.0012	0.0011	0.001	0.0012	0.0012	0.0008	0.00074	0.001
Copper	mg/l	0.13	1.3		6.5	<0.0013	0.0022	<0.0013	<0.0013	<0.0013	0.0014	<0.0013	0.0017
Cyanide	mg/l	0.04	0.4		1	<0.0061	0.0066	<0.0061	<0.0061	<0.0061	<0.0061	<0.0061	<0.0061
Fluoride	mg/l	0.8	8		20	**6.9**	**24**	**2.2**	**2.2**	**2.5**	**3.8**	**3.4**	**5.8**
Iron	mg/l	0.15	1.5		3	0.0019	0.0028	0.011	0.0021	0.003	0.0026	0.0022	0.0017
Lead	mg/l	0.0015	0.015		0.075	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	<0.00024	**0.0043**	<0.00024
Manganese	mg/l	0.025	0.25		0.5	0.014	**0.066**	0.005	0.025	0.071	0.004	0.01	0.019
Mercury	mg/l	0.0002	0.002		0.01	<0.0000072	<0.0000072	0.000037	0.000021	0.0000077	0.000014	<0.0000072	<0.0000072
Molybdenum	mg/l	0.05				0.00094	0.038	<0.00090	0.001	<0.00090	<0.00090	0.004	0.021
Nickel	mg/l	0.02	0.2		0.5	<0.0016	<0.0016	0.0027	<0.0016	0.0018	0.0025	0.0036	0.0036
Nitrate-Nitrite as N	mg/l	2	20		50	<0.04	1.3	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Phenol	mg/l	1.2	12		30	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016	<0.016
Selenium	mg/l	0.01	0.1		0.25	**0.018**	**3.4**	<0.0047	<0.0047	<0.0047	<0.0047	<0.0047	0.006
Silver	mg/l	0.01	0.1		0.25	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043	<0.00043
Sulfate	mg/l	125	1250		2500	**1400**	**2000**	**1400**	**1400**	**1500**	**1400**	**1500**	**1600**
Thallium	mg/l	0.0004	0.004		0.01	<0.00010	0.00014	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010	<0.00010
Vanadium	mg/l					<0.00051	<0.00051	<0.00051	<0.00051	<0.00051	<0.00051	<0.00051	<0.00051
Zinc	mg/l	2.5	25		50	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021	<0.0021

Note: A value highlighted in *bold* exceeds the NR 538 Category 1 Standard

Leaching From Products Containing Coal Combustion Products

Fly ash has found great applications in construction products like concrete, CLSM and in the manufacture of Portland cement. It is well established that leaching of trace elements from concrete and fly ash-stabilized clay is negligible. Concrete is very dense and impermeable, making it hard for water to penetrate into the interior of a concrete structure. The reaction products in concrete are stable, dense and do not leach significantly in the natural environment.

The composition of CLSM material is different from that of concrete. It is a low-strength material, often with a compressive strength of less than 300 psi. When prepared with large amounts of fly ash, the permeability is also very low. However, the potential for future removal and handling could allow the material to be broken up into smaller particles with more leachable surface area. Hence, ASTM D-398 Extraction Analysis has been performed on this material to determine the amount of trace elements leached out of high fly ash content CLSM. Table 10-8 shows the total results of total elemental analysis for CLSM produced with PWPP Units 2 and 3 fly ash. Table 10-9 gives the results of ASTM D-3987 Extraction Analysis for the same material. The extract meets all requirements for Category 2 per NR 538.

Table 10-8: Total Elemental Analysis – CLSM Produced with Port Washington Power Plant Units 2 & 3 Fly Ash

Parameter	Detection Level	Units	NR 538 Category 1 Standard	NR 538 Category 2 & 3 Standard	Collected 11/19/97 AB 59506	Collected 11/19/97 AB 59507
Antimony – PIXE	166	Mg/kg	6.3		<166	<199
Arsenic - SW-846	0.06	mg/kg	0.042	21	57	58
Barium - SW-846	0.056	mg/kg	1100		168	160
Beryllium - SW-846	0.06	mg/kg	0.014	7	3.3	3.6
Boron - SW-846	0.014	mg/kg	1400		200	180
Cadmium - SW-846	0.005	mg/kg	7.8		1.3	0.92
Chromium - PIXE	39.8	mg/kg	14.5 as Hex		171	239
Lead - PIXE	41.6	mg/kg	50		212	160
Mercury - SW-846	0.0037	mg/kg	4.7		<0.0037	<0.0037
Molybdenum - SW-846	0.19	mg/kg	78		12	9.2
Nickel	13.1	mg/kg	310		103	94.7
Thallium - PIXE	33.5	mg/kg	1.3		<33.5	<25.5
Vanadium - PIXE	80.6	mg/kg	110		<80.6	<81.1
Zinc - PIXE	14.6	mg/kg	4700		179	173

PIXE - Proton Induced X-Ray Emission Spectroscopy
SW-846 - Test Methods for Evaluating Solid Waste Physical/Chemical Methods

Table 10-9: ASTM D3987 Extraction Analysis – CLSM Produced With Port Washington Power Plant Units 2 & 3 Fly Ash

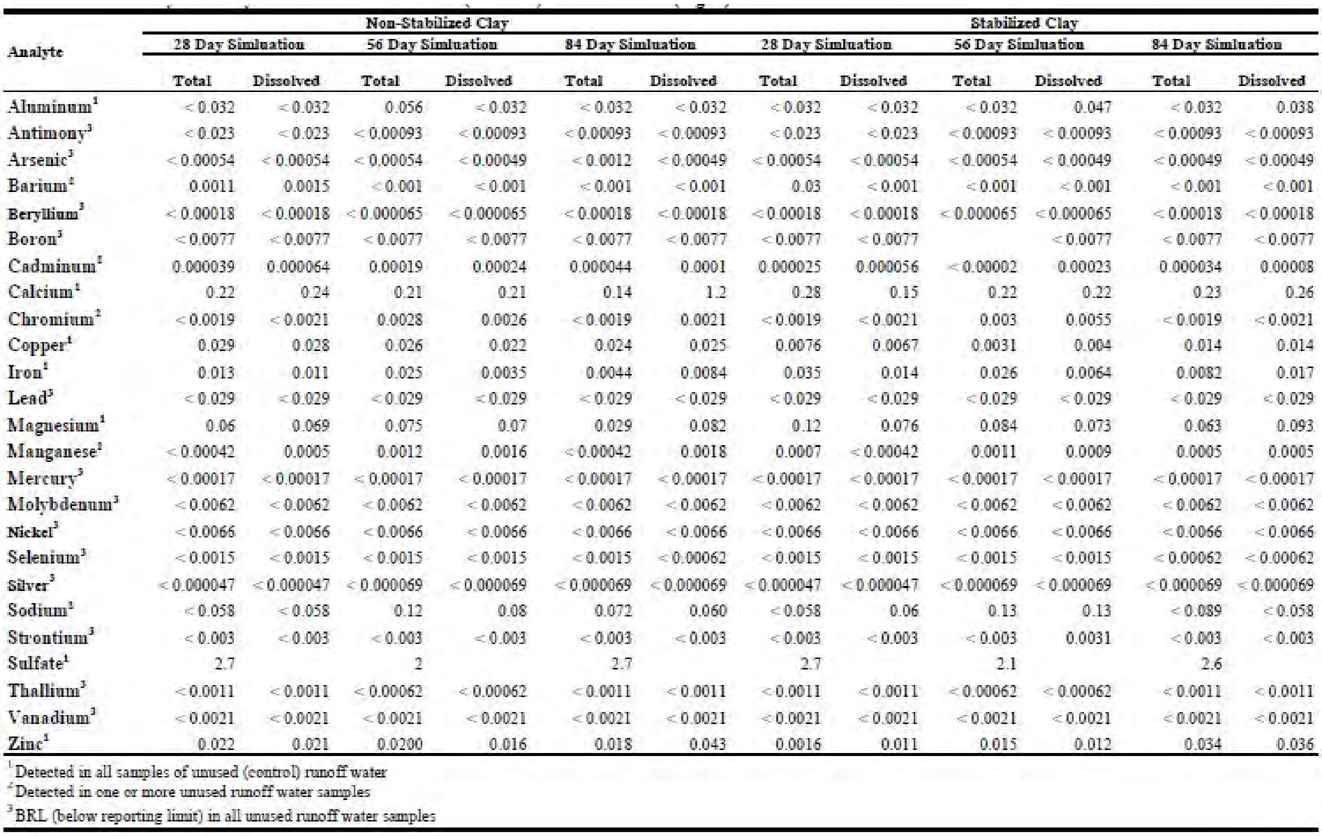
Parameter	Detection Level	Units	NR 538 Category 1 Standard	NR 538 Category 2 & 3 Standard	Collected 11/19/97 AB 59630	Collected 11/19/97 AB 59631
Aluminum	0.011	mg/l	1.5	15	6	5.5
Antimony	0.0015	mg/l	0.0012	0.12	0.0051	0.005
Arsenic	0.0006	mg/l	0.005	0.05	0.03	0.031
Barium	0.0009	mg/l	0.4	4	0.041	0.047
Beryllium	0.0002	mg/l	0.0004	0.004	<0.0002	<0.0002
Cadmium	0.0001	mg/l	0.0005	0.005	0.0001	<0.0001
Chloride	0.15	mg/l	125		2	3.2
Chromium	0.0005	mg/l	0.01	0.1	0.029	0.03
Copper	0.0012	mg/l	0.13		0.0047	0.0053
Iron	0.0007	mg/l	0.15		0.0013	0.002
Lead	0.0007	mg/l	0.0015	0.015	<0.0007	<0.0007
Manganese	0.0015	mg/l	0.025	0.25	0.0015	<0.0015
Mercury	0.00067	mg/l	0.0002	0.002	<0.00067	<0.00067
Molybdenum	0.0029	mg/l	0.05		0.2	0.25
Nickel	0.0044	mg/l	0.02		<0.0044	<0.0044
Nitrate- Nitrite as N	0.02	mg/l	2		0.05	0.03
Selenium	0.0007	mg/l	0.01	0.1	0.049	0.051
Silver	0.00014	mg/l	0.01	0.1	<0.00014	<0.00014
Sulfate	0.09	mg/l	125	1250	52	63
Thallium	0.0014	mg/l	0.0004	0.004	<0.0014	0.0017
Zinc	0.0013	mg/l	2.5		0.0061	0.0046

*Note: Boron leach standards have been added to NR538 since these tests were performed as shown on Tables 10-3, 10-5 and 10-7.

In 2010, a study was performed to evaluate the surface water runoff from OCPP Class C fly ash-stabilized and non-stabilized clay soil exposed surfaces. The primary objective was to determine the potential leaching of fly ash constituents into surface water runoff over fly ash-stabilized clay soil and to assess any adverse environmental impacts to surface water from such runoff. This study involved laboratory simulations using natural soil and fly ash-stabilized soil as test pads exposed to simulated rainfall over varying lengths of time. Then the measurements of analyte concentrations in the runoff water were compared to established benchmarks for surface water quality protection (84).

Table 10-10 shows the results for the analysis performed on the control synthetic precipitation samples collected immediately prior to each simulation. Analytical results for recirculated runoff water with all simulations using stabilized and non-stabilized clay are shown in Table 10-11 and 10-12, respectively.

Table 10-10: Summary of Analytical Results for Unused (Control) Runoff Water (mg/L)



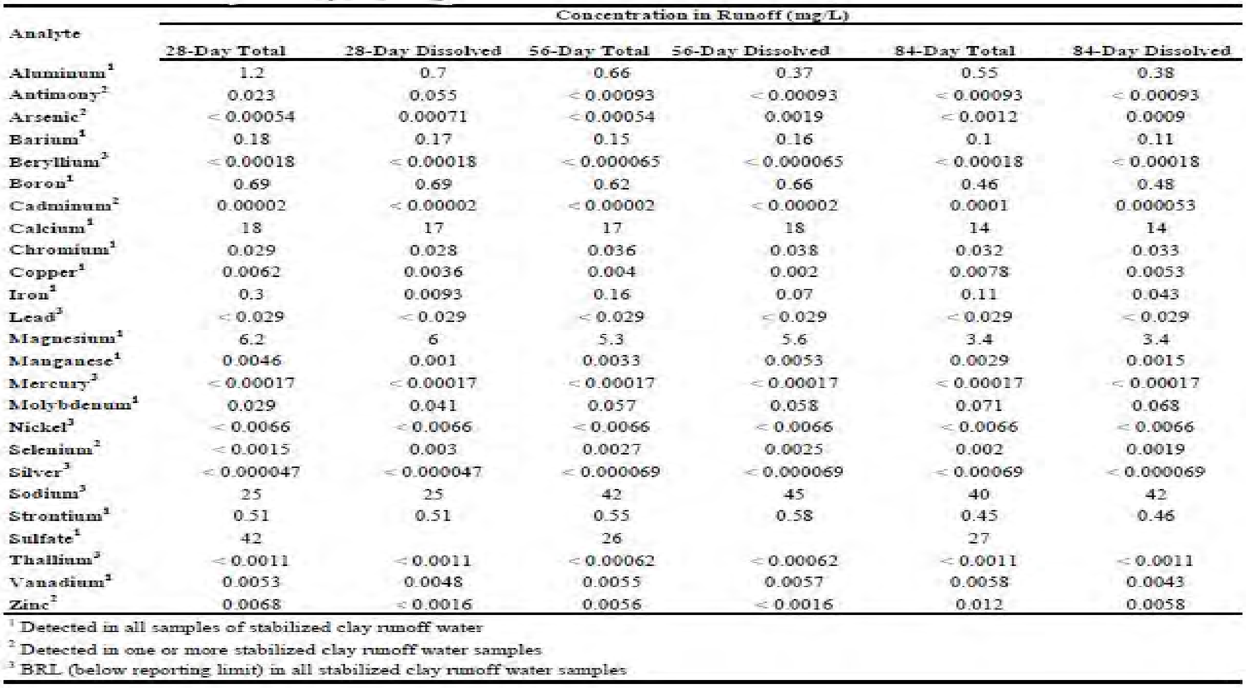
Analyte	Non-Stabilized Clay						Stabilized Clay					
	28 Day Simluation		56 Day Simluation		84 Day Simluation		28 Day Simluation		56 Day Simluation		84 Day Simluation	
	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
Aluminum[1]	< 0.032	< 0.032	0.056	< 0.032	< 0.032	< 0.032	< 0.032	< 0.032	< 0.032	0.047	< 0.032	0.038
Antimony[3]	< 0.023	< 0.023	< 0.00093	< 0.00093	< 0.00093	< 0.00093	< 0.023	< 0.023	< 0.00093	< 0.00093	< 0.00093	< 0.00093
Arsenic[3]	< 0.00054	< 0.00054	< 0.00054	< 0.00049	< 0.0012	< 0.00049	< 0.00054	< 0.00054	< 0.00054	< 0.00049	< 0.00049	< 0.00049
Barium[2]	0.0011	0.0015	< 0.001	< 0.001	< 0.001	< 0.001	0.03	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Beryllium[3]	< 0.00018	< 0.00018	< 0.000065	< 0.000065	< 0.00018	< 0.00018	< 0.00018	< 0.00018	< 0.000065	< 0.000065	< 0.00018	< 0.00018
Boron[3]	< 0.0077	< 0.0077	< 0.0077	< 0.0077	< 0.0077	< 0.0077	< 0.0077	< 0.0077		< 0.0077	< 0.0077	< 0.0077
Cadminum[2]	0.000039	0.000064	0.00019	0.00024	0.000044	0.0001	0.000025	0.000056	< 0.00002	0.00023	0.000034	0.00008
Calcium[1]	0.22	0.24	0.21	0.21	0.14	1.2	0.28	0.15	0.22	0.22	0.23	0.26
Chromium[2]	< 0.0019	< 0.0021	0.0028	0.0026	< 0.0019	0.0021	< 0.0019	< 0.0021	0.003	0.0055	< 0.0019	< 0.0021
Copper[1]	0.029	0.028	0.026	0.022	0.024	0.025	0.0076	0.0067	0.0031	0.004	0.014	0.014
Iron[2]	0.013	0.011	0.025	0.0035	0.0044	0.0084	0.035	0.014	0.026	0.0064	0.0082	0.017
Lead[3]	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029
Magnesium[1]	0.06	0.069	0.075	0.07	0.029	0.082	0.12	0.076	0.084	0.073	0.063	0.093
Manganese[2]	< 0.00042	0.0005	0.0012	0.0016	< 0.00042	0.0018	0.0007	< 0.00042	0.0011	0.0009	0.0005	0.0005
Mercury[3]	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017
Molybdenum[3]	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062
Nickel[3]	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066
Selenium[3]	< 0.0015	< 0.0015	< 0.0015	< 0.0015	< 0.0015	< 0.00062	< 0.0015	< 0.0015	< 0.0015	< 0.0015	< 0.00062	< 0.00062
Silver[3]	< 0.000047	< 0.000047	< 0.000069	< 0.000069	< 0.000069	< 0.000069	< 0.000047	< 0.000047	< 0.000069	< 0.000069	< 0.000069	< 0.000069
Sodium[2]	< 0.058	< 0.058	0.12	0.08	0.072	0.060	< 0.058	0.06	0.13	0.13	< 0.089	< 0.058
Strontium[3]	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	0.0031	< 0.003	< 0.003
Sulfate[1]	2.7		2		2.7		2.7		2.1		2.6	
Thallium[3]	< 0.0011	< 0.0011	< 0.00062	< 0.00062	< 0.0011	< 0.0011	< 0.0011	< 0.0011	< 0.00062	< 0.00062	< 0.0011	< 0.0011
Vanadium[3]	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021	< 0.0021
Zinc[1]	0.022	0.021	0.0200	0.016	0.018	0.043	0.0016	0.011	0.015	0.012	0.034	0.036

[1] Detected in all samples of unused (control) runoff water

[2] Detected in one or more unused runoff water samples

[3] BRL (below reporting limit) in all unused runoff water samples

Table 10-11: Summary of Analytical Results for Recirculated Runoff Water for Stabilized Clay under Various Test Simulations



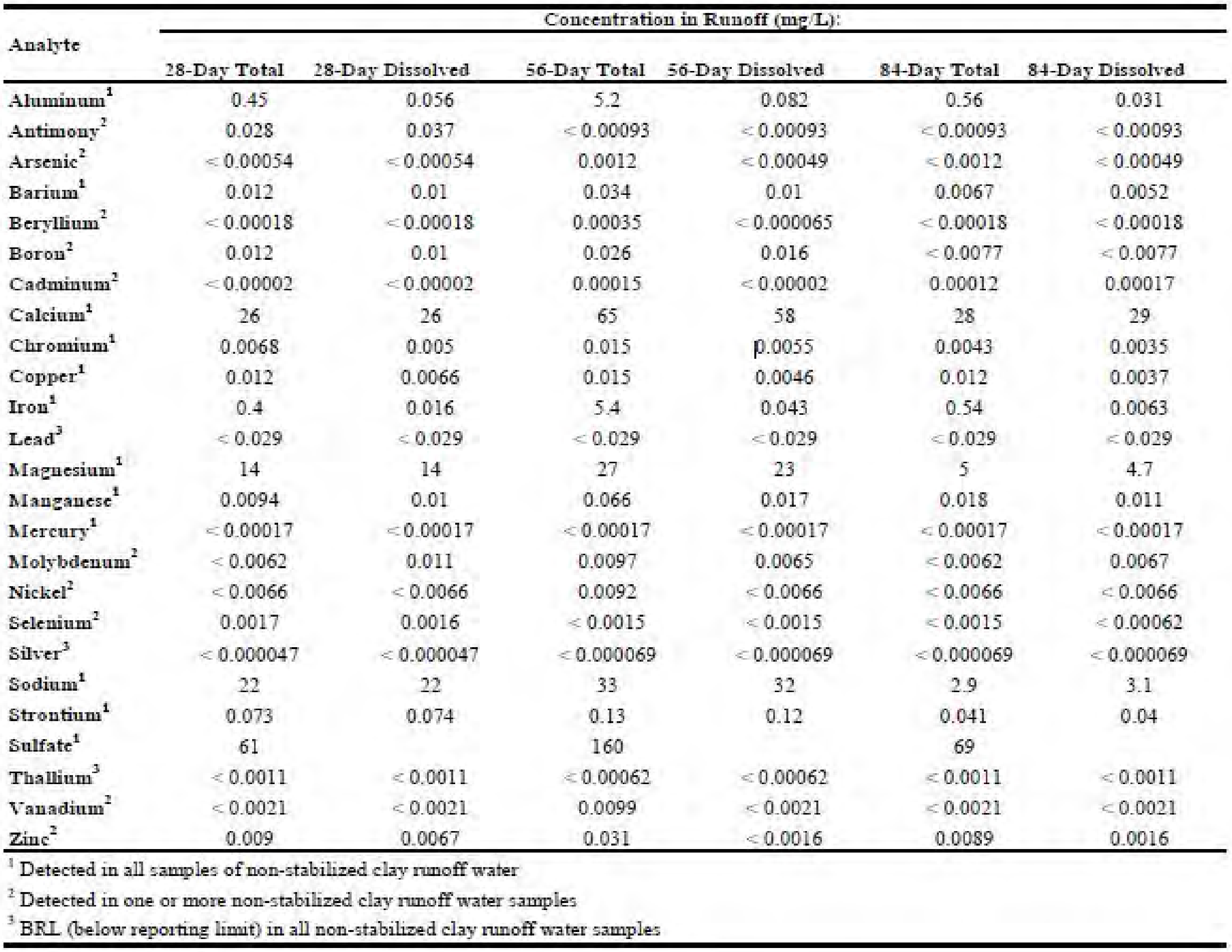
Analyte	Concentration in Runoff (mg/L)					
	28-Day Total	28-Day Dissolved	56-Day Total	56-Day Dissolved	84-Day Total	84-Day Dissolved
Aluminum[1]	1.2	0.7	0.66	0.37	0.55	0.38
Antimony[2]	0.023	0.055	< 0.00093	< 0.00093	< 0.00093	< 0.00093
Arsenic[2]	< 0.00054	0.00071	< 0.00054	0.0019	< 0.0012	0.0009
Barium[1]	0.18	0.17	0.15	0.16	0.1	0.11
Beryllium[3]	< 0.00018	< 0.00018	< 0.000065	< 0.000065	< 0.00018	< 0.00018
Boron[1]	0.69	0.69	0.62	0.66	0.46	0.48
Cadminum[2]	0.00002	< 0.00002	< 0.00002	< 0.00002	0.0001	0.000053
Calcium[1]	18	17	17	18	14	14
Chromium[1]	0.029	0.028	0.036	0.038	0.032	0.033
Copper[1]	0.0062	0.0036	0.004	0.002	0.0078	0.0053
Iron[1]	0.3	0.0093	0.16	0.07	0.11	0.043
Lead[3]	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029
Magnesium[1]	6.2	6	5.3	5.6	3.4	3.4
Manganese[1]	0.0046	0.001	0.0033	0.0053	0.0029	0.0015
Mercury[3]	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017
Molybdenum[1]	0.029	0.041	0.057	0.058	0.071	0.068
Nickel[3]	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066	< 0.0066
Selenium[2]	< 0.0015	0.003	0.0027	0.0025	0.002	0.0019
Silver[3]	< 0.000047	< 0.000047	< 0.000069	< 0.000069	< 0.00069	< 0.000069
Sodium[3]	25	25	42	45	40	42
Strontium[1]	0.51	0.51	0.55	0.58	0.45	0.46
Sulfate[1]	42		26		27	
Thallium[3]	< 0.0011	< 0.0011	< 0.00062	< 0.00062	< 0.0011	< 0.0011
Vanadium[1]	0.0053	0.0048	0.0055	0.0057	0.0058	0.0043
Zinc[2]	0.0068	< 0.0016	0.0056	< 0.0016	0.012	0.0058

[1] Detected in all samples of stabilized clay runoff water

[2] Detected in one or more stabilized clay runoff water samples

[3] BRL (below reporting limit) in all stabilized clay runoff water samples

Table 10-12: Summary of Analytical Results for Recirculated Runoff Water for Non-Stabilized Clay under Various Test Simulations



Analyte	Concentration in Runoff (mg/L):					
	28-Day Total	28-Day Dissolved	56-Day Total	56-Day Dissolved	84-Day Total	84-Day Dissolved
Aluminum[1]	0.45	0.056	5.2	0.082	0.56	0.031
Antimony[2]	0.028	0.037	< 0.00093	< 0.00093	< 0.00093	< 0.00093
Arsenic[2]	< 0.00054	< 0.00054	0.0012	< 0.00049	< 0.0012	< 0.00049
Barium[1]	0.012	0.01	0.034	0.01	0.0067	0.0052
Beryllium[2]	< 0.00018	< 0.00018	0.00035	< 0.000065	< 0.00018	< 0.00018
Boron[2]	0.012	0.01	0.026	0.016	< 0.0077	< 0.0077
Cadminum[2]	< 0.00002	< 0.00002	0.00015	< 0.00002	0.00012	0.00017
Calcium[1]	26	26	65	58	28	29
Chromium[1]	0.0068	0.005	0.015	0.0055	0.0043	0.0035
Copper[1]	0.012	0.0066	0.015	0.0046	0.012	0.0037
Iron[1]	0.4	0.016	5.4	0.043	0.54	0.0063
Lead[3]	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029	< 0.029
Magnesium[1]	14	14	27	23	5	4.7
Manganese[1]	0.0094	0.01	0.066	0.017	0.018	0.011
Mercury[1]	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017	< 0.00017
Molybdenum[2]	< 0.0062	0.011	0.0097	0.0065	< 0.0062	0.0067
Nickel[2]	< 0.0066	< 0.0066	0.0092	< 0.0066	< 0.0066	< 0.0066
Selenium[2]	0.0017	0.0016	< 0.0015	< 0.0015	< 0.0015	< 0.00062
Silver[3]	< 0.000047	< 0.000047	< 0.000069	< 0.000069	< 0.000069	< 0.000069
Sodium[1]	22	22	33	32	2.9	3.1
Strontium[1]	0.073	0.074	0.13	0.12	0.041	0.04
Sulfate[1]	61		160		69	
Thallium[3]	< 0.0011	< 0.0011	< 0.00062	< 0.00062	< 0.0011	< 0.0011
Vanadium[2]	< 0.0021	< 0.0021	0.0099	< 0.0021	< 0.0021	< 0.0021
Zinc[2]	0.009	0.0067	0.031	< 0.0016	0.0089	0.0016

[1] Detected in all samples of non-stabilized clay runoff water

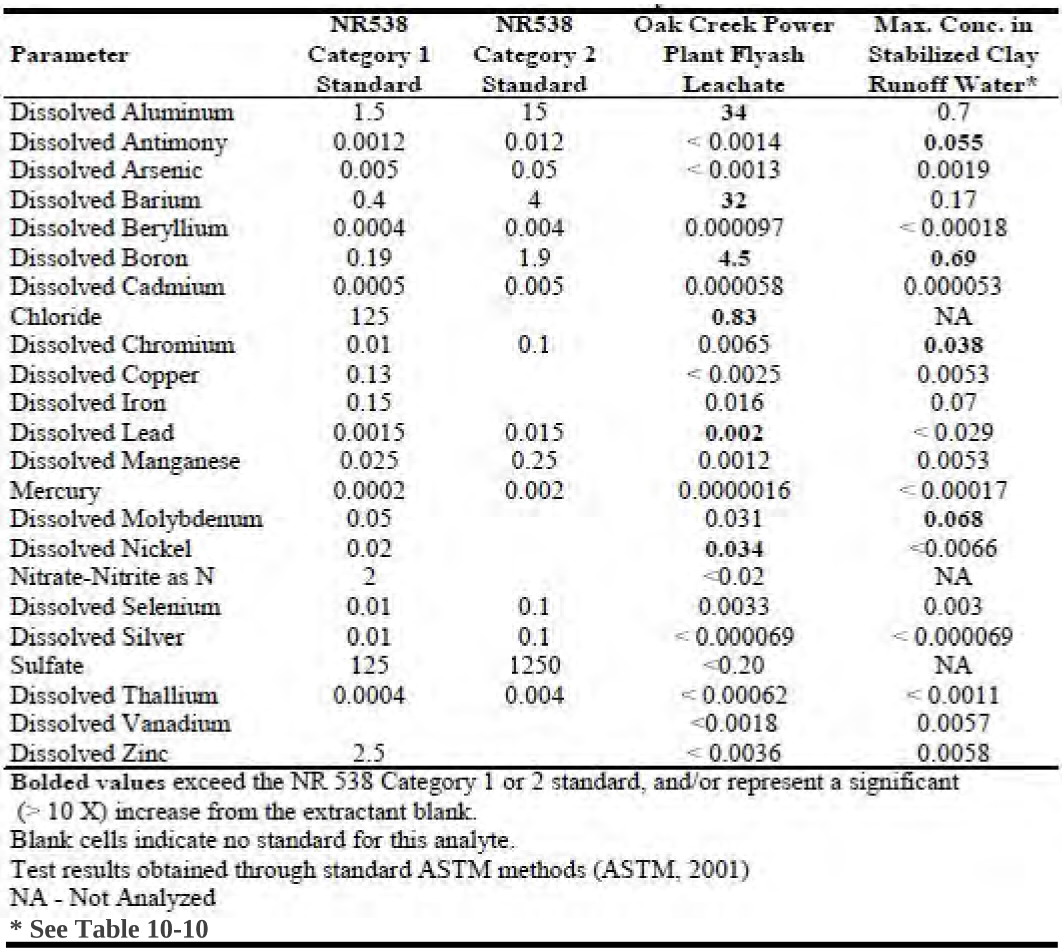
[2] Detected in one or more non-stabilized clay runoff water samples

[3] BRL (below reporting limit) in all non-stabilized clay runoff water samples

Additionally, a comparison between the OCPP composite fly ash leachate testing and the maximum dissolved concentration measured in runoff water from stabilized clay is shown in Table 10-13.

The synthetic precipitation was tested for the total and dissolved metal concentrations prior to its use in the simulations. The detected analytes and their measured concentrations were generally consistent with naturally occurring levels of trace inorganic constituents in natural waters, hence providing an appropriate simulation of field conditions. Moreover, a comparison of results of the analysis of control water used for stabilized versus non-stabilized simulations indicated very low variability in the constituent make-up of the runoff water used in the test simulation, suggesting that the runoff simulations did not constitute any addition to the leachable fraction of fly ash-stabilized soil. Both the fly ash-stabilized and non-stabilized clay samples for recirculated runoff water resulted in a high degree of consistency between dissolved and total analysis for each simulation, indicating that the trace metals are present as dissolved constituents in runoff water and are not associated with suspended solids or colloidal matter in the water. This indicates that the fly ash has little effect on the dissolution chemistry for the trace metals from the soil matrix. The results indicated by the tables have shown that a relatively small number of analytes are likely to be present in runoff water generated from the surface of clay soils stabilized with OCPP fly ash.

Table 10-13: Summary Results (mg/L) for 2005 Leachate Test of OCPP Bulk Fly Ash



Parameter	NR538 Category 1 Standard	NR538 Category 2 Standard	Oak Creek Power Plant Flyash Leachate	Max. Conc. in Stabilized Clay Runoff Water*
Dissolved Aluminum	1.5	15	**34**	0.7
Dissolved Antimony	0.0012	0.012	< 0.0014	**0.055**
Dissolved Arsenic	0.005	0.05	< 0.0013	0.0019
Dissolved Barium	0.4	4	**32**	0.17
Dissolved Beryllium	0.0004	0.004	0.000097	< 0.00018
Dissolved Boron	0.19	1.9	**4.5**	**0.69**
Dissolved Cadmium	0.0005	0.005	0.000058	0.000053
Chloride	125		**0.83**	NA
Dissolved Chromium	0.01	0.1	0.0065	**0.038**
Dissolved Copper	0.13		< 0.0025	0.0053
Dissolved Iron	0.15		0.016	0.07
Dissolved Lead	0.0015	0.015	**0.002**	< 0.029
Dissolved Manganese	0.025	0.25	0.0012	0.0053
Mercury	0.0002	0.002	0.0000016	< 0.00017
Dissolved Molybdenum	0.05		0.031	**0.068**
Dissolved Nickel	0.02		**0.034**	<0.0066
Nitrate-Nitrite as N	2		<0.02	NA
Dissolved Selenium	0.01	0.1	0.0033	0.003
Dissolved Silver	0.01	0.1	< 0.000069	< 0.000069
Sulfate	125	1250	<0.20	NA
Dissolved Thallium	0.0004	0.004	< 0.00062	< 0.0011
Dissolved Vanadium			<0.0018	0.0057
Dissolved Zinc	2.5		< 0.0036	0.0058

Bolded values exceed the NR 538 Category 1 or 2 standard, and/or represent a significant (> 10 X) increase from the extractant blank.
Blank cells indicate no standard for this analyte.
Test results obtained through standard ASTM methods (ASTM, 2001)
NA - Not Analyzed
*** See Table 10-10**

Radioactivity of Coal Ash (85)

Based on the elimination of combustible materials and concentration as a result of coal combustion, the Ra-226 concentrations in ash can be on the order of 1-30 pCi/g. Analyses of various ashes and ash products produced at We Energies plants in 1993 and 2003 found Ra-226 concentrations in the range of 1 – 3 pCi/g. This is comparable to the concentrations in soil (0.2 – 3 pCi/g) and within the range of 1 – 8 pCi/g found in ash from analyses of other fly ash in the US (Cement and Concrete Containing Fly Ash, Guideline for Federal Procurement, Federal Register, Vol. 48 (25), January 28, 1983, Rules and Regulations; Zielinski and Budahn, Fuel Vol. 77 (1998) 259-267).

Given that the ash may be landfilled or may be used in building materials as an aggregate or cementing material, the doses resulting from these applications have been studied to determine if there is any risk. The British Nuclear Radiation Protection Board conducted a detailed evaluation of the doses from fly ash released to the air to people living within 500 meters (547 yards) of a plant stack, to landfill workers burying fly ash, to workers manufacturing building products from fly ash, and to people living in a house built with fly ash building products. The maximum doses determined from this evaluation were 0.15 mrem/yr for the person living near the plant, 0.13 mrem/yr from releases from the ash landfill, 0.5 mrem/yr for workers manufacturing building products, and 13.5 mrem/yr to a resident of a home constructed with fly ash building materials. The latter is close to the 13 mrem/yr from living in a conventional brick/masonry house.

The levels of radioactivity are within the range found in other natural products. The doses resulting from using the ash in various products are comparable to doses from other human activities and from other natural sources. The doses from the radionuclides in ash are much less than the 300 mrem/yr received from normal background radiation. See Appendix B for the report prepared by Dr. Kjell Johansen for We Energies.

Radiochemistry Tests Performed on We Energies Coal Combustion Products (86)

Radiochemistry tests were performed on fly ash and bottom ash samples from MCPP, VAPP, OCPP, PPPP, PIPP, PPPP gypsum, PPPP filter cake, and PIPP spent powdered activated carbon (TOXECON^{TM}) sorbent. Using γ-ray spectroscopy, the concentrations of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in We Energies CCP was determined. Table 10-14 shows a summary of activity concentrations of radionuclides and the effective dose equivalent (ede). The test results ranged from 4.57 x 10^{-8} mSv/yr ede for gypsum to 1.73 x 10^{-6} mSv/yr ede for filter cake. These results were six to eight orders of magnitude lower than both the maximum allowable ede exposure from radiation in consumer products (0.1 mSv/yr) and exposure beyond the natural background radiation (3.0 mSv/yr) in North America. Additionally, all We Energies' CCP except filter cake met the EPA's water quality radionuclide limits for radium (5 pCi/g), thorium (5 pCi/g) and potassium (40 pCi/g).These results indicates that We Energies' CCP are safe in terms of both primordial and cosmogenic radionuclides, and fall within both national and international recommendations. The other parameters that can be extracted from the radiochemistry test results are external activity concentration index, internal activity concentration index and radium equivalent activity. These parameters are used to evaluate the compliance of specific building materials with international recommendations.

Table 10-14: Summary of Activity Concentration of Radionuclides ^{226}Ra, ^{232}Th, and ^{40}K and Ede for We Energies CCP (2010)

Coal Combustion Products (CCP)	**Activity concentrations (Bq/kg)**			**Effective Dose Equivalent (mSv/yr) x 10^{-7} per gram of CCP**
	^{226}Ra	**^{232}Th**	**^{40}K**	
MCPP Mixed Ash	105.1	81.8	333.0	7.97
VAPP Fly Ash	74.7	67.7	392.2	6.52
OCPP Fly Ash	121.0	111.4	111.0	9.92
PPPP Fly Ash	117.7	108.8	199.8	10.90
PIPP Units 3-6 Fly Ash	132.1	97.7	440.3	10.70
PIPP Units 7-9 Fly Ash	109.9	86.2	303.4	8.44
PPPP Recovered Ash	80.7	65.9	259.0	7.38
VAPP Bottom Ash	53.3	44.4	159.1	4.13
OCPP Bottom Ash	111.0	110.3	73.3	8.22
PPPP Bottom Ash	82.5	85.5	125.8	8.30
PIPP Units 3-6 Bottom Ash	81.8	80.7	558.7	9.75
PIPP Units 7-9 Bottom Ash	84.0	66.2	222.0	7.17
PPPP Gypsum	9.3	0.4	13.0	0.457
PPPP Filter Cake	362.6	12.2	192.4	17.30
PIPP Spent PAC Sorbent	111.4	37.4	159.1	7.89

Coal Ash Exemptions

The WDNR monitors the beneficial utilization of CCPs. NR 538 was adopted to categorize by-products and to recommend self-implementing rules to be followed for utilization. However, CCPs have been beneficially utilized for a long time and the WDNR has granted We Energies specific exemptions for many proven applications such as use in concrete, asphalt, CLSM, soil amendment and various aggregate applications.

With increased understanding of coal combustion products and its relationships with the natural environment, We Energies continues to perform research and seek exemptions for additional beneficial use applications.

Table 10-15 provides data on some of the metals that can be typically found in fly ash and soil as compounds along with typical ranges. Of course, one would expect to find higher natural concentrations in area geology where specific metals are mined.

Table 10-15: Typical Metals Found in Fly Ash and Soil

Element	Fly Ash Mean ppm	Fly Ash Range ppm	Soil Mean ppm	Soil Range ppm
Aluminum	128,000	106,990 - 1,139,700	71,000	10,000 – 300,000
Arsenic	28	11 – 63	6	0.1 - 40
Barium	1278	73 - 2,100	500	100 - 3,000
Cadmium	1.8	0.68 – 4.4	0.06	0.01 - 0.7
Chromium	86	34 – 124	100	5 - 3,000
Copper	94	18 – 239	20	2 – 100
Iron	33,000	17,050 – 45,910	38,000	3,000 – 550,000
Lead	89	63 – 111	10	2 – 200
Manganese	171	54 – 673	850	100 - 4,000
Mercury	0.01	0.00008 - 0.1	0.03	0.01 - 0.3
Nickel	41	8-65	40	10 - 1,000
Selenium	9.9	3 – 16	0.3	0.01 - 2
Vanadium	246	184 – 268	100	20 – 500
Zinc	63	9 – 110	50	10 – 300

Regulations of Ash Utilization - Wisconsin Department of Natural Resources

The Wisconsin Department of Natural Resources has the authority to regulate the utilization of individual by-products, including coal combustion products, in the State of Wisconsin. It encourages the use of industrial by-products as an alternative to sending these materials to solid waste landfills. Chapter NR 538 has been an important step in the evolution of using industrial by-products in a beneficial way. The NR 538 sets rules for 13 predefined industrial by-product utilization applications.

The purpose of Chapter NR 538 is "to allow and encourage to the maximum extent possible, consistent with the protection of public health and the environment and good engineering practices, the beneficial use of industrial by-products in a nuisance-free manner." NR 538 does not govern hazardous waste and metallic mining waste, nor does it apply to the design, construction or operations of industrial waste water facilities, sewerage systems and waterworks treating liquid wastes.

Figures 10-1 to 10-5 give flowchart guidance for beneficial use of industrial by-products in accordance with NR 538. This flowchart can be used as a ready-reference to help understand the various requirements and beneficial applications governed under NR 538. In the State of Wisconsin, the NR 500 series of rules cover all aspects of operation, maintenance and post closure monitoring of landfills; and includes NR 538 on the Beneficial Use of Industrial By-products.

The WDNR NR538 can be found on the web at:

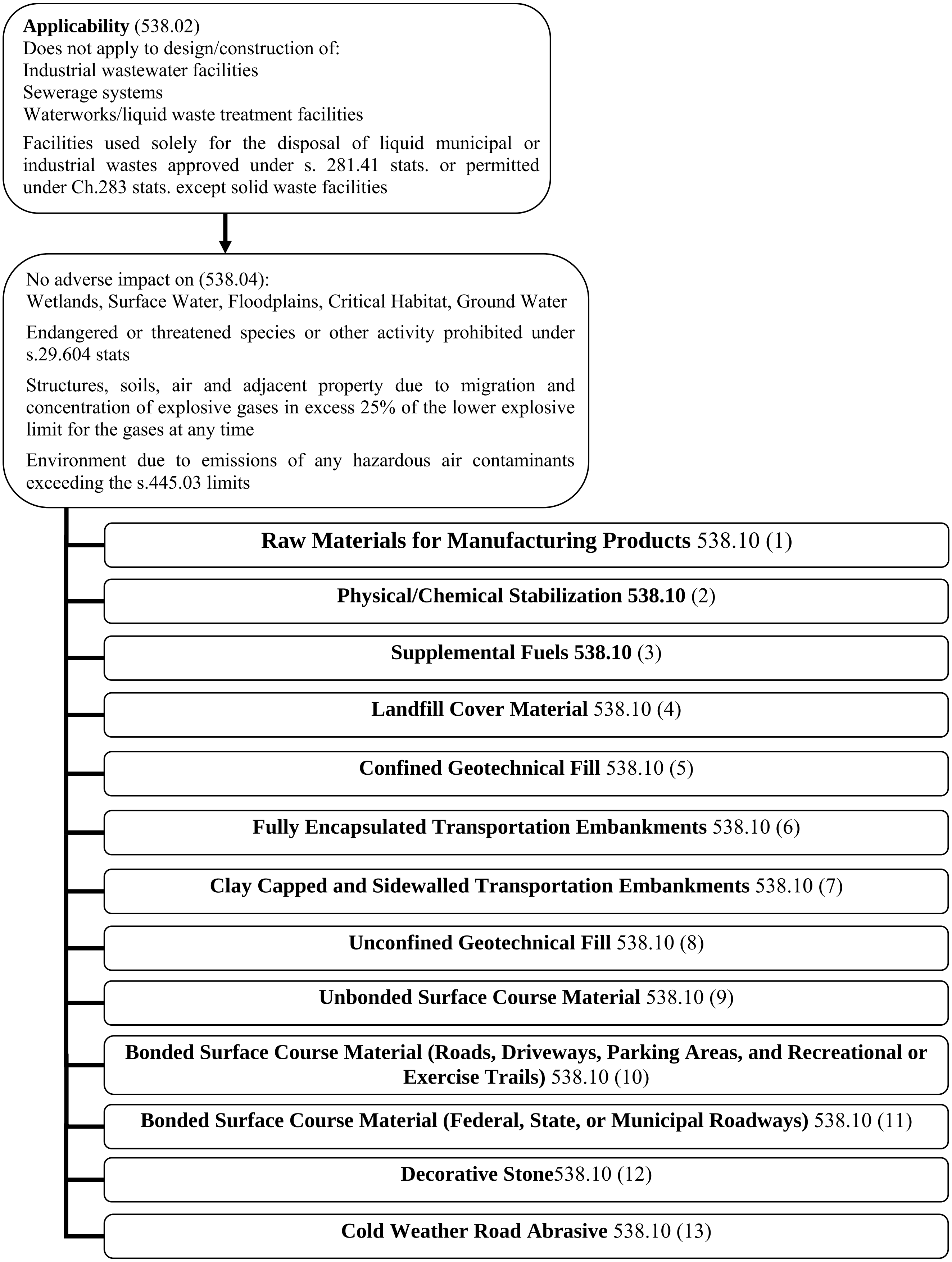
http://www.legis.state.wi.us/rsb/code/nr/nr538.pdf

Regulations of We Energies Ash Utilization - Michigan Department of Environmental Quality

The Michigan Department of Environmental Quality (MDEQ) is responsible for regulating ash utilization in Michigan. The regulations in Michigan are different than in Wisconsin. Fly ash has been used in concrete widely. However, other land applications have been limited. In the State of Michigan: Act 451 of 1994 (as amended) Part 115: Solid Waste Management, Section 324, covers all aspects of landfill design, permitting, construction, operation, maintenance and groundwater monitoring. The Section 324.11514, Promotion of Recycling and Reuse of Materials, covers beneficial use of industrial waste materials

Readers are referred to the following web location for Michigan statutes and rules:

http://www.deq.state.mi.us/documents/deq-wmd-swp-part115.pdf



Applicability (538.02)
Does not apply to design/construction of:
Industrial wastewater facilities
Sewerage systems
Waterworks/liquid waste treatment facilities

Facilities used solely for the disposal of liquid municipal or industrial wastes approved under s. 281.41 stats. or permitted under Ch.283 stats. except solid waste facilities

No adverse impact on (538.04):
Wetlands, Surface Water, Floodplains, Critical Habitat, Ground Water

Endangered or threatened species or other activity prohibited under s.29.604 stats

Structures, soils, air and adjacent property due to migration and concentration of explosive gases in excess 25% of the lower explosive limit for the gases at any time

Environment due to emissions of any hazardous air contaminants exceeding the s.445.03 limits

Raw Materials for Manufacturing Products 538.10 (1)

Physical/Chemical Stabilization 538.10 (2)

Supplemental Fuels 538.10 (3)

Landfill Cover Material 538.10 (4)

Confined Geotechnical Fill 538.10 (5)

Fully Encapsulated Transportation Embankments 538.10 (6)

Clay Capped and Sidewalled Transportation Embankments 538.10 (7)

Unconfined Geotechnical Fill 538.10 (8)

Unbonded Surface Course Material 538.10 (9)

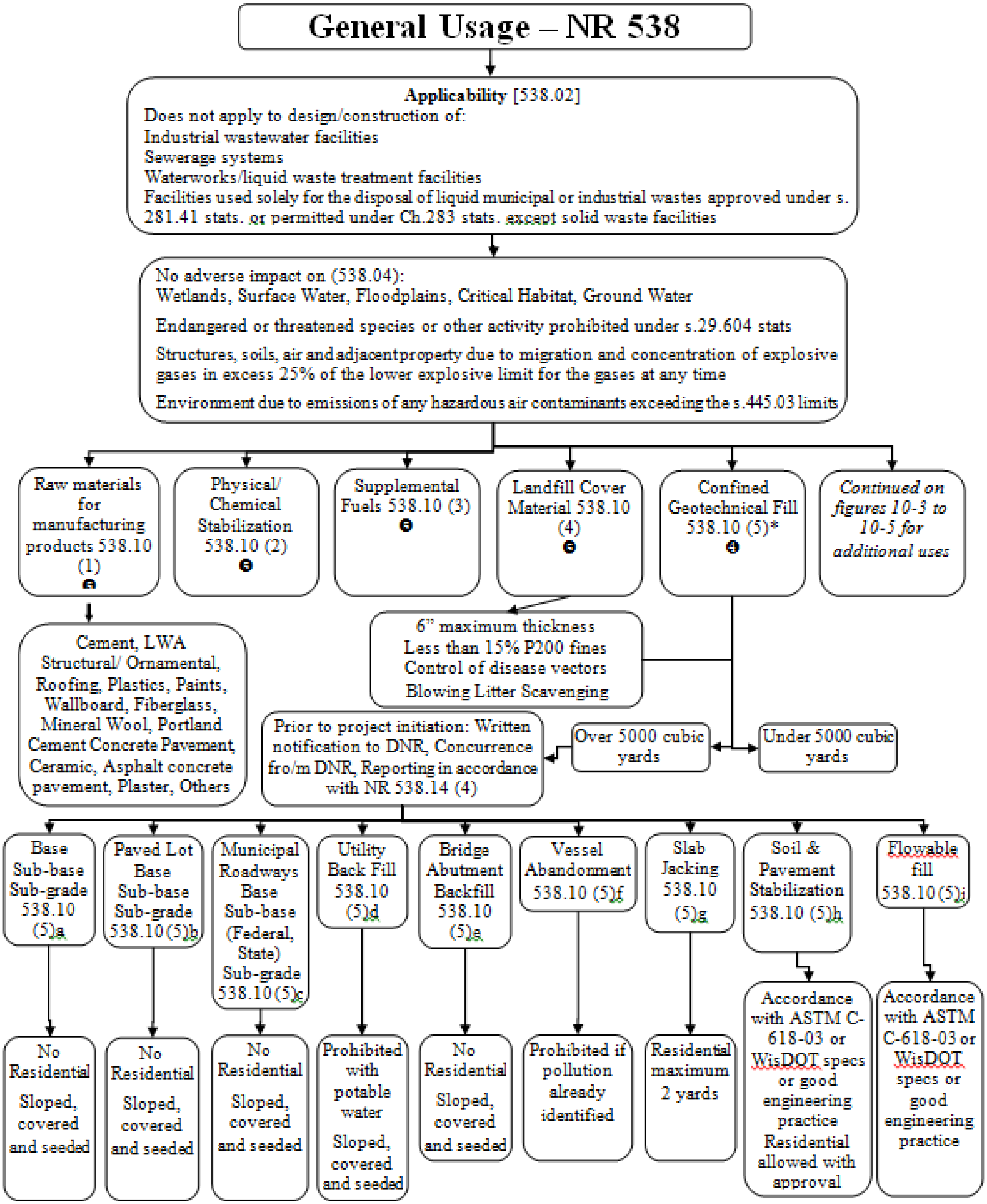
Bonded Surface Course Material (Roads, Driveways, Parking Areas, and Recreational or Exercise Trails) 538.10 (10)

Bonded Surface Course Material (Federal, State, or Municipal Roadways) 538.10 (11)

Decorative Stone538.10 (12)

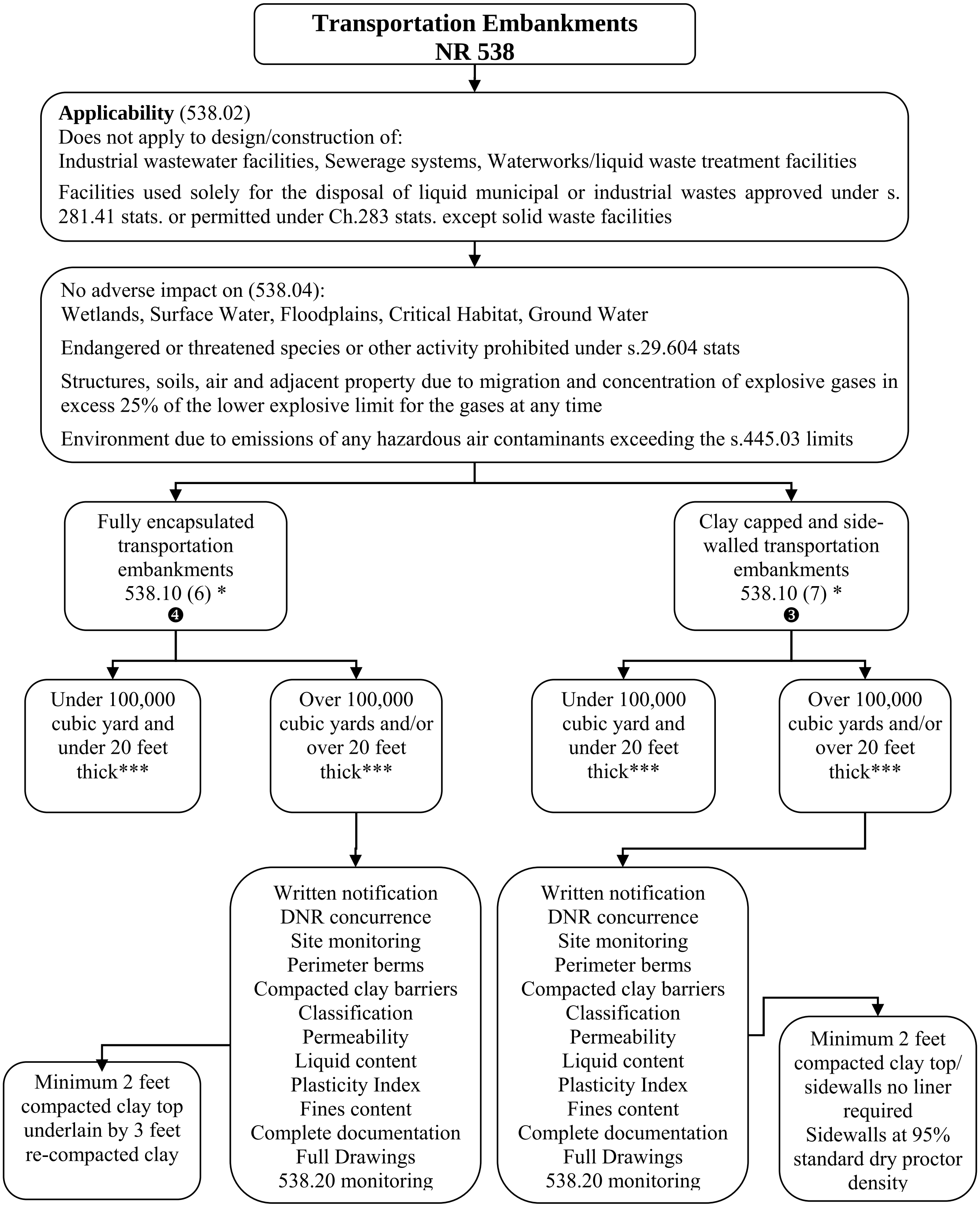
Cold Weather Road Abrasive 538.10 (13)

Figure 10-1: NR 538 Beneficial Use of Industrial By-Products



*Use Property Owner Notification – form 4400-199 Wisconsin DOT
**See attachments for details ***Use affidavit – form 4400-200 Wis.DOT
⓿ Industrial By-product Category – By product must have category number equal or lower than the one shown

Figure 10-2: Flow Chart for General Usage of Industrial By Products


Transportation Embankments
NR 538

Applicability (538.02)
Does not apply to design/construction of:
Industrial wastewater facilities, Sewerage systems, Waterworks/liquid waste treatment facilities
Facilities used solely for the disposal of liquid municipal or industrial wastes approved under s. 281.41 stats. or permitted under Ch.283 stats. except solid waste facilities

No adverse impact on (538.04):
Wetlands, Surface Water, Floodplains, Critical Habitat, Ground Water
Endangered or threatened species or other activity prohibited under s.29.604 stats
Structures, soils, air and adjacent property due to migration and concentration of explosive gases in excess 25% of the lower explosive limit for the gases at any time
Environment due to emissions of any hazardous air contaminants exceeding the s.445.03 limits

Fully encapsulated transportation embankments 538.10 (6) * ❹

Clay capped and side-walled transportation embankments 538.10 (7) * ❸

Under 100,000 cubic yard and under 20 feet thick***

Over 100,000 cubic yards and/or over 20 feet thick***

Under 100,000 cubic yard and under 20 feet thick***

Over 100,000 cubic yards and/or over 20 feet thick***

Written notification
DNR concurrence
Site monitoring
Perimeter berms
Compacted clay barriers
Classification
Permeability
Liquid content
Plasticity Index
Fines content
Complete documentation
Full Drawings
538.20 monitoring

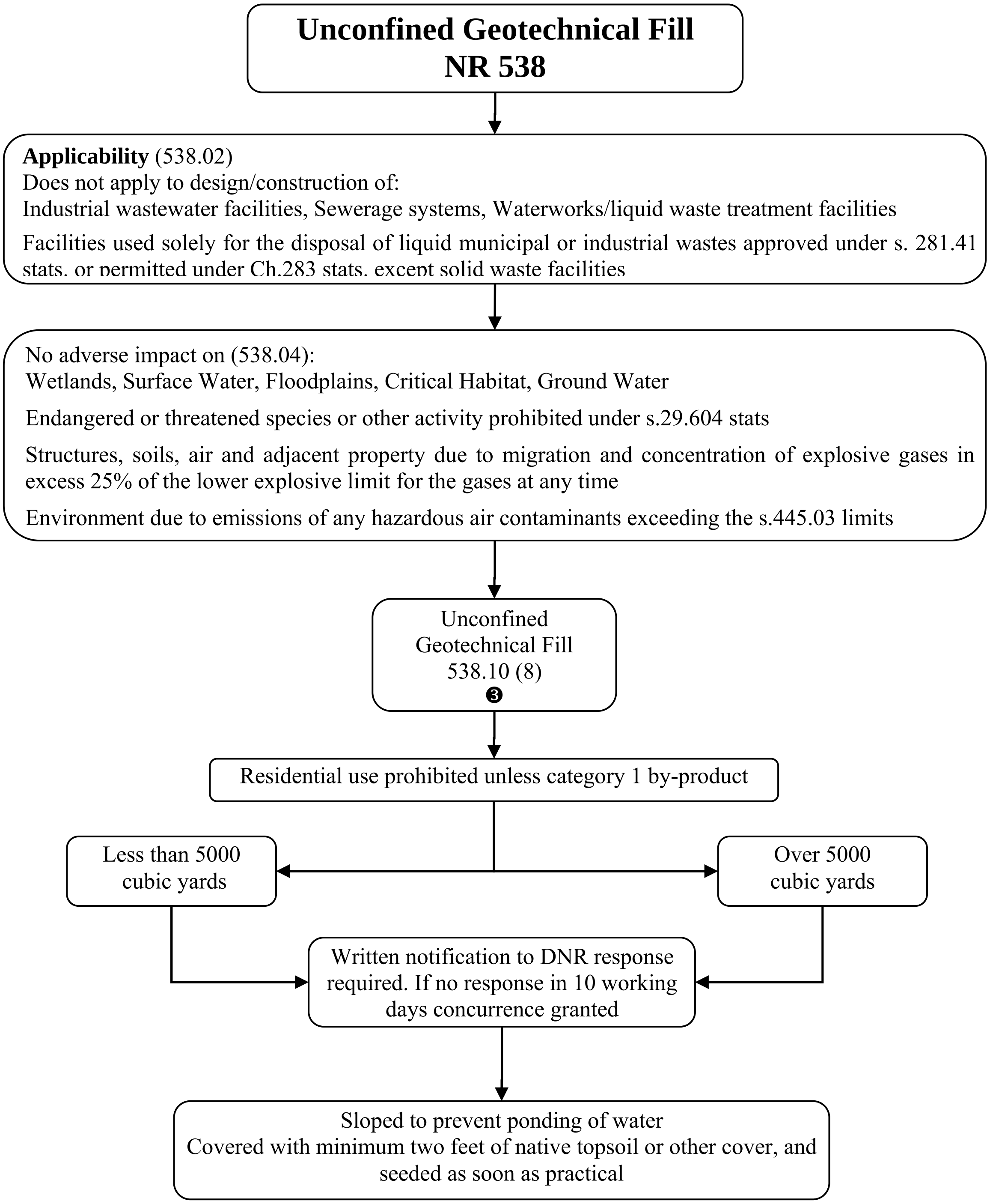
Written notification
DNR concurrence
Site monitoring
Perimeter berms
Compacted clay barriers
Classification
Permeability
Liquid content
Plasticity Index
Fines content
Complete documentation
Full Drawings
538.20 monitoring

Minimum 2 feet compacted clay top underlain by 3 feet re-compacted clay

Minimum 2 feet compacted clay top/ sidewalls no liner required
Sidewalls at 95% standard dry proctor density

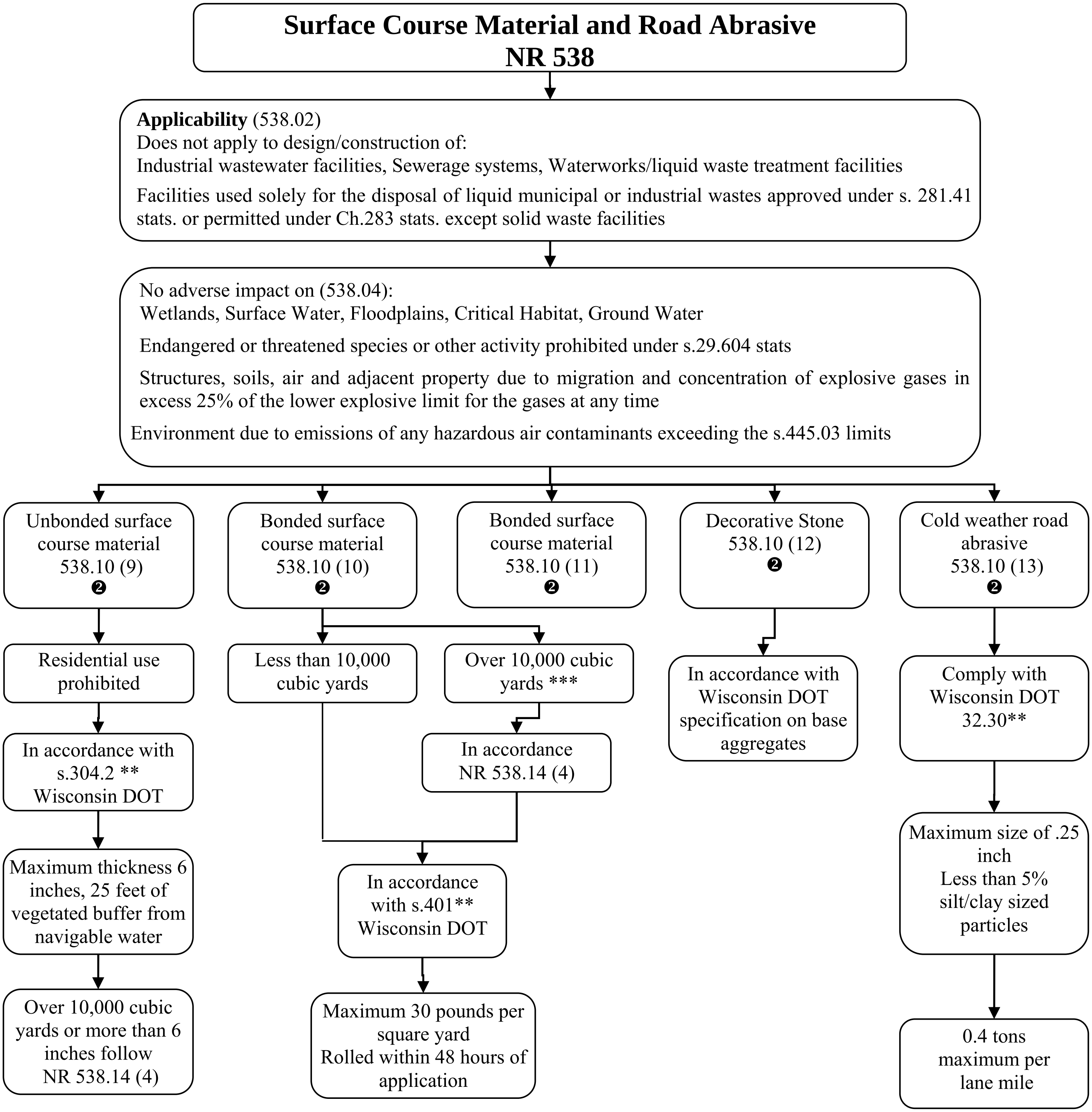
* Use Property Owner Notification – form 4400-199 Wisconsin DOT
** See attachments for complete details
*** Use affidavit – form 4400-200 Wisconsin DOT
⓿ Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure10-3: Flow Chart for Application of Industrial By-products in Transportation Embankments



* Use Property Owner Notification – form 4400-199 Wisconsin DOT
** See attachments for complete details
*** Use affidavit – form 4400-200 Wisconsin DOT
⓿ Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure10-4: Flow Chart for Application of Industrial By-products in Unconfined Geotechnical Fill



* Use Property Owner Notification – form 4400-199 Wisconsin DOT

** See attachments for complete details

*** Use affidavit – form 4400-200 Wisconsin DOT

⓿ Industrial By-product Category – By-product must have category number equal or lower than the one shown

Figure10-5: Flow Chart for Application of Industrial By-products as Surface Course Material and Road Abrasive

Ammonia Removal-Ash Beneficiation (US Patent 6,755,901)

Coal-fired power plants are utilizing several proven technologies to improve the quality of air emissions through the reduction of nitrogen oxides (NO_x). These include Low NO_x burners, Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), and Amine Enhanced Lean Gas Reburn (AEFLGR). These modifications and additions to coal-fired combustion systems normally result in additional residual carbon and/or ammonia compounds. We Energies has developed the ammonia liberation process (ALP) as a way to overcome the far reaching effects that the installation of NO_x reduction technologies may have. The process developed by We Energies employs the application of heat to liberate the ammonia compounds from the ash, consume undesirable carbon and render the ash a marketable product. The process design employs few moving parts to keep wear and maintenance low. The system is adaptable to meet the different ash characteristics generated by the various NO_x reduction systems as well as the quantity of ash needing beneficiation.

Ammonia Removal Process

The type of NO_x reduction process used typically determines the type and characteristics of the ammonia contaminants. In general the most common and abundant species are the bisulfate and sulfate forms. These species have the required removal temperatures of 813°F and 808°F, respectively. The ammonia liberating process preheats the ash and then feeds it to a processing bed where its temperature is increased to about 1,000°F with hot fluidizing air. The fluidizing air is supplied by a burner and forced through a porous metal media. This high temperature media provides support for the ash and distribution for the air flow. The heat breaks down or consumes the contaminants and the air flow carries the contaminants away from the ash. The ash leaves the processing bed and is cooled with a heat exchanger. This reclaimed heat can be used to preheat the incoming untreated ash. The clean ash is transferred to storage for subsequent use. The contaminated air flow leaving the processing bed is passed through a baghouse where any fugitive ash is captured and returned to the ash exiting the processing bed. The dust free ammonia laden gas may then be passed into a wet scrubber for removal of the contaminants for disposal or passed back into the combustion process or NO_x reduction process.

ALP Pilot Plant Test

We Energies has assembled and tested a small-scale prototype ALP unit. The unit is operated under the parameters described above. The properties of fly ash before and after the tests are shown below. The amount of ammonia in the ash was significantly reduced. The resulting fly ash is a marketable ash that could be beneficially utilized as a "green" construction material.

ASTM C-618 Class F Fly Ash
Ammonia Removal Results

Base Case - Ammonia Before Processing	160 mg/kg
Baghouse Ash – Ammonia After Processing	16 mg/kg
Product Bin Ash – Ammonia After Processing	Less than 2 mg/kg

ASTM C-618 Class F Fly Ash
Loss on Ignition Results

Base Case - LOI Before Processing	2.7%
Baghouse Ash - LOI After Processing	2.6%
Product Bin Ash – LOI After Processing	2.8%

High Carbon Bituminous Coal Fly Ash *
Loss on Ignition Results

Base Case - LOI Before Processing	16.2%
Baghouse Ash - LOI After Processing	9.9%
Product Bin Ash – LOI After Processing	7.2%

*(No Ammonia Present in Fly Ash)

Mercury Removal-Ash Beneficiation (Patent 7,217,401)

The emission of mercury compounds from all sources, including coal-fired power plants, has drawn national and international attention due to the fact that certain forms of mercury have deleterious effects on wildlife and can be toxic to humans. Activated carbon injection (ACI) is by far the most effective and widely accepted technology to remove mercury from the flue gas of power plants. However, the implementation of ACI ahead of the primary electrostatic precipitator (ESP) or baghouse will inevitably increase the mercury concentration and carbon content in coal ash.

We Energies conducted a study to develop and demonstrate a technology to liberate and recapture the mercury adsorbed onto activated carbon and fly ash, and provide high quality fly ash for reuse in concrete applications or to recycle sorbents used for mercury removal (88).

A bench scale study was done to select an optimum removal and combination of temperature and retention time to maximize mercury (Hg) recovery. Fly ash samples taken from Presque Isle Power Plant (PIPP) were used in the experiments. The total Hg concentration in the sample was determined by cold-vapor generation atomic fluorescence spectroscopy (AFS). Samples were treated in a muffle furnace in an inert atmosphere at different temperatures ranging from 371°C to 538°C for retention times of one to five minutes. A nitrogen atmosphere was maintained to keep the carbon from igniting. The percent of Hg liberated from the ash samples was determined by measuring the total Hg left in the ash after thermal treatment. PIPP fly ash Units 5 & 6 was derived from western bituminous coal and collected using a precipitator. The original total Hg concentration in the sample was 0.42 ppm. The results indicated that both temperature and retention time are important parameters in the thermal desorption process. At temperatures lower than 482°C, the maximum Hg removal was 40% even with prolonged thermal treatment. More Hg can be removed with higher temperature and longer treatment. At 538°C, 90% of the Hg was liberated from the fly ash within four minutes. Figure 10-6 shows the rate of Hg removal from PIPP fly ash in the muffle furnace using different combinations of temperature and retention time.

Based upon the test results obtained from the bench scale study, a test program was designed to generate experimental data from a pilot apparatus. The pilot test apparatus is comprised of seven main components: a cone-shaped hopper, air slide, baghouse, burner, collector underneath the air slide, Hg condenser, and wet scrubber. During each fly ash processing run, samples were fed into the air slide through the cone-shaped hopper. The speed of sample going through the system was controlled by a rotary feeder. Inside the air slide, samples were heated by hot air coming from the burner. The temperature inside the air slide was controlled by adjusting the air flow rate of the burner. A data logger connected to five thermocouples located at the burner, baghouse inlet, and the inlet, midpoint and outlet of the air slide, were used to record the temperature readings. After traveling through the air slide, part of the sample went to the collector at the discharge end of the air slide and the rest of the sample went to the baghouse. Hot air that exited the baghouse passed through a mercury condenser and wet scrubber before being emitted into the ambient environment. Fly ash samples from Presque Isle Power Plant (PIPP), Valley Power Plant (VAPP) and Pleasant Prairie Power Plant (PPPP) were used for the pilot study. Hg concentration and carbon content were measured before and after thermal treatment for comparative purposes. Loss on ignition was used as the indicator of carbon content.

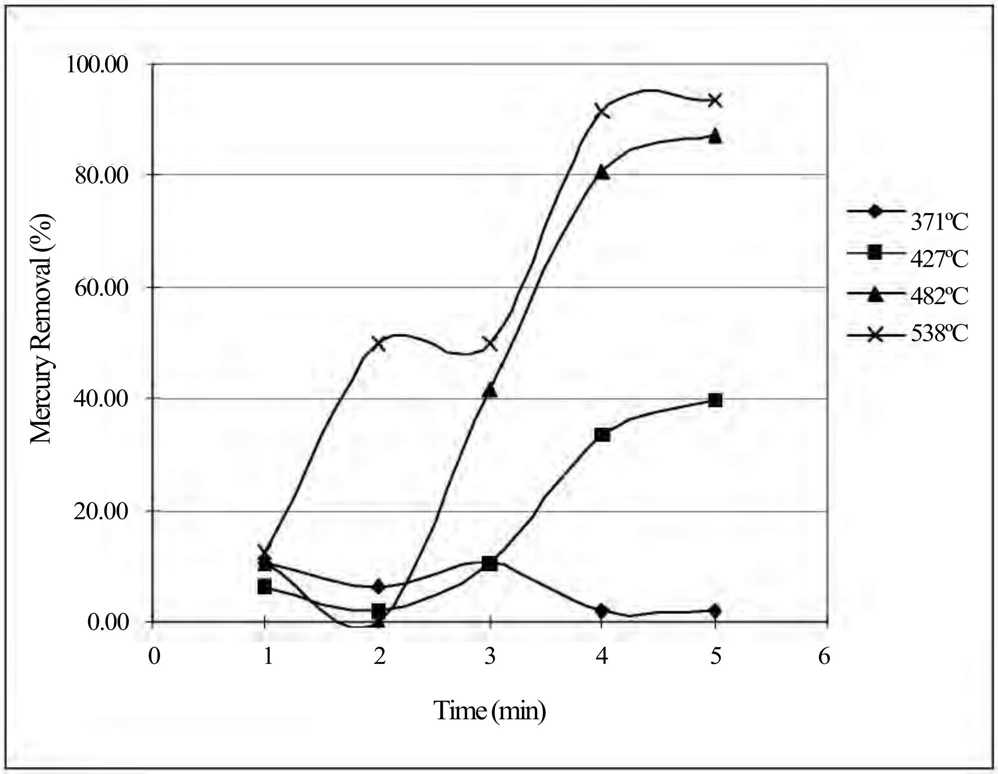


Figure 10-6: Effect of temperature and retention time on mercury removal from PIPP fly ash.

A total of ten fly ash samples from three different power plants were used in the pilot study. The pilot study was conducted in two phases: first, ash samples (two from PIPP, one from PPPP and one from VAPP) were treated in the pilot scale apparatus under fixed temperature and rotary feeding rate (retention time); second, fly ashes (three split samples from PIPP and three split samples from PPPP) were tested under different temperatures and rotary feeding speed. The Hg concentrations in these fly ash samples ranged from 0.11 ppm to 1.00 ppm. For each test in phase one, the initial temperature of the air slide inlet was set at 538°C and the rotary feeding speed was set at 1000 rpm. The results of these tests are shown in Table 10-16. All four initial tests indicated that Hg could be liberated from various ash samples at 538°C using the pilot scale apparatus. The majority of the sample passing through the air slide discharged to the collector under the air slide with very low concentrations of Hg detected in these samples. A small proportion of the sample passed with the air flow to the baghouse and contained a higher Hg content.

Table 10-16: Phase I Pilot test data of Mercury Liberation from PIPP, PPPP and VAPP Samples at 538°C and Rotary Feeding Speed of 1000rpm

Sample Description		PIPP-I	PPPP	VAPP	PIPP-II
Samples collected before Experiment					
	Hg Content (ppm)	0.18	0.97	0.20	0.15
	Loss on ignition	26.7	3.2	33.5	21.7
Samples collected under the air slide					
	Hg content (ppm)	0.05	0.14	0.03	0.03
	Hg Removed (%)	74.4	85.6	84.5	79.3
	Loss on Ignition	38.1	9.8	36.9	26.1
Samples collected under the Baghouse					
	Hg content (ppm)	0.38	1.00	0.38	0.32
	Hg Increased (%)	111.1	3.1	90.0	113.3
	Loss on Ignition (%)	22.6	10.5	26.9	22.0

Further experiments were performed to determine how temperature and rotary feeding speed would impact the Hg desorption process using PIPP and PPPP samples. Three experiments were run with the rotary feeder speed set at 800, 1000 and 1200 rpm and the air slide inlet temperature set at 538°C using PIPP samples. The initial Hg content in these samples was around 0.14 ppm. PPPP samples were treated with different heating temperatures, 538°C, 593°C and 649°C and the rotary feeder speed fixed at 1000 rpm. The results are shown in Table 10-17.

Data analysis shows no obvious correlation between the rotary feeding speed and Hg removal. The Hg content in fly ash samples collected under the air slide was 77.3% to 89.3% lower than that found in the original samples. It is possible that rotary feeder speed does not significantly impact the retention time of samples in the air slide.

Table 10-17: Effects of Temperature and Retention Time on Mercury Liberation (Pilot Test Phase II)

Sample Description			**PIPP**			**PPPP**	
Experiment Sequence		1st	2nd	3rd	4th	5th	6th
Rotary Feeder Speed (RPM)		800	1000	1200	1000	1000	1000
Temperature (ºF)		538	538	538	538	593	649
Samples collected before Experiment							
	Hg Content (ppm)	0.14	0.14	0.11	0.69	0.62	1.00
	LOI (%)	25.7	25.3	26.6	2.7	2.6	2.7
Samples collected under the air slide							
	Hg content (ppm)	0.025	0.015	0.025	0.10	0.054	0.055
	Hg Removal (%)	82.14	89.29	77.27	85.51	91.29	94.50
	LOI (%)	42.3	31.3	14.6	3.2	1.9	1.8
Samples collected in the Baghouse							
	Hg content (ppm)	0.38	0.40	0.36	0.81	1.2	1.4
	Hg Increased (%)	171.43	185.71	227.27	17.39	93.55	40.00
	LOI (%)	22.7	20.9	20.5	5.3	3.9	4.0

Multi-Pollutant Control Using TOXECON Process

We Energies demonstrated the EPRI Toxecon process system at the Presque Isle Power Plant (PIPP) located in Marquette, MI. The Toxecon process (shown in Figure 10-7) captures high particulate matter (PM) in pulsed-jet baghouses coupled with activated carbon injection (sorbent technology) to achieve high mercury capture. It can capture over 90% of the mercury contained in the combustion process emissions with mercury fixation on the activated carbon.

The separation of mercury from the powdered activated carbon (PAC) would potentially allow for mercury sorbent regeneration and reuse the exhausted activated carbon through thermal desorption (90).This research used both a pilot-scale high temperature air slide (HTAS) – U.S. Patent 7,217,401 (104) and bench-scale thermogravimetric analyzer (TGA) demonstrating this thermal removal of mercury in spent powdered activated carbon from the Toxecon process. "The HTAS removed 65, 83, and 92% of mercury captured with PAC when ran at 900ºF, 1000ºF, and 1200ºF, respectively, while the TGA removed 46 and 100% of mercury at 800ºF and 900ºF, respectively. Scanning electron microscopy images and energy dispersive X-ray analysis show no change in PAC particle aggregation or chemical composition. Thermally treated sorbents had a higher surface area and pore volume than the untreated samples indicating regeneration. The optimum temperature of PAC regeneration in the HTAS was 1000ºF. At this temperature, the regenerated sorbent had sufficient adsorption capacity similar to its virgin counterpart at 33.9% loss on ignition. Consequently, the regenerated PAC may be recycled back into the system by blending it with the virgin PAC" (90).

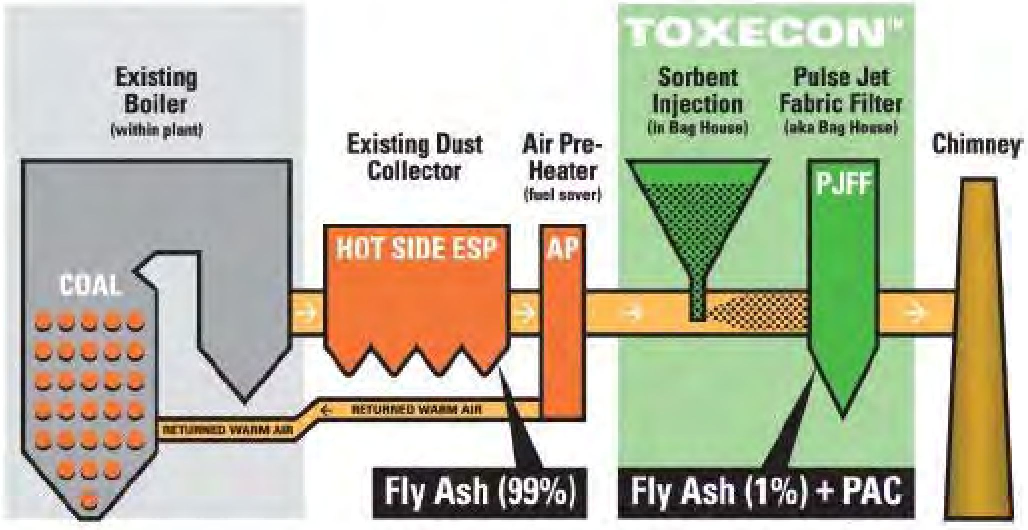


Figure 10-7: Incorporation of the Toxecon equipment to an existing plant's particulate control device

U.S. EPA Mercury Emission Regulation

Based on the Federal Requirements to regulate mercury emissions from power plants, the U.S. EPA issued a maximum available control technology rule (MACT) under Section 112 of the Clean Air Act for mercury requiring a 91% reduction in mercury emissions from coal-fired power plants.

Use of Ash Landfill Leachate (Mineral Water) in Concrete (U.S. Patent 8,236,098)

Coal combustion products (CCP) such as fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) materials are beneficially used extensively in the construction and building industries. Excess CCP are commonly stored today in monofill landfills that are lined, covered, and constructed with leachate collection systems. Once collected, the leachate is typically trucked or piped to a wastewater facility for treatment at a cost. The leachate is composed of water from stabilization, precipitation, dust control, and compaction and is enriched with minerals from the CCP placed in the landfill. The monofill landfill leachate is therefore rich in CCP constituent elements and minerals such as calcium, sodium, potassium, boron, magnesium, sulfate, chloride, aluminum, silica, and other trace elements, many of which can be helpful as activators in cementitious reactions during concrete production. Consequently, the landfill leachate can be used as mixing water for concrete production with beneficial effects of increased compressive strength, reduced shrinkage, and accelerated hydration. For example, a building material such as “green” bricks could be manufactured using mineral rich leachate water as an ingredient while conserving normally used drinking water. Benefits include conservation of fresh water sources, reduced loading on wastewater treatment facilities, beneficial effects to concrete products, and eliminating the costs associated with purchasing drinking water as an ingredient as well as the cost of wastewater treatment. We Energies has a patent pending for the use of monofill CCP leachate in concrete production.

Materials for Making Concrete

The materials for making concrete and other building materials may include Portland cement, pozzolan, specialty admixtures, aggregates and liquid landfill leachate. The composition of these materials will depend on the function and the properties of the finished product but will have a compressive strength suitable for various construction applications.

Concrete mixtures generally use only sufficient water to make the mixture workable for placement and to yield hardened concrete having a compressive strength of greater than 8.3 MPa (1200 psi) after 28 days of curing. Portland cement is a well-known cement that upon mixing with water binds the other materials present in the mixture into concrete. Typically, fresh concrete has mixing water exceeding the amount needed for hydration for purposes of workability, handling, and finishing. Sulfate in small prescribed amounts can yield a shrinkage compensating effect, and actually reduce shrinkage cracking in concrete. In fact, specialty Type K cements are produced specifically to yield this effect.

A concrete may also be made from a composition including pozzolan. A pozzolan is a siliceous or aluminosiliceous material, which independently has few or fewer cementitious properties, but in the presence of an activator such as a lime-rich medium such as calcium hydroxide, shows better cementitious properties. Examples of pozzolans include fly ash, silica fume, metakaolin, ground granulated blast furnace slag, and some finely divided natural minerals.

Various activators are suitable for use with pozzolans in a composition. For example, the activator can be selected from alkali metal carbonates, alkali metal silicates, alkali metal hydroxides, alkali metal oxides, alkali metal fluorides, alkali metal sulfates, alkali metal carboxylates, alkali metal nitrates, alkali metal nitrites, alkali metal phosphates, alkali metal sulfites, alkali metal halides, alkaline earth metal carbonates, alkaline earth metal silicates, alkaline earth metal hydroxides, alkaline earth metal oxides, alkaline earth metal fluorides, alkaline earth metal sulfates, alkaline earth metal carboxylates, alkaline earth nitrates, alkaline earth metal nitrites, alkaline earth metal phosphates, alkaline earth metal sulfites, alkaline earth metal halides, and other mixtures. Sodium, potassium and lithium are examples of alkali metals, whereas magnesium and calcium are examples of alkaline earth metals. The activator can also be selected from calcium oxide, calcium hydroxide, calcium silicate, and calcium carbonate. In addition, activators can be either Portland cement or cement kiln dust or an organic acid such as citric acid.

The amount of Portland cement, pozzolan, activator, aggregate, and landfill leachate can be varied depending on the physical properties desired in the building materials. The compressive strength of a concrete can be controlled by varying the weight ratio of Portland cement to pozzolan (e.g., fly ash). The liquid landfill leachate may replace all or part of the tap water to produce a concrete. The pH and conductivity of the liquid landfill leachate may range from 8 to 11, and 1000 to 100,000 micromhos, respectively. Air-entrainment of 5% or higher by weight may be included to provide workability and increased resistance to deterioration of the concrete due to freezing and thawing cycles.

Water is needed in the production of concrete to provide a media for hydration reactions, and to facilitate the production of a material which is workable and easy to place and compact. The landfill leachate provides both the media for hydration and elements and minerals which can act as activators in cementitious reactions. Higher performance concrete is made when hydration reactions are accelerated and shrinkage is reduced with increased compressive strength when compared to concrete made in a conventional way.

Acceleration of hydration of cement in concrete results in a more rapid increase in setting time and compressive strength. Liquid landfill leachate can be utilized in a sufficient amount such that the composition sets in the desired timeframe with the specified compressive strength.

Materials used in the examples

Type I Portland cement with a specific gravity of 3.15 and a Blaine fineness of 380 m^2/kg was used. The Portland cement complied with ASTM C 150-07. Fly ash conforming to ASTM C 618-05 Class C, and having physical and chemical properties in Table 10-18 and Table 10-19 was used. The coarse aggregate used was crushed quartzite of 25 millimeters (about 1 inch) maximum size with a specific gravity of 2.65, and water absorption of 0.15%.The fine aggregate used was local natural sand with a fineness modulus of 2.71, a specific gravity of 2.65, and water absorption of 0.5%.The air-entraining admixture used was MB-AE 90 with a recommended dosage ranging from ¼ to 4 fl oz/cwt (16-260 mL/100 kg) of cementitious material. It was supplied by BASF to provide air-entrainment of 5% or higher.

Table 10-18: Chemical Properties of Fly Ash

Chemical Properties	Weight %
SiO_2	39.75
Al_2O_3	21.14
Fe_2O_3	5.41
$SiO_2+Al_2O_3+Fe_2O_3$	66.30
CaO	20.60
MgO	4.27
SO_3	1.95
Na_2O	1.65
K_2O	0.68
LOI	0.69

Table 10-19: Physical Properties of Fly Ash

Physical Properties	Amount
Moisture content	0.04%
Fineness amount retained on #325 sieve	15.9%
Density	2.55 Mg/m^3
Shape	Spherical of average size of 10µm

Tap water from the Milwaukee Water Works, Milwaukee, Wisconsin, USA was used for the base case. Based on a 2008 Annual Water Quality Report, this tap water had (among other things) a maximum pH of 7.80, a maximum conductivity of 335 micromhos, a maximum boron concentration of 0.022 mg/L, maximum concentration of calcium of 38.0 mg/L, a maximum concentration of iron of 0.076 mg/L, a maximum concentration of magnesium of 13 mg/L, a maximum concentration of potassium of 1.6 mg/L, a maximum concentration of sodium of 13.0 mg/L, and a maximum concentration of sulfate of 27.0 mg/L.

Landfill leachate from a landfill having coal combustion products such as fly ash and bottom ash was used for comparison. The landfill leachate had a pH of 10.1, a conductivity of 21,100 micromhos, boron concentration of 53 mg/L, calcium concentration of 220 mg/L, iron concentration of 0.035 mg/L, magnesium concentration of 72 mg/L, potassium concentration of 80 mg/L, sodium concentration of 5,300 mg/L, and sulfate concentration of 11,000 mg/L.

Mixture Proportions Used in "Proof of Concept" Examples

Four concrete mixtures were tested. These included two reference mixtures based on tap water and fly ash, designated as RFA below and a tap water and fly ash-Portland cement blend (56:44), designated as RBC below. These concretes (RFA/RBC) were compared with concretes of similar composition based on landfill leachate in place of tap water (designated as WFA/WBC). The specified concrete mixture proportions (in lbs per yd^3) are presented in Table 10-20.

Table 10-20: Summary of the Mix Proportions Used in the Examples

	Case 1 (RFA/WFA)	**Case 2 (RBC/WBC)**
Class C Fly Ash	700	382
Portland Cement	0	305
Water* (approximately)	270	270
¾ " Coarse Aggregate	1810	1810
Sand	1450	1450
Water/Cementitious materials ratio (estimate)	0.40	0.40

* For a 4-5" slump

Normally, the application of at least three aggregate types is recommended to meet the requirements for optimal aggregate proportioning. With the aggregates used, the 55:45 coarse aggregates – fine aggregates (sand) mix provides the best particle size distribution that matches the optimal 0.45 power curve (as shown in Table 10-21). The concrete mixtures were designed for a relatively low w/c of 0.44 and a water content of 275-290 lbs/yd^3. The water content was adjusted to provide a slump of 5.5±2.5 inches. The air-entraining admixture content was also adjusted for mixtures RFA, RBC, WFA, WBC, respectively. The resulting (corrected for the yield) concrete mixture proportioning per yd^3 is presented in Table 10-22.

Table 10-21: Particle Size Distribution of Aggregates

Sieve Size		Aggregates Passing, %			
No./in	**mm**	**Coarse**	**Sand**	**Mix**	**0.45 power mix**
1.5	37.5	100.0	-	100.0	100.0
1	25.0	100.0	-	100.0	100.0
0.75	19.0	98.0	-	98.9	88.4
0.50	12.5	49.0	-	71.7	73.2
0.38	9.5	29.4	100.0	60.8	64.7
No. 4	4.75	2.0	99.8	45.5	47.4
No. 8	2.36	-	87.8	39.1	34.6
No. 16	1.18	-	71.6	31.9	25.3
No. 30	0.60	-	51.4	22.9	18.7
No. 50	0.425	-	14.8	6.6	16.0
No. 100	0.150	-	3.9	1.7	10.0
No. 200	0.075	-	1.6	0.7	7.3

Table 10-22: Concrete Mixture Proportions

Composition	Unit	Mixture Type			
		RFA	**RBC**	**WFA**	**WBC**
Cement	lb/yd^3	-	286	-	276
Fly Ash	lb/yd^3	628	359	658	346
Tap Water	lb/yd^3	278	286	-	-
Landfill leachate	lb/yd^3	-	-	291	275
Coarse Aggregates	lb/yd^3	1625	1700	1702	1639
Sand	lb/yd^3	1302	1363	1364	1314
Air-Entraining admixture	gal/yd^3	0.22	0.11	0.23	0.11

Casting and Curing of Test Specimens

All the concrete mixtures were mixed for 5 minutes in a laboratory drum mixer. The ASTM C-192 “Standard Practice of Making and Curing Concrete Test Specimens in the Laboratory” was used for the preparation of concrete specimens. Tests were conducted on fresh concrete mixtures to determine slump, temperature, air content, unit weight (density), yield of fresh concrete, and setting times (initial and final). From each concrete mixture, 21 (three for each age tested) 100 x 200 mm (4” x 8”) cylinders were cast to determine compressive strength at the age of 1, 3, 7, 14, 28, 56 and 91 days. The specimens were cast in two layers with vibration. Linear shrinkage or expansion of concrete was investigated using 3” x 3” x 11” beams, using three specimens for each mix. After casting, all molded specimens were covered with plastic sheets and left in the curing room for 24 hours. They were then demolded and the specimens were returned to the moist-curing room at 73.4 ± 3^{o}F (23.0 ± 1.7^{o}C) and 96 ± 1% relative humidity (RH) until they reached the testing age.

Testing of Fresh Concrete

The following properties of fresh concrete were investigated: Slump in accordance with ASTM C-143 “Standard Test Method for Slump of Hydraulic Cement Concrete”; Fresh Density (Unit Weight) in accordance with ASTM C-138 “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete”; Air Content in accordance with ASTM C-231 “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method”; and Setting Time in accordance with ASTM C-403 “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance”. The results are presented in Table 10-23.

Testing of Mechanical Properties

The compressive strength of each concrete mixture was determined following ASTM C-39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” on three cylinders at 1, 3, 7, 14, 28, 56, and 91 days. The mean value of the three cylinder strengths at a particular age was reported as the compressive strength value. The results are also presented in Table 10-23.

Table 10-23: Fresh Properties, Compressive Strength and Shrinkage of Investigated Concretes

Properties		**Units**	**Mixture Type**			
			RFA	**RBC**	**WFA**	**WBC**
Fresh	Density (Unit Weight)	lb/ft^3	148	154	155	149
	Density (Unit Weight)	lb/yd^3	3837	3994	4018	3851
	Air Content	%	5.5	5.5	5.8	6.5
	Slump (after 5 min)	in	8.0	5.5	8.0	6.0
	Slump (after 15 min)	in	4.5	3.5	3.0	5.0
	Initial Setting	hour:min	0:30	16:40	0:50	11:50
	Final Setting	hour:min	1:10*	24:55	1:40*	15:50
	Compressive Strength					
Hardened	1 day	psi	319	164	180	522
	3 days	psi	598	1,484	195	2,601
	7 days	psi	940	3,118	248	3,445
	14 days	psi	1,148	4,053	280	4,357
	28 days	psi	1,242	4,816	394	5,627
	56 days	psi	1,532	5,897	434	6,310
	91 days	psi	1,567	7,084	437	6,991
	Deformation Strain,**					
	14 days	in/in x10^{-6}	17	55	-27	39
	28 days	in/in x10^{-6}	11	27	-7	15
	56 days	in/in x10^{-6}	-141	-300	-105	-264
	91 days	in/in x10^{-6}	-211	-323	-95	-300

* Final setting was not detectable for #1 and #3; reported values were obtained by interpolation of experimental data.

** Positive and negative signs correspond to expansion (swelling) and shrinkage respectively; exposure conditions: until the age of 28 days curing at 73 °F and 95% RH; afterwards, environmental exposure at 73 °F and 50% RH.

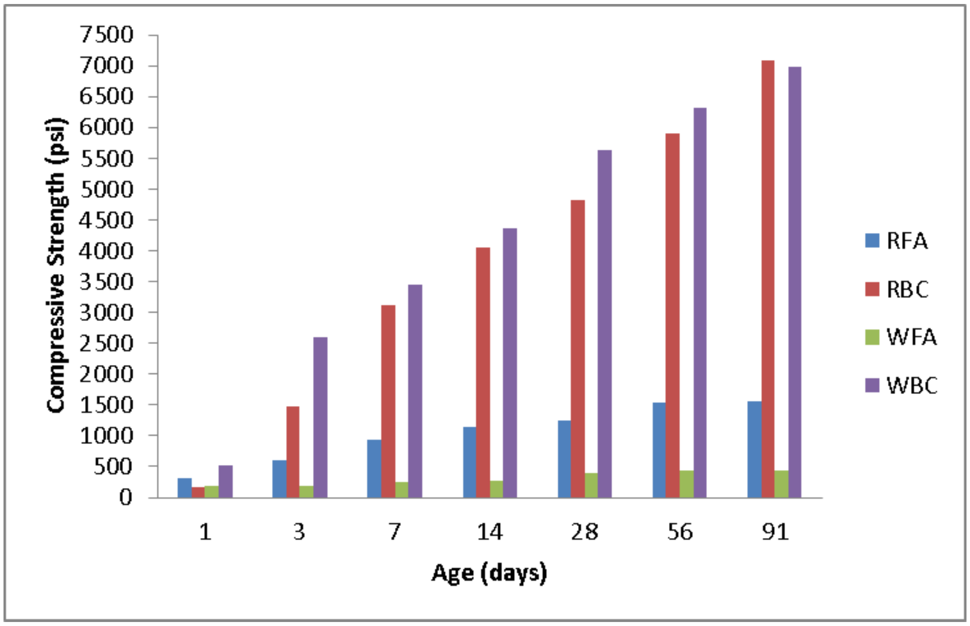


Figure 10-8: Compressive strength comparison of the four different mixtures of concrete. RFA –reference mixture with fly ash. RBC -reference mixture with blend of fly ash and Portland cement. WFA and WBA have similar composition with mixture of special processed water

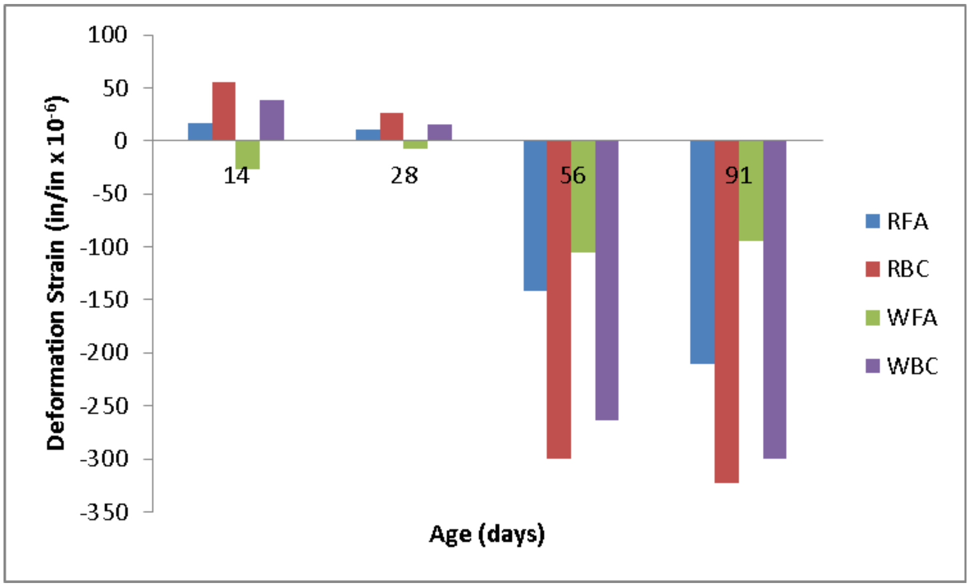


Figure 10-9: Deformation strain of the four different mixtures of concrete. Positive and negative deformation strain corresponds to the expansion (swelling) and shrinkage respectively.

Testing of Shrinkage

Water content, mortar paste fraction, admixture selection, cement and pozzolan types and quantities, coupled with aggregate characteristics and mix design proportions have the most significant impact on concrete's drying shrinkage characteristics. Careful selection of these variables is critical. ASTM C-157, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" was used to determine the length change of hardened fly ash concrete. The results are presented in Table 10-23 and Figure 10-9 above.

Results and Discussion

Fresh Concrete Properties

The initial slump of the investigated concrete mixtures was in the range of 5.5 to 8 inches. The Class C fly ash (only cementitious material) concretes demonstrated very quick slump loss, after 15 minutes reaching 56 and 38% of initial slump value or 4.5 and 3 inches for the RFA and WFA concretes respectively. All investigated concrete mixtures presented had air content between 5.5% and 6.5%. However, it should be noted that to provide the above-mentioned air content, the fly ash-based mixtures required a relatively high dosage of air-entraining admixture.

The average temperature of the concrete mixtures was 74 ± 2 ºF. The Class C fly ash (only cementitious material) concretes demonstrated very quick setting, with an initial setting time of 30 and 50 minutes for the RFA and WFA concretes respectively. Because of low strength and specimen rupture, it was impossible to determine the final setting time for these types of concretes; thus, final time values were obtained by extrapolating the experimental data. For practical application of such concrete, the addition of retarding admixture is required to extend the setting times to acceptable levels. Specimens RBC and WBC had extended initial/final setting times of 16:40/24:55 and 11:50/15:50 respectively, which is a clear sign of retarded hydration of cement. Consequently, it can be noted that the application of landfill leachate (specimen WBC) allows considerable acceleration of hydration resulting in shorter setting times.

Mechanical Properties

The compressive strength of the investigated concrete is shown in Table 10-23 and Figure 10-8 above. The control concrete based on fly ash developed higher compressive strengths as compared with Portland cement-fly ash concrete at an age of one day. Concrete based on fly ash-Portland cement blend had a higher compressive strength (vs. RFA) after three days of hardening. At the age of 91 days, such concrete had more than a four-fold increase of compressive strength as compared with the reference fly ash concrete. The application of landfill leachate in fly ash concrete (specimen WFA) reduced strength as compared with RFA in all ages of hardening. However, the application of landfill leachate (specimen WBC) in concrete based on fly ash-Portland cement blend considerably improves early (seven days and less) strength and provides better strength through the 56-day age and near the same strength at the 91 day age (6991 psi vs. 7084 psi).

Shrinkage Properties

The results of shrinkage tests are reported in Table 10-23 and Figure 10-9. At the age of 91 days, the control fly ash-based concrete (RFA) demonstrated only 65% of shrinkage as compared with Portland cement-fly ash concrete, 211 vs 323 microstrain, respectively. The application of landfill leachate (specimens WFA and WBC) reduces shrinkage as compared with its corresponding reference concrete. For example, for concrete based on fly ash-Portland cement blend, the shrinkage reached 323 and 300 microstrain, for tap water and landfill leachate specimens respectively. Interestingly, the application of landfill leachate also resulted in reduced swelling (due to exposure to 95% RH until 28-day age). Fly ash concrete with landfill leachate (specimen WFA) had a very low drying shrinkage at the ages of 56 and 91 days (105 and 95 microstrain) respectively.

Conclusions

It can be seen from the tests above that the use of landfill leachate to produce concrete can be beneficial. The application of landfill leachate does not cause any pronounced difference in workability of investigated fly ash concrete. Fly ash concretes demonstrated very quick setting, with initial setting time of 30 and 50 minutes for RFA and WFA concretes respectively. The use of landfill leachate on fly ash-Portland cement-based concrete (specimen WBC) allows considerable acceleration of hydration that result in shorter setting times as compared with the reference (RBC).

The conducted investigation demonstrates that the replacement of tap water with landfill leachate results in fly ash-Portland cement-based concrete with significantly enhanced strength, especially in early ages of hardening. The observed performance improvement is a very important feature related to the application of landfill leachate, which can be effectively used in many practical construction applications such as producing concrete for precast products, highways, and cast-in-place applications.

It has been demonstrated that the application of landfill leachate results in reduction of shrinkage as compared with corresponding reference concrete. For concrete based on fly ash-Portland cement blend, the 91-day shrinkage reached 323 and 300 microstrain for tap water and landfill leachate specimens respectively. The application of landfill leachate also resulted in reduced swelling, suggesting the formation of a less porous microstructure, hindering shrinkage-swelling deformation of concrete.

It can therefore be seen that the application of landfill leachate provides an economically advantageous means of using coal combustion products sustainably. The methodology described herein, produces concrete with increased compressive strength, reduced linear shrinkage, and accelerated hydration of cement. Fresh water, as a sometimes scarce natural resource is also conserved.

Chapter 11

Carbon Dioxide is a Coal Combustion Product

Introduction

Carbon dioxide (CO_2) gas is used for various commercial applications, including food grade food processing and industrial gases. In the case of food processing, soft drink beverage carbonation processes are volumetrically small applications and require conformance with a stringent purity standard. Production of food grade carbon dioxide is relatively inexpensive, generated by air stripping methods with a high level of control over contaminants and undesirable constituents affecting health, odor and taste.

Industrial CO_2 uses include refrigeration and cooling applications, metals treatment (hardening agent), welding (shield gas to prevent oxidation), sand-blasting (solid form), propellant (aerosol cans), dry cleaning (replacing solvents), cold sterilization (with ethylene oxide), coffee de-caffeination, fire extinguishers and pH adjustment (reduction) in sewerage treatment plants.

Virtually all of the commercial or industrial uses for CO_2 involve a process which ultimately releases the unreacted or excess gas to the atmosphere. Energy used to capture CO_2 during refinery operations, the largest source of CO_2 production, is incidental to the overall refining process and is subsidized by the higher value gas and chemical stocks produced therein. Power plants as an alternative source for CO_2 could substitute for these sources, but would result in a displacement of volume without reducing the net CO_2 emissions.

A well-known use for CO_2 is in tertiary oil well flooding for secondary oil recovery – extracting additional oil from depleted oil fields. It increases the yield from oil fields by boosting pressure in the formation and by thinning the oil to increase flowability (dissolves into oil and decreases viscosity). Pipeline systems are required to convey the gas in compressed form to western oil production regions. This approach serves a beneficial function in allowing additional oil recovery, and sequesters the gas in deep geological formations where it is not part of the atmosphere.

Reports from the oil transportation industry indicate that economics of CO_2 gas transportation for oilfield use is directly related to proximity to pipeline hubs or networks.

Southern Illinois is the practical limit of the pipeline network in the Midwest. However, additional sources indicate that there are options for sequestering CO_2 in Illinois with existing oil and gas wells or geologic formations which do not exist in Wisconsin.

The feasibility of underground storage of CO_2 has been researched extensively by We Energies – Gas Control. This effort has been in conjunction with a search for natural gas storage in local geological formations, with the conclusion that there is very limited local capacity available for underground storage. Historically, the company has obtained underground storage for natural gas in lower Michigan. The need for natural gas storage and the price structure for this commodity preempt CO_2 issues today.

Another issue which is currently under review by regulators and the industry regarding underground CO_2 sequestration is the viability and permitting of different types of geological formations and well networks. In review, different types of formations exhibit different characteristics affecting their ability to retain CO_2 in a permanently fixed condition. This involves porosity parameters, confining geology, pressures and material reactivity. Deep geologic sequestration is the most viable option for management of CO_2 because large potential volumes are involved, but there may be a significant restriction placed on locations where it can be safely and efficiently implemented.

There are several large sources of CO_2 in industry which supply the bulk of demand for the gas. Ethanol plants and bio-diesel plants produce large amounts of CO_2. These types of production facilities have greatly increased in number in recent years, outstripping commercial demand for CO_2. The effect of commercial and industrial reuse of CO_2 therefore, is not expected to reduce CO_2 emissions to the atmosphere in any appreciable way since the scale of CO_2 utilization is small in comparison to the anthropogenic CO_2 generation in industry, without even considering natural sources. The industrial utilization of CO_2 therefore cannot break-even with production. For example, according to industrial gas distributors, ethanol production generates over 30,000 tons of CO_2 per day alone. There are 35 bio-diesel plants currently operating and producing CO_2, and new plants are under construction. Petroleum refineries also produce a minimum of 3% of liquefied CO_2 from cracking a given volume of petroleum at refineries. This means that there is a potential for large amounts of the CO_2 gas being in the market in the near future. There is therefore an opportunity for practical measures to mitigate excess CO_2 in the atmosphere. Some of these measures include but are not limited to algae farming, carbon capture, and CO_2 mineralization using various by-product materials such as cement kiln dust (CKD), lime kiln dust (LKD), recycled concrete fines (RCF), Class C fly ash (CFA), and blast furnace slag (Slag).

Algae Farming

Algae farming has been considered for CO_2 capture and use, as a recycling method rather than a sequestering strategy. In essence, a highly active algae consumes CO_2 from a power plant flue gas and converts it to a carbon fuel (oil) oxygen and a biomass byproduct. The biomass, with a high BTU content (9,000 BTU/lb) can be dried and burned as power plant fuel or refined to produce commercial products such as bio diesel fuel and ethanol.

CO_2 Capture

The CO_2 capture pilot project at Pleasant Prairie Power Plant (P4) was designed to test the economics and efficiency of the ALSTOM chilled ammonia process using a small slip stream of flue gas from the plant. The site was selected in part because of the presence of a wet scrubbing system for sulfur, providing a clean and cooled flue gas (130 °F), and the presence of an ammonia stock at the site due to the selective catalytic reduction (SCR) unit. The ALSTOM system, while designed to produce a liquefied CO_2 which could be collected and transported via tanker for use or sequestration, was built in pilot scale to only produce gaseous CO_2. Additional compression and associated costs would have been required to convert this gas to liquid for easier transport. This fact greatly affected the ability to find utilization options for CO_2 in current applications.

CO_2 Mineralization Using Various By-Product Materials

We Energies has developed and patented processes for the mineralization of CO_2. Initial work involved the use of Class C fly ash and the proof of concept testing was performed at the Center for By-products Utilization at the University of Wisconsin-Milwaukee. This work was followed by a large-scale field demonstration at the Pleasant Prairie Power Plant landfill site in 2007. The process utilized a proprietary foaming agent (Elastizell, Inc.) which produces a high level of discrete bubbles which are mixed with the Class C fly ash and water. The lime reacts with CO_2 producing carbonates which are incorporated into the concrete. The resultant solid has very low weight, in the range of 70 pounds per cubic foot which can be crushed and used as a lightweight aggregate. The quantity of CO_2 utilized is relatively small, requiring only the normal CO_2 levels in the atmosphere. A high temperature source of CO_2 such as a power plant flue gas at approximately 300 °F would require cooling to be effective but could be helpful in winter for production and curing.

Further work was conducted on lime containing by-product materials including cement kiln dust (CKD), lime kiln dust (LKD), recycled concrete fines (RCF), class C fly ash (CFA), and blast furnace slag (Slag) to produce additional materials foamed with CO_2 containing gases (ambient air, pure CO_2, and power plant flue gas) (shown in Table 11-1). Test cylinders were made and cured for 7, 14, 28, 56, 91, and 182 days from which carbonation potential and compressive strength were determined at each curing age. The results are shown in Figures 11-1 to 11-3 and Tables 11-2 and 11-3 for carbonation and Figures 11-6 to 11-8 and Table 11-4 for compressive strength.

Laboratory Mixture Proportions and Data

The amount of ingredients used, for each 1.8 cubic feet (0.051 cubic meter) batch of foamed material produced are shown on Table 11-1. The wet cylinder weight was targeted at 4.8 pounds +/- one pound (2.2 kg +/- 0.45 kg) for consistency of density. Additional quantities of carbon dioxide based foam were required with pure CO_2 gas to obtain the desired range of density due to the instability of the foam after formation.

Table 11-1: Mixture proportions and Data for 1.8 ft^3 (0.51 m^3) Batches (91)

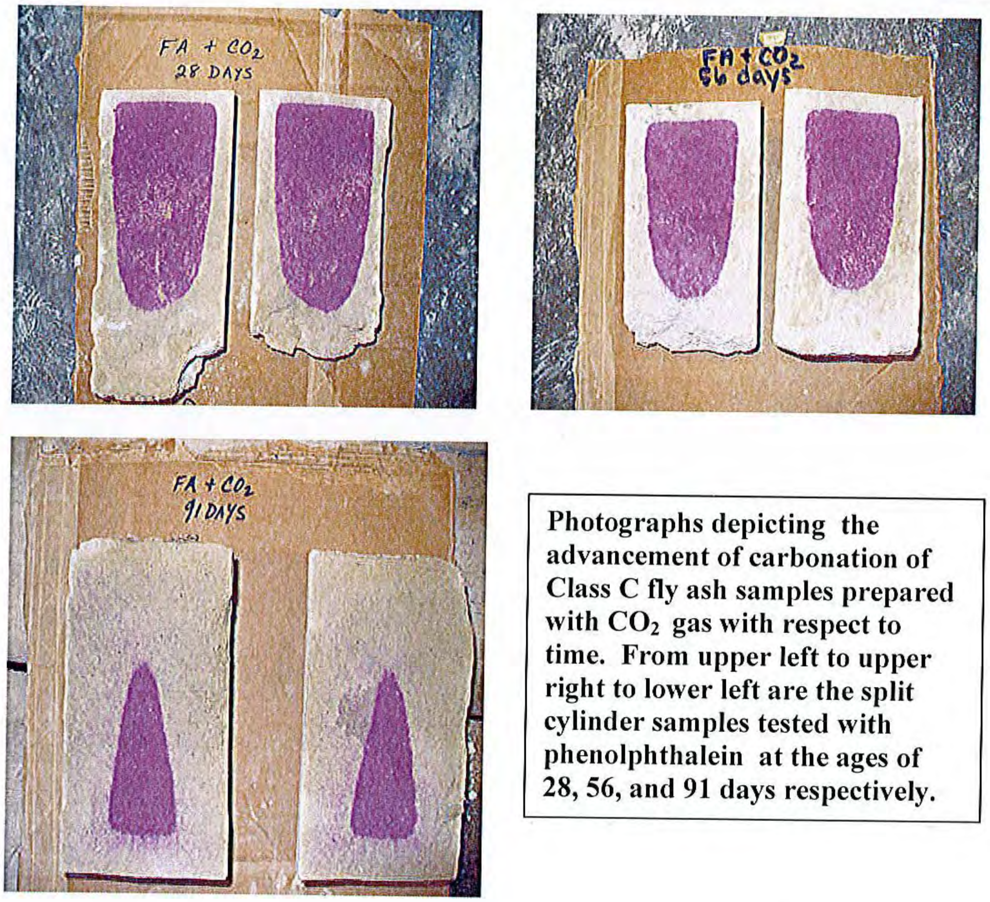
	CKD+Air	LKD+Air	RCF+Air	CFA+Air	Slag+Air
Mineral (lb)	85.0	105.0	84.0	105.0	107.0
Foam (gal)	3.0	6.0	9.0	3.4	6.5
Water (lb)	64.0	44.0	25.0	44.0	43.0
Retarder (ml)	0.0	0.0	91.0	179.0	0.0
Class C Fly Ash (lb)	0.0	0.0	53.0	0.0	0.0
Flow (in)	10.0	9.0	7.0	19.0	7.5
Temperature Rise (^{o}F)	34.0	20.0	23.0	11.0	10.0
Wet Cylinder Wt (lb)	4.8	4.0	5.0	4.5	4.9

Carbonation Testing per RILEM (92)

Carbon dioxide in the presence of moisture may penetrate the surface of mortar or concrete, and react with alkaline components in the cement paste, in the mortar or concrete, mainly $Ca(OH)_2$. This process (carbonation) leads to a reduction of the pH value of the pore solution to less than 9 (92). The reduction of the pH-value can be made visible by the color change of an indicator solution such as phenolphthalein which turns non-carbonated mortar or concrete dark pink or fuchsia, and the carbonated mortar or concrete remains colorless. All of the test specimens made with various types of foamed mortar were stored together for three days indoors in the laboratory where they were made. The plastic cylinder molds were removed from the test specimens and they were moved to a curing chamber and subjected to roughly a 0.03% CO_2 concentration found in the ambient air, with the lab temperature of 20ºC +/- 2ºC (70ºF +/- 3ºF), and relative humidity of 65% +/- 25%. A humidifier was used to add moisture to the curing chamber air during storage when the indoor air was dry in the room where the curing chamber was located. Conditions of storage such as time, humidity, and temperature were recorded. The test cylinders were spaced in the curing chamber so that air was able to reach the test surfaces unhindered at all times. For this reason, a free space of at least 0.8 inch (20 mm) was left around the specimens. "Carbonation occurs at the highest rates at relative humidity from about 40 to 70 percent. Near 0 or 100 percent, there is little or no carbonation." (92)

Table 11-2 and Figure 11-1 show the depth of carbonation for each of the five by-product materials when produced with integral foamed CO_2 contained in ambient air and carbonation advancement of Class C fly ash mortars respectively. Figure 11-2 shows the graphical representation of carbonation depth progression as a function of time. The CFA cast cylinders carbonated most rapidly attaining full thickness carbonation at an age of 56 days. RCF cast cylinders carbonated to full thickness at 6 months. All of the other by-product materials did not attain full carbonation within the 6 month period with the foam formed with ambient air. CKD attained a carbonation depth of 1.0 inch (44 mm), LKD with 1.25 inches (54 mm) and Slag with 1.25 inches (54 mm) of carbonation at the age of 6 months.

If the CFA hardened foamed material were crushed into a ¾ inch (19 mm) aggregate at an early age, and carbonation occurred inward from outside edges similar to the cylinders tested, the aggregate would achieve carbonation in less than 7 days of storage. Similarly, carbonation of up to a 3/4 inch (19 mm) nominal size aggregate could be accomplished for RCF in 14 days, Slag in 28 days and CKD and LKD in 56 days.



Photographs depicting the advancement of carbonation of Class C fly ash samples prepared with CO_2 gas with respect to time. From upper left to upper right to lower left are the split cylinder samples tested with phenolphthalein at the ages of 28, 56, and 91 days respectively.

Figure 11- 1: Carbonation Depth Advancement for Class C Fly Ash mortars (91)

Table 11-2: Carbonation Depth for Hardened By-Product Materials Foamed With Ambient Air (91)

Age (days)	CKD (in)	LKD (in)	RCF (in)	CFA (in)	Slag (in)
7	0.03125	0.00000	0.06250	1.07650	0.12500
14	0.12500	0.21875	0.37500	1.12500	0.25000
28	0.25000	0.31250	0.50000	1.37500	0.56250
56	0.40625	0.50000	1.00000	2.00000	0.75000
91	0.62500	0.93750	1.50000	2.00000	1.00000
182	1.00000	1.25000	2.00000	2.00000	1.25000

NOTE: 1.00 in = 2.54 cm.

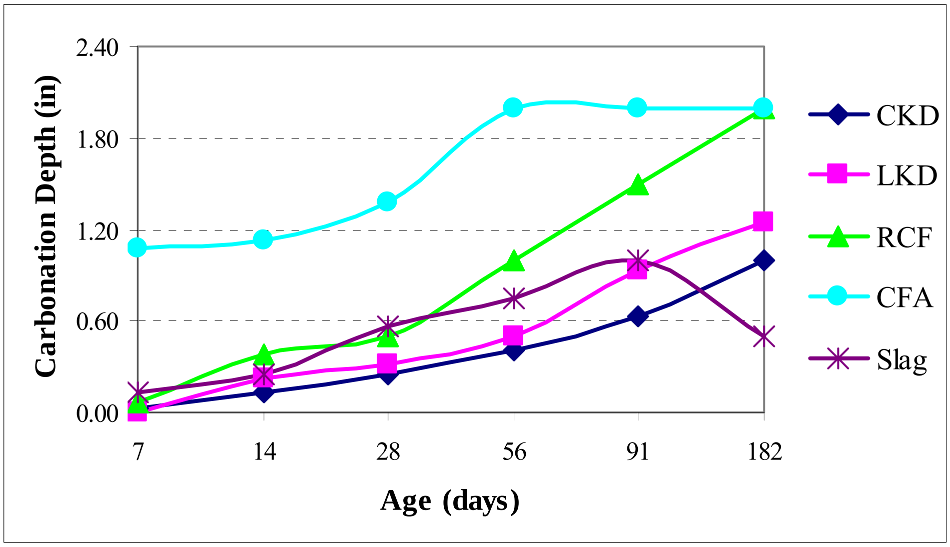
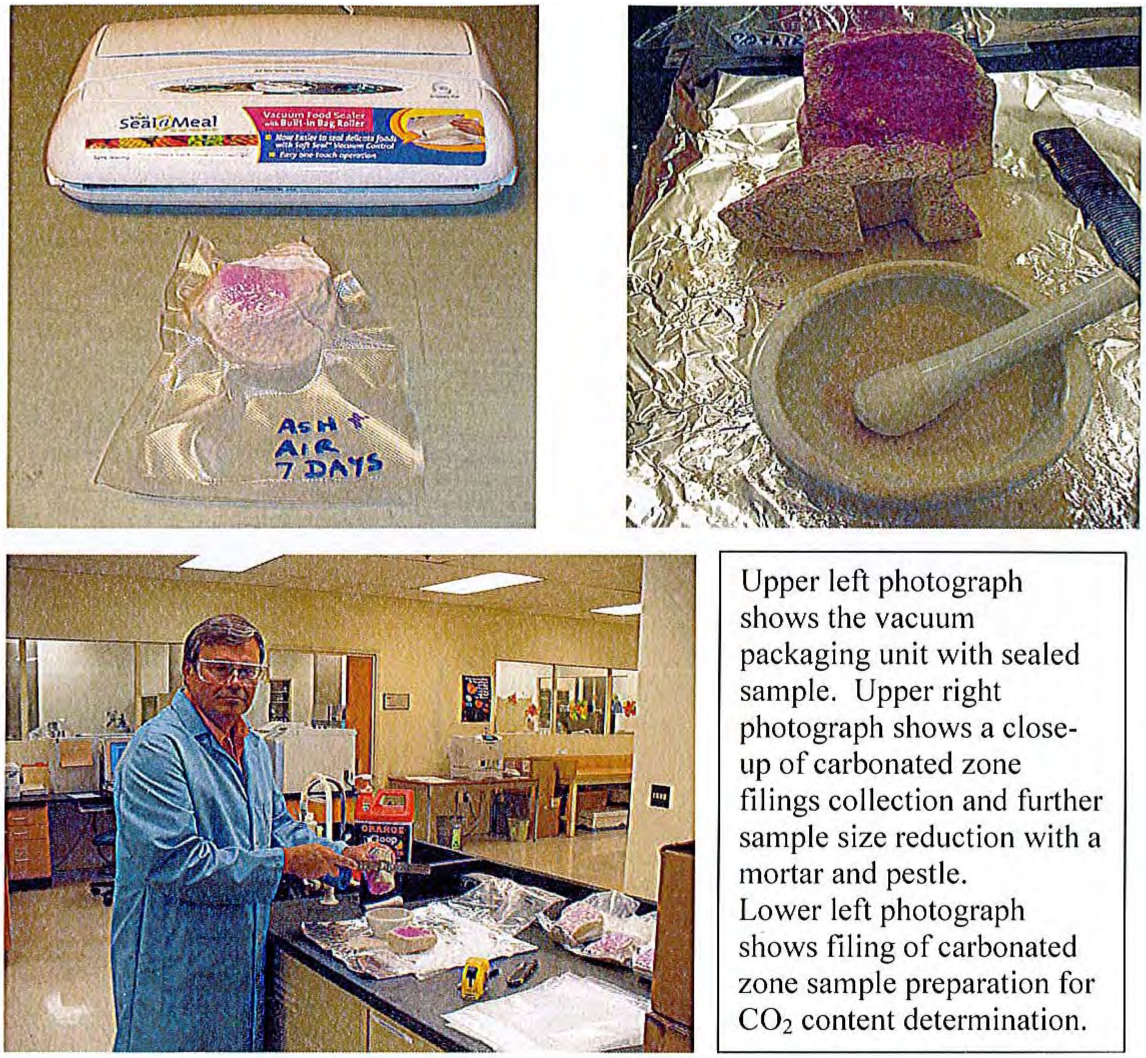


Figure 11-2: By-Product Mixtures Carbonation Depth Progression versus Time (91)

Quantification of CO_2 Mineralization

A portion of the carbonated cylinder (as determined from the phenolphthalein indicator test), from each type of mortar material, was sealed in a plastic food-grade bag for testing of carbon dioxide content in accordance with ASTM C-25, "Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime" (93) as shown in Figure 11-3. Immediately after compression testing and carbonation testing, samples were vacuum-sealed in the plastic bags. The samples were removed from the vacuum-sealed plastic bags at the time of testing for CO_2 by mass determination. Later, the carbonated portion of the sample was removed from the vacuum-sealed bags and prepared for quantification of CO_2. The samples were filed to the full depth of carbonation, and the filings were collected for further preparation by grinding in a mortar and pestle, shown in Figure 11-3. The ASTM C-25 (93) gravimetric test method was used for quantifying the amount of carbon dioxide contained within a mineral sample. The samples were decomposed with hydrochloric acid and the liberated CO_2 was passed through a series of scrubbers to remove water and sulfides. The CO_2 was absorbed with Ascarite, a special sodium hydroxide absorbent, and the gain in weight of the absorption tube was determined and calculated as percent CO_2. The balance, calibration weights, Ascarite absorber, and standard sample (reagent grade Na_2CO_3) are shown in Figure 11-4. The wet chemistry apparatus is shown on Figure 11-5.



Upper left photograph shows the vacuum packaging unit with sealed sample. Upper right photograph shows a close-up of carbonated zone filings collection and further sample size reduction with a mortar and pestle.
Lower left photograph shows filing of carbonated zone sample preparation for CO_2 content determination.

Figure 11-3: Sample Preservation and Preparation for CO_2 Content Tests (91)

Table 11-3: CO_2 Content of Various By-Product Carbonated Materials by Percent Mass with Ambient Air at Different Curing Ages (91)

Age	CKD	LKD	RCF	CFA	Slag
(Days)	(%CO_2)	(%CO_2)	(%CO_2)	(%CO_2)	(%CO_2)
0	9.5	22.2	14.6	0.1	1.4
7	21.8	20.7	11.8	0.9	2.5
14	18.3	23.3	11.7	1.1	5.1
28	19.1	24.0	11.5	1.2	3.2
56	19.9	24.8	12.2	1.5	3.8
91	20.2	25.0	15.4	1.4	7.3
182	20.7	25.9	12.8	1.6	5.2

Figure 11-4: Balance, Calibration Weights, Ascarite Absorber and Standard Sample (Reagent Grade Na_2CO_3) (91)

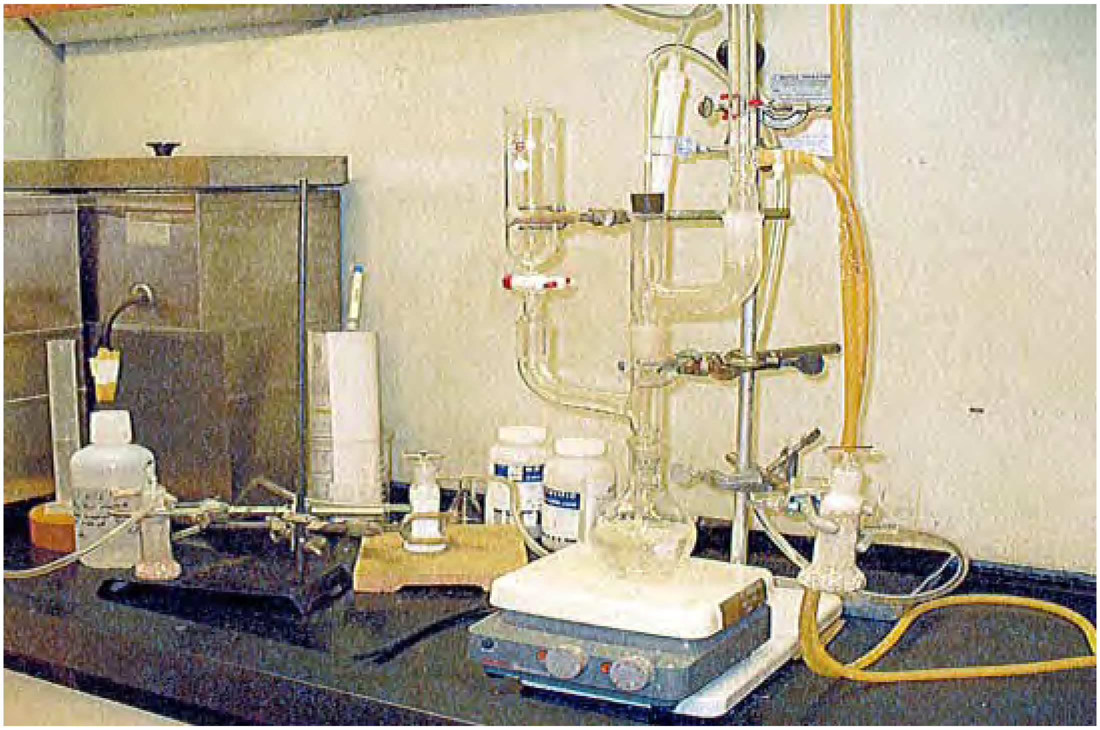


Figure 11-5: ASTM C-25, “Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime,” (93) Gravimetric Method Wet Chemistry Apparatus (91)

Table 11-3 provides the results of ASTM C-25, "Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime," (93) gravimetric testing method for CO_2 by mass for various by-product materials. The CO_2 content determined for these materials at an age of zero days represents the mass percentage of CO_2 in a sample of the raw material, before it was used in production of the mortar. The CKD was provided by Lafarge North America from the cement manufacturing facility located in Alpena, Michigan. The LKD was provided by Western Lime Corporation from the lime manufacturing facility located in Eden, Wisconsin. The RCF was provided by A.W. Oakes and Son, Inc. from the recycled concrete crushing facility located in Racine, Wisconsin. The CFA was provided by We Energies from the Pleasant Prairie Power Plant located in Pleasant Prairie, Wisconsin. The power plant uses sub-bituminous coal from the Powder River Basin of Wyoming. The slag was provided by Holcim (US) Inc. from the slag manufacturing facility located in Chicago, Illinois. All other values given in Table 11-3 are from the carbonated portion of the cured cylinders and are the values obtained from ASTM C-25 testing of the by-product materials foamed with the ambient air. The initial amount CO_2 (by mass) contained in the by-product materials powder before testing was 9.5%, 22.2%, 14.6%, 0.1% and 1.4% of CO_2 for CKD, LKD, RCF, CFA and Slag, respectively. These amounts increased after 182 days to 20.7%, 25.9%, 1.6%, and 5.2% for the CKD, LKD, CFA and Slag based materials foamed with ambient air respectively. However, CO_2 content for the RCF based materials decreased to 12.6%. This decrease may actually represent the greater variability that is inherent in a crushed concrete sample consisting primarily of a composite of coarse and fine aggregate materials, various cementitious materials, and also by the relatively small samples used in analysis. The total amount of CO_2 was highest in the LKD aggregates followed by CKD, RCF, Slag and CFA aggregate materials for all of the CO_2 containing gases used.

The phenolphthalein indicator tests are intended to record the depth of carbonation at points in time, and these percent CO_2 by mass tests are intended to record the mass percentage of CO_2 embodied within the full-depth of the carbonated zone as indicated by the phenolphthalein indicator test at these same points in time.

Compressive Strength Testing

Four-inch (100-mm) diameter by eight-inch (200-mm) long specimens were cast, cured, and tested in a compression testing machine located in the University of Wisconsin-Milwaukee Concrete Laboratory, see Figures 11-6 and 11-7. The compressive strength of the five by-product-based materials at the ages of 7, 14, 28, 56, 91, and 182 day ages was determined (Table 11-4). An average compressive strength was obtained for the three cylinders tested in compression for each of the five test mixture materials at the ages indicated. The by-product based materials tested are low-strength compared to concrete and fall in the range of CLSM, with a required compressive strength of 1200 psi (8.3 MPa) or less. The variations in strength test results appear amplified on the graphs (Figure 11-8) because of the smaller y-axis scale for compressive strength compared to conventional concrete, but actually fall in the expected compressive strength variability range for cylinder specimens tested in compression.

Figure 11-6: Compressive Strength Cylinder Storage (91)

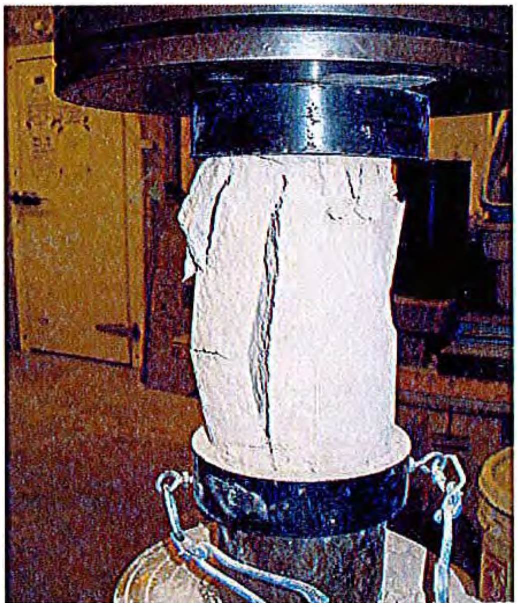


Figure 11-7: Compressive Strength Cylinder Testing (91)

Table 11-4: Average compressive strength test results (91)

Age (days)	CKD+Air (psi)	LKD+Air (psi)	RCF+Air (psi)	CFA+Air (psi)	Slag+Air (psi)
7	49	24	11	35	105
14	167	73	8	46	141
28	234	123	11	31	100
56	207	84	65	37	91
91	297	130	27	23	162
182	216	54	N/A	69	173

NOTE: N/A = Not Available; 145 psi = 1 MPa

At the conclusion of testing (day 182), the CKD mixture had the highest compressive strength of 216 psi (1.49 MPa) followed by the slag mixtures at 173 psi (1.19 MPa). The compressive strength of the other three by-product materials concluded below 75 psi (0.52 MPa).

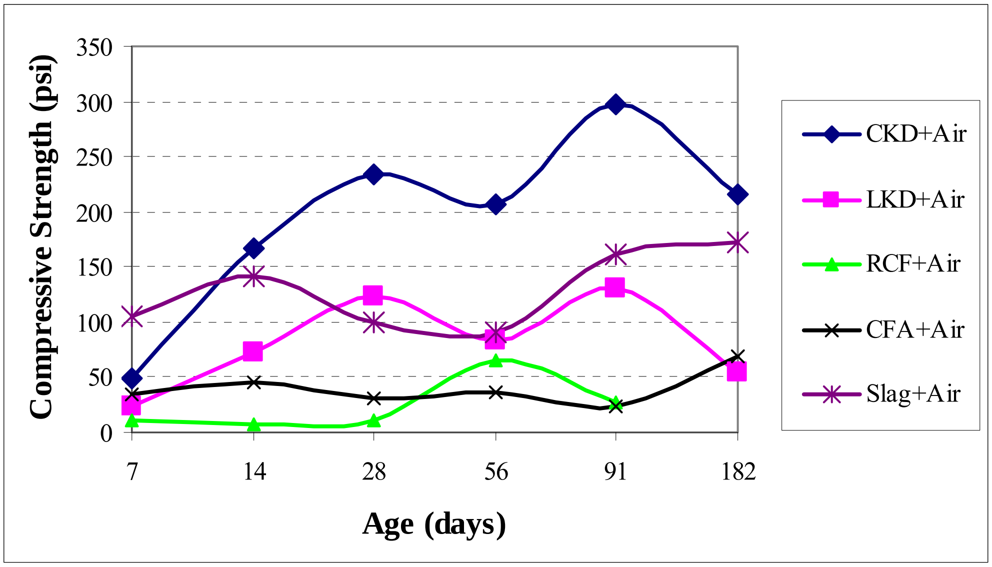


Figure 11-8: Compressive Strength versus Time of By-Product Material Mixtures Foamed with Ambient Air (91)

Crushing and Screening

The fractured test cylinders after strength testing were saved from each type of material and mixture associated with the different types of foamed controlled low strength materials (CLSM) produced with different gases. These materials were later crushed into aggregates. Initial crushing feasibility testing was performed with the Los Angeles (LA) Abrasion testing apparatus that was available at the UW-Milwaukee Concrete Laboratory. The LA Abrasion tumbler was equipped with steel balls similar to a ball mill. The tumbling and rotating balls impacted on the fractured cylinders essentially converting the hardened low-strength material into rounded shapes, and a powdery material as shown in Figure 11-9. This was not satisfactory for production of a crushed-stone type of aggregate.

Figure 11-9: LA Abrasion Equipment Crushing of CLSM Test Cylinder Samples after Strength Testing (91)

A laboratory-scale double-roller aggregate crusher, located at Payne and Dolan Incorporated's crushed stone quarry operations in Waukesha, Wisconsin, was used for further evaluation of CLSM as aggregates. This equipment is routinely used for crushing rock cores. The fractured test cylinders were placed directly into the double rollers, at the top of the crusher. This resulted in crushed aggregate pieces that were collected in a pan located below the double-rollers, see Figure 11-10. This crusher produced a typical crushed stone type of angular shaped aggregate. The amount of fines was larger than would typically be found for natural crushed stone. This is likely due to the significantly lower compressive strengths of these low density by-product CLSM materials.

Aggregate Testing

The crushed aggregate materials were tested for the following characteristics that would allow for comparison to other materials:

- Dry Bulk Density, by ASTM C-29, "Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate." (94)
- Absorption, by ASTM C-127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate." (95)
- Specific Gravity, by ASTM C-127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate." (95)
- Gradation by ASTM C-136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates." (96)
- Staining by ASTM C-641, "Standard Test Method for Iron Staining Materials in Lightweight Concrete Aggregates." (97)

Figure 11-10: Double Roller Crushing of Fractured Compressive Strength Test Cylinder Samples. (Upper Left: Feeding cylinder fragments into crusher. Upper Right: Double-roller crusher unit. Lower Left: Top view of the double-roller crusher. Lower Right: Collection pan with collected crushed by-product aggregates) (91)

The physical properties test results for the five different by-product-based aggregates are shown on Table 11-5. The aggregate grain size distribution curves for each material and other supporting aggregate classification data are shown in Figures 11-13 to 11-17 and

Tables 11-6 to 11-10. Figure 11-11 shows photographs of the equipment used for the aggregate testing including the oven drying of the aggregate, dry-rodded unit weight test, sieve analysis, and the emptying of a sieve for the weighing process on a laboratory-scale. Figure 11-12 shows the 24-hour soaking of the aggregates, drying with towels to the saturated surface dry condition, and obtaining an underwater weight for the aggregates. Some of the aggregate samples had a density below that of water and therefore they floated.

Table 11-5: Physical properties of By-Product-Based Aggregates (91)

	Density[1] (lb/ft^3)	Absorption[2] (%)	Specific Gravity[3]	Fineness Modulus[4]	Staining[5]
CKD+Air	46.6	41.6	0.99	4.98	0
LKD+Air	56.0	31.4	0.99	4.15	0
RCF+Air	69.4	18.1	1.39	1.74	0
CFA+Air	64.0	19.9	1.08	2.90	0
Slag+Air	44.1	33.0	1.24	6.42	0

Notes:
1: Dry Bulk Density, ASTM C-29 (94)
2: Absorption, ASTM C-127 (95)
3: Relative Density (Specific Gravity) Oven Dry, ASTM C-127 (95)
4: Fineness Modulus, ASTM C-136 (96)
5: Staining by Visual Classification Method, ASTM C-641 (97)
6: 1.00 lb/ft^3 = 16.0356 kg/m^3

The bulk density in a dry-rodded state is shown in Table 11-5. It is defined in ASTM C-29, “Standard Test Method for Bulk Density (Unit Weight) and Voids in Concrete,” as “the mass of a unit volume of bulk aggregate material, in which the volume includes the volume of the individual particles and the volume of the voids between the particles.” (94). The bulk density relationship is important for planning packaging and transportation commercial arrangements. The density compared to other materials is also helpful in planning geotechnical and concrete product applications. The dry-rodded bulk densities for the by-product-based aggregates fall in the range of 44.1 to 69.4 lb/ft^3 (707 to 1113 kg/m^3). Absorption and specific gravity are also shown in Table 11-5. Absorption is defined in ASTM C-127, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” as “the increase in mass of aggregate due to water penetration into the pores of the particles during a prescribed period of time, but not including water adhering to the outside surface of the particles, expressed as a percentage of dry mass.” (95) The aggregates were soaked in water for 24 hours (plus or minus 4 hours) and then dried in towels to the saturated surface dry (SSD) condition.

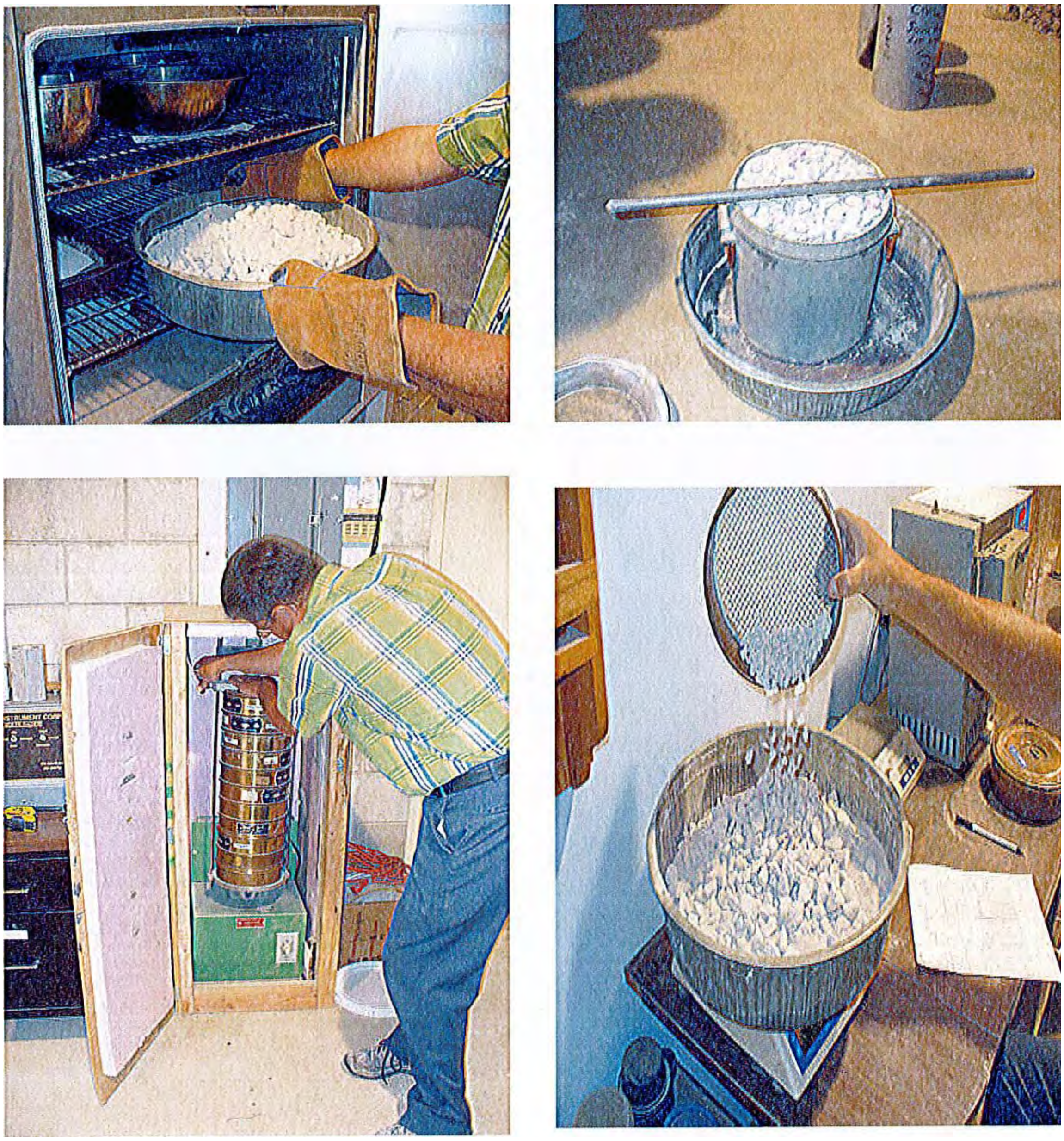


Figure 11-11: Photographs of Aggregate Physical Properties Tests. (Upper left photograph shows the oven drying of the crushed aggregate, upper right photograph depicts the dry-rodded unit weight test, lower left photograph depicts the grain size distribution sieve apparatus and the lower right photo graph depicts the emptying and weighing of the sieved samples) (91)

Upper left photograph shows the soaking of the aggregate for obtaining the weight in the saturated surface dry condition. Upper right photograph shows the drying of the aggregates to saturated surface dry condition. Lower left photograph shows the basket and balance used to obtain the underwater weight of the sample for determination of the aggregate's specific gravity.

Figure 11-12: Additional Photographs of Aggregate Physical Properties Tests (91)

The absorption values ranged from a low value of 18.1 percent for the RCF aggregate material to a high of 41.6 for the CKD aggregate material. The absorption property is important in calculating the change in density from a dry to SSD condition for storage, packaging and transportation purposes. Absorption is also an important property for performing water content calculations in concrete mixture proportioning, and in calculating internal curing potential for lightweight aggregate concrete. Specific gravity is defined in ASTM C-127, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” as “the ratio of the density of the aggregate (oven dry) to the density of distilled water at a stated temperature” (95) which in this case was 73°F (23°C). Specific gravity is commonly used for volume calculations in concrete, asphalt and other mixture proportioning purposes. The fineness modulus property of the by-product-based aggregates are shown in Table 11-5. Fineness modulus is defined in ASTM C-136, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” and calculated “by adding the total percentages of material in a sample that is coarser than each of the following sieves (cumulative percentages retained), and dividing the sum by 100: 150-µm (No. 100), 300- µm (No. 50), 600-µm (No. 30), 1.18-mm (No. 16), 2.36-mm (No. 8), 4.75-mm (No. 4), 9.5-mm (⅜-in.), 19.0-mm (¾-in.), 37.5-mm (1½-in.) and larger increasing in the ratio of 2:1.” In this study, the sieves conclude at 19.0-mm (¾-in.) because this was the planned top-size of the aggregates. The fineness modulus property is used primarily as an indication of aggregate relative fineness or coarseness. Fineness modulus ranged from a low of 1.74 for RCF aggregates to a high of 6.42 for the Slag aggregates, and the higher the fineness modulus value, the coarser the aggregate

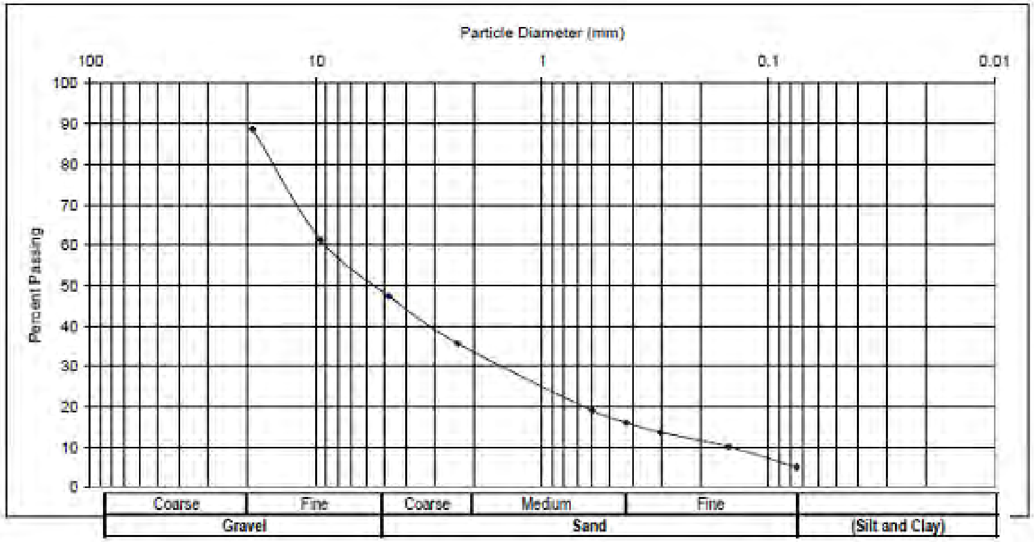
Project Name: Mineralization
Type of Sample: CKD + AIR

Date: August 18, 2007
Reported By: Bruce Ramme

ASTM Designation: C 136

Mechanical Analysis Data

Sieve	Sieve Opening (mm)	Percent Passing (%)
3/4 in.	19.050	89
3/8 in.	9.525	61
#4	4.750	47
#8	2.360	36
#16	1.180	26
#30	0.600	19
#40	0.425	16
#50	0.300	14
#100	0.150	10
#200	0.075	5
Pan	#N/A	0



Remarks: Gravel 53 % Sand 42 %
Passing #200 Sieve (Silt & Clay) 5 %

Figure 11-13: Laboratory Test Results of Physical Properties of Aggregate: Grain Size Distribution Curve for CKD + Ambient Air Crushed Aggregate (91)

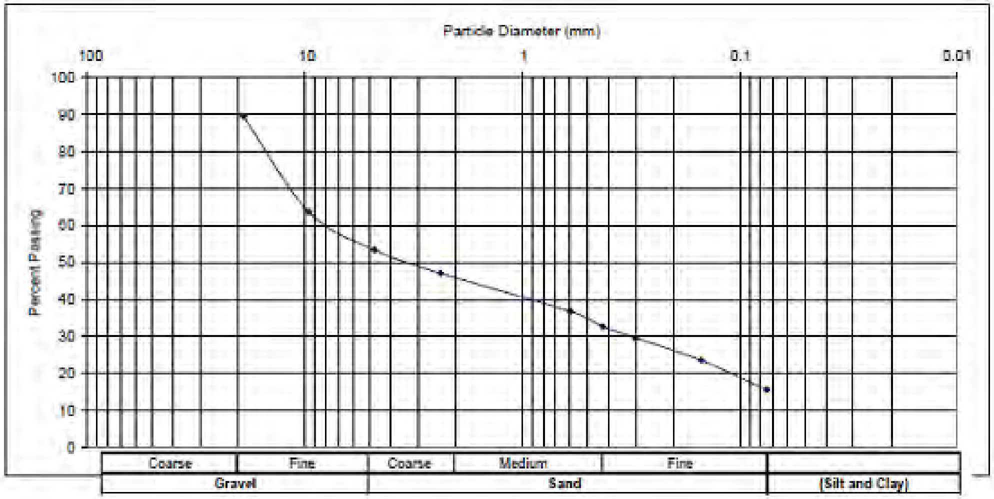
Laboratory Test Results of Physical Properties of Aggregate

Project Name:	**Mineralization**	**Date:**	**August 20, 2007**
Type of Sample:	**LKD + AIR**	**Reported By:**	**Bruce Ramme**

ASTM Designation: ASTM C 136

Mechanical Analysis Data

Sieve	Sieve Opening (mm)	Percent Passing (%)
3/4 in.	19.050	89
3/8 in.	9.525	64
#4	4.750	53
#8	2.360	47
#16	1.180	42
#30	0.600	37
#40	0.425	33
#50	0.300	30
#100	0.150	24
#200	0.075	16
Pan	#N/A	0



Remarks: Gravel 47 % Sand 38 %

Passing #200 Sieve (Silt & Clay) 16 %

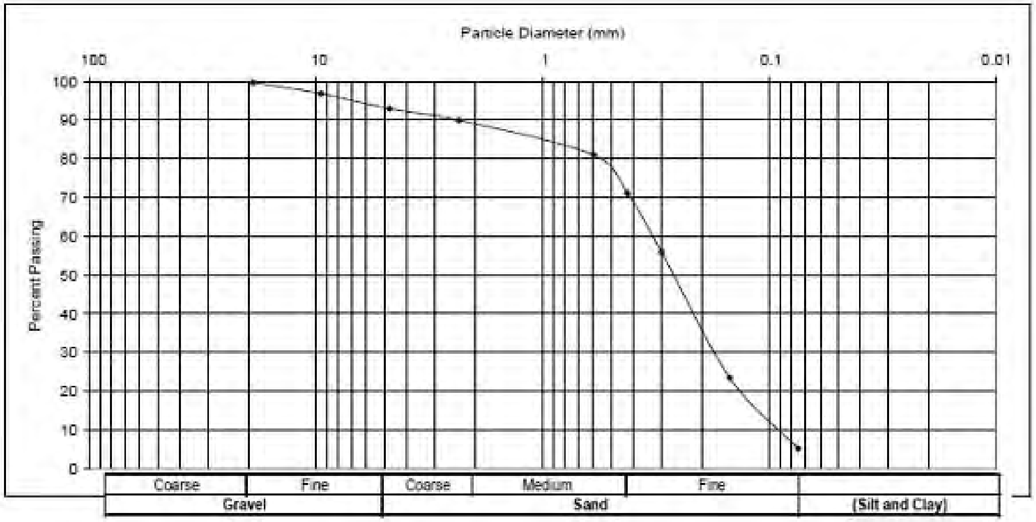
Figure 11-14: Laboratory Test Results of Physical Properties of Aggregate: Grain Size Distribution Curve for LKD + Ambient Air Crushed Aggregate (91)

Project Name:	**Mineralization**	**Date:**	**August 24, 2007**
Type of Sample:	RCF + AIR	**Reported By:**	**Bruce Ramme**

ASTM Designation: C 136

Mechanical Analysis Data

Sieve	Sieve Opening (mm)	Percent Passing (%)
3/4 in.	19.050	100
3/8 in.	9.525	97
#4	4.750	93
#8	2.360	90
#16	1.180	86
#30	0.600	81
#40	0.425	71
#50	0.300	56
#100	0.150	23
#200	0.075	5
Pan	#N/A	0



Remarks: Gravel 7 % Sand 88 %

Passing #200 Sieve (Silt & Clay) 5 %

Figure 11-15: Laboratory Test Results of Physical Properties of Aggregate: Grain Size Distribution Curve for RCF + Ambient Air Crushed Aggregate (91)

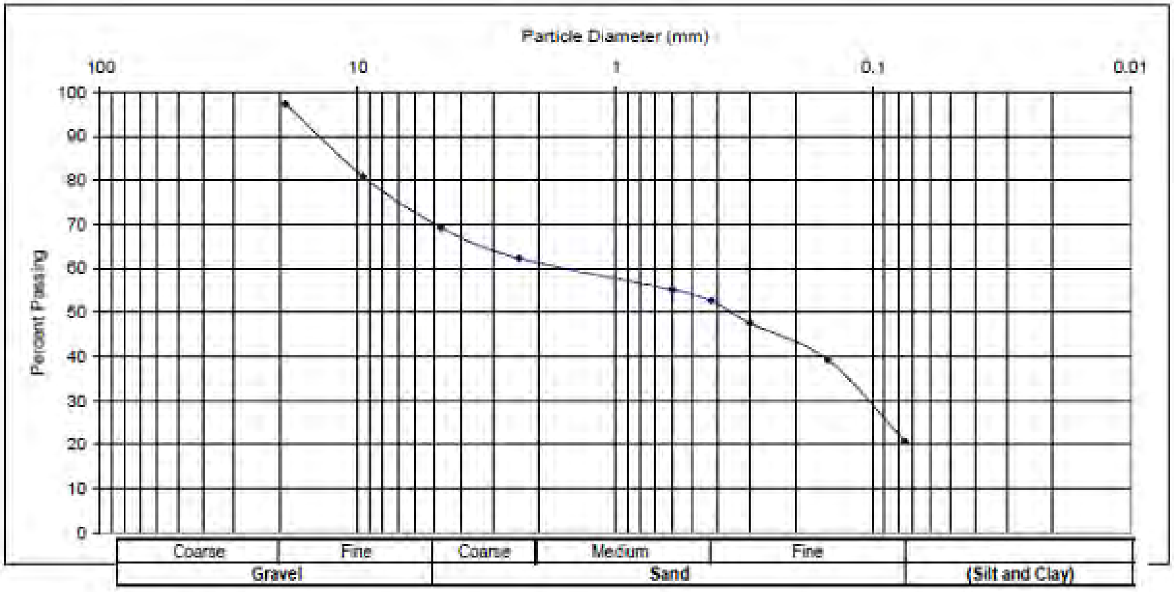
Project Name: Mineralization
Type of Sample: CFA + AIR

ASTM Designation: C 136

Date: August 19, 2007
Reported By: Bruce Ramme

Mechanical Analysis Data

Sieve	Sieve Opening (mm)	Percent Passing (%)
3/4 in.	19.050	97
3/8 in.	9.525	81
#4	4.750	69
#8	2.360	62
#16	1.180	59
#30	0.600	55
#40	0.425	53
#50	0.300	48
#100	0.150	39
#200	0.075	21
Pan	#N/A	0



Remarks: Gravel 31 % Sand 49 %
Passing #200 Sieve (Silt & Clay) 21 %

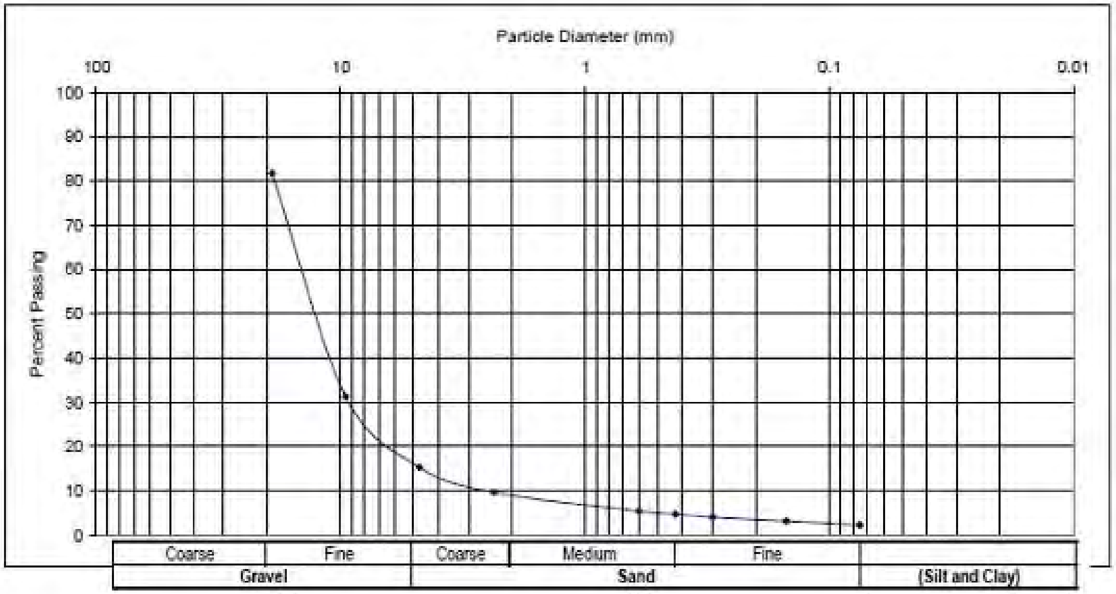
Project Name: Mineralization
Type of Sample: SLAG + AIR

Date: August 22, 2007
Reported By: Bruce Ramme

ASTM Designation: C 136

Mechanical Analysis Data

Sieve	Sieve Opening (mm)	Percent Passing (%)
3/4 in.	19.050	82
3/8 in.	9.525	31
#4	4.750	15
#8	2.360	10
#16	1.180	7
#30	0.600	5
#40	0.425	5
#50	0.300	4
#100	0.150	3
#200	0.075	2
Pan	#N/A	0



Remarks: Gravel 85 % Sand 13 %
Passing #200 Sieve (Silt & Clay) 2 %

Figure 11-17: Laboratory Test Results of Physical Properties of Aggregate: Grain Size Distribution Curve for Slag + Ambient Air Crushed Aggregate (91)

Table 11-6: Laboratory Test Results of Physical Properties of Aggregate: Mechanical Analyses for CKD + Ambient Air Crushed Aggregate (91)

Project Name: Mineralization **Date: 8/18/2007**
Type of Sample: CKD + AIR **Reported By: Bruce Ramme**

Specific Gravity and Absorption (ASTM C 127)

Dry Mass in Air (g)	3189
SSD Mass in Air (g)	4516
Sample Mass in Water (g)	1304
Relative Specific Gravity	0.99
Absorption (%)	41.6

Dry Bulk Density (ASTM C 29)

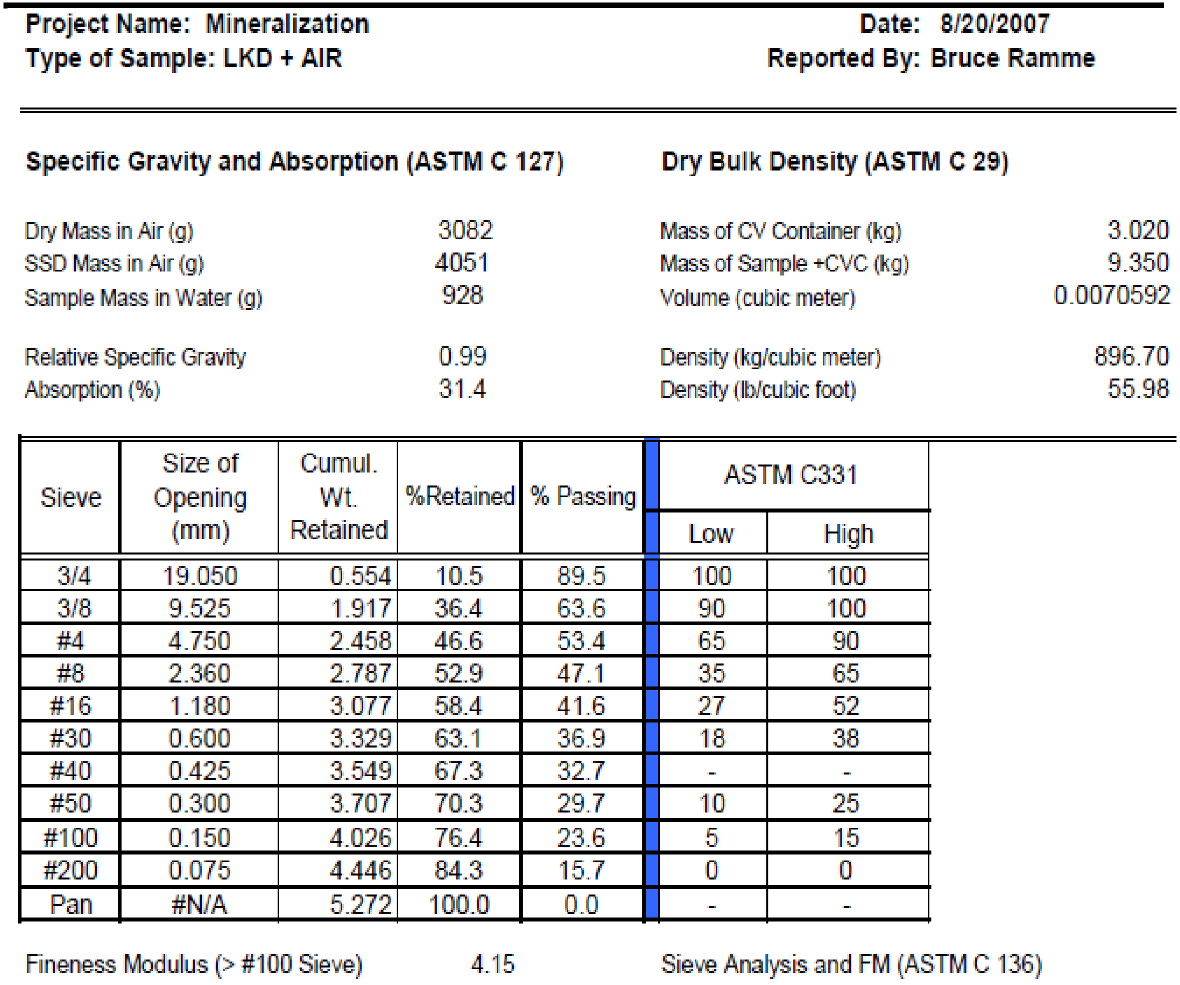
Mass of CV Container (kg)	3.019
Mass of Sample +CVC (kg)	8.287
Volume (cubic meter)	0.0070592
Density (kg/cubic meter)	746.26
Density (lb/cubic foot)	46.59

Sieve	Size of Opening (mm)	Cumul. Wt. Retained	%Retained	% Passing	ASTM C 331	
					Low	High
3/4	19.050	0.570	11.3	88.7	100	100
3/8	9.525	1.954	38.7	61.3	90	100
#4	4.750	2.654	52.6	47.4	65	90
#8	2.360	3.246	64.4	35.6	35	65
#16	1.180	3.735	74.1	25.9	27	52
#30	0.600	4.084	81.0	19.0	18	38
#40	0.425	4.232	83.9	16.1	-	-
#50	0.300	4.355	86.4	13.6	10	25
#100	0.150	4.535	89.9	10.1	5	15
#200	0.075	4.789	95.0	5.0	0	0
Pan	#N/A	5.043	100.0	0.0	-	-

Fineness Modulus (> #100 Sieve) 4.98

Sieve Analysis and FM (ASTM C 136)

Table 11-7: Laboratory Test Results of Physical Properties of Aggregate: Mechanical Analyses for LKD + Ambient Air Crushed Aggregate (91)



Project Name:	**Mineralization**
Type of Sample:	**LKD + AIR**
Date:	**8/20/2007**
Reported By:	**Bruce Ramme**

Specific Gravity and Absorption (ASTM C 127)

Dry Mass in Air (g)	3082
SSD Mass in Air (g)	4051
Sample Mass in Water (g)	928
Relative Specific Gravity	0.99
Absorption (%)	31.4

Dry Bulk Density (ASTM C 29)

Mass of CV Container (kg)	3.020
Mass of Sample +CVC (kg)	9.350
Volume (cubic meter)	0.0070592
Density (kg/cubic meter)	896.70
Density (lb/cubic foot)	55.98

Sieve	Size of Opening (mm)	Cumul. Wt. Retained	%Retained	% Passing	ASTM C331	
					Low	High
3/4	19.050	0.554	10.5	89.5	100	100
3/8	9.525	1.917	36.4	63.6	90	100
#4	4.750	2.458	46.6	53.4	65	90
#8	2.360	2.787	52.9	47.1	35	65
#16	1.180	3.077	58.4	41.6	27	52
#30	0.600	3.329	63.1	36.9	18	38
#40	0.425	3.549	67.3	32.7	-	-
#50	0.300	3.707	70.3	29.7	10	25
#100	0.150	4.026	76.4	23.6	5	15
#200	0.075	4.446	84.3	15.7	0	0
Pan	#N/A	5.272	100.0	0.0	-	-

Fineness Modulus (> #100 Sieve) 4.15

Sieve Analysis and FM (ASTM C 136)

Table 11-8: Laboratory Test Results of Physical Properties of Aggregate: Mechanical Analyses for RCF + Ambient Air Crushed Aggregate (91)

Project Name: Mineralization **Date: 8/24/2007**

Type of Sample: RCF + AIR **Reported By: Bruce Ramme**

Specific Gravity and Absorption (ASTM C 127)		**Dry Bulk Density (ASTM C 29)**	
Dry Mass in Air (g)	3043	Mass of CV Container (kg)	3.022
SSD Mass in Air (g)	3594	Mass of Sample +CVC (kg)	10.864
Sample Mass in Water (g)	1409	Volume (cubic meter)	0.0070592
Relative Specific Gravity	1.39	Density (kg/cubic meter)	1110.89
Absorption (%)	18.1	Density (lb/cubic foot)	69.35

Sieve	Size of Opening (mm)	Cumul. Wt. Retained	%Retained	% Passing	ASTM C 331	
					Low	High
3/4	19.050	0.012	0.2	99.8	100	100
3/8	9.525	0.162	3.1	96.9	90	100
#4	4.750	0.366	7.0	93.0	65	90
#8	2.360	0.520	10.0	90.0	35	65
#16	1.180	0.712	13.7	86.3	27	52
#30	0.600	0.982	18.9	81.1	18	38
#40	0.425	1.498	28.8	71.2	-	-
#50	0.300	2.289	44.1	55.9	10	25
#100	0.150	3.978	76.6	23.4	5	15
#200	0.075	4.928	94.8	5.2	0	0
Pan	#N/A	5.196	100.0	0.0	-	-

Fineness Modulus (> #100 Sieve) 1.74 Sieve Analysis and FM (ASTM C 136)

Table 11-9: Laboratory Test Results of Physical Properties of Aggregate: Mechanical Analyses for CFA + Ambient Air Crushed Aggregate (91)

Project Name: Mineralization **Date: 8/19/2007**
Type of Sample: CFA + AIR **Reported By: Bruce Ramme**

Specific Gravity and Absorption (ASTM C 127)

Dry Mass in Air (g)	3013
SSD Mass in Air (g)	3613
Sample Mass in Water (g)	811
Relative Specific Gravity	1.08
Absorption (%)	19.9

Dry Bulk Density (ASTM C 29)

Mass of CV Container (kg)	3.019
Mass of Sample +CVC (kg)	10.254
Volume (cubic meter)	0.0070592
Density (kg/cubic meter)	1024.90
Density (lb/cubic foot)	63.98

Sieve	Size of Opening (mm)	Cumul. Wt. Retained	%Retained	% Passing	ASTM C 331	
					Low	High
3/4	19.050	0.143	2.7	97.3	100	100
3/8	9.525	1.027	19.2	80.8	90	100
#4	4.750	1.645	30.7	69.3	65	90
#8	2.360	2.022	37.7	62.3	35	65
#16	1.180	2.209	41.2	58.8	27	52
#30	0.600	2.404	44.9	55.1	18	38
#40	0.425	2.539	47.4	52.6	-	-
#50	0.300	2.811	52.5	47.5	10	25
#100	0.150	3.255	60.8	39.2	5	15
#200	0.075	4.245	79.2	20.8	0	0
Pan	#N/A	5.358	100.0	0.0	-	-

Fineness Modulus (> #100 Sieve) 2.90

Sieve Analysis and FM (ASTM C 136)

Table 11-10: Laboratory Test Results of Physical Properties of Aggregate: Mechanical Analyses for Slag + Ambient Air Crushed Aggregate (91)

Project Name:	**Mineralization**	**Date:**	**8/22/2007**
Type of Sample:	**SLAG + AIR**	**Reported By:**	**Bruce Ramme**

Specific Gravity and Absorption (ASTM C 127)		**Dry Bulk Density (ASTM C 29)**	
Dry Mass in Air (g)	4252	Mass of CV Container (kg)	3.021
SSD Mass in Air (g)	5656	Mass of Sample +CVC (kg)	8.005
Sample Mass in Water (g)	1557	Volume (cubic meter)	0.0070592
Relative Specific Gravity	1.04	Density (kg/cubic meter)	706.03
Absorption (%)	33.0	Density (lb/cubic foot)	44.08

Sieve	Size of Opening (mm)	Cumul. Wt. Retained	%Retained	% Passing	ASTM C 331 Low	ASTM C 331 High
3/4	19.050	0.918	18.3	81.7	100	100
3/8	9.525	3.451	68.7	31.3	90	100
#4	4.750	4.251	84.6	15.4	65	90
#8	2.360	4.534	90.3	9.7	35	65
#16	1.180	4.665	92.9	7.1	27	52
#30	0.600	4.748	94.5	5.5	18	38
#40	0.425	4.785	95.3	4.7	-	-
#50	0.300	4.817	95.9	4.1	10	25
#100	0.150	4.865	96.9	3.1	5	15
#200	0.075	4.904	97.6	2.4	0	0
Pan	#N/A	5.023	100.0	0.0	-	-

Fineness Modulus (> #100 Sieve) 6.42

Sieve Analysis and FM (ASTM C 136)

Staining

A "temporary" blue-green staining was observed at the center of cured ground granulated blast furnace slag cylinders when fractured during strength testing. The temporary staining is described as "greening" in a publication of the Slag Cement Association (100). "The blue-green color is attributed to a complex reaction of sulfide sulfur in slag cement with other compounds in the Portland cement. The degree and extent of the coloration depends on the rate of oxidation, the percentage of slag used, curing conditions, and the porosity of the concrete surfaces. … If greening does occur, it usually appears within a week of concrete placement and typically disappears within a week after oxidation starts. Surface greening diminishes as oxidation progresses and does not need to be treated" (100). It should be noted that the slag cement used in this project was used without Portland cement or other cementitious materials and still produced the temporary blue-green staining color. The staining was very bright in color, and indeed temporary, eventually disappearing from the surfaces of the aggregates produced from slag. ASTM C-641, "Standard Test Method for Iron Staining Materials in Lightweight Concrete Aggregates" provides a visual colorimetric method that was used to determine the staining potential of the five by-product-based aggregates. The test involves selecting two-100 gm samples of aggregate with a specific gradation passing the ⅜ inch (9.5 mm) sieve and retained on the No. 30 (600 µm) sieve. The sample is then placed at a uniform thickness on a white-filter paper that is then wrapped with cheesecloth. The wrapped sample was saturated in distilled water, and placed in a steam bath for 16 hours of continuous exposure.

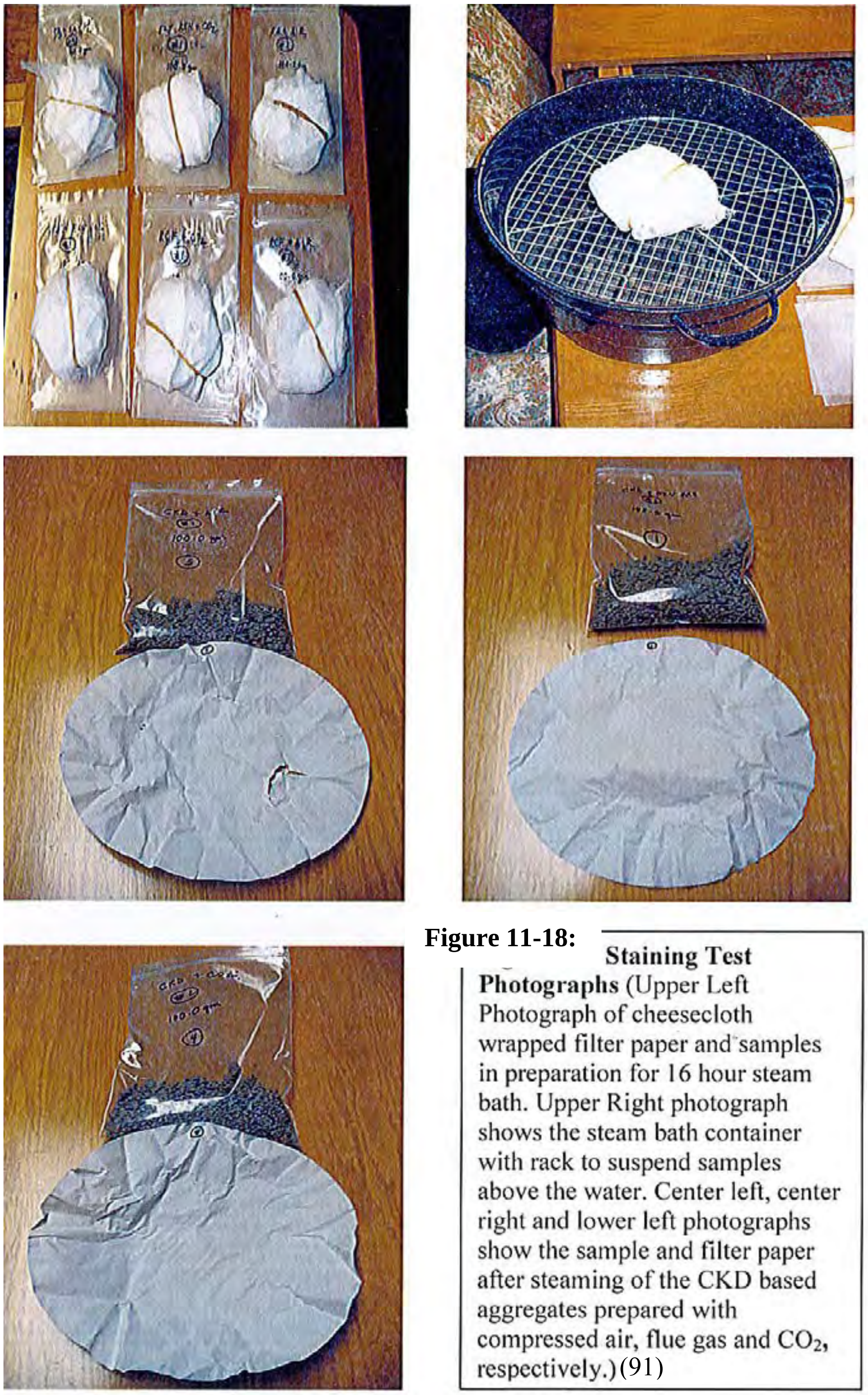


Figure 11-18: Staining Test Photographs (Upper Left Photograph of cheesecloth wrapped filter paper and samples in preparation for 16 hour steam bath. Upper Right photograph shows the steam bath container with rack to suspend samples above the water. Center left, center right and lower left photographs show the sample and filter paper after steaming of the CKD based aggregates prepared with compressed air, flue gas and CO_2, respectively.)(91)

The sample was then removed from the filter paper, and the filter paper was oven dried on a watch glass. ASTM C-641 provides examples of filter paper staining for comparison. In this case, all of the samples tested had no staining with a rating of zero. These results are not entirely surprising as the iron content indicated in the oxides (Fe_2O_3) analysis of the by-product was not too high, even the highest in the Class C fly ash, had a Fe_2O_3 content of only 5.5%. All of the other by-product materials had measured values below 2.0% for Fe_2O_3. Photographs of an example of the staining test apparatus, cheesecloth-filter paper wrapped samples, and the filter paper results for each CKD aggregate material prepared are shown on Figure 11-18.

In summary, all five of the by-product material based aggregates did not demonstrate staining effects when tested per ASTM C-641, "Standard Test Method for Iron Staining Materials in Lightweight Concrete Aggregates."

Comparison to Commercial Aggregate Materials

The by-product-based crushed aggregate material properties were compared to published values for natural or lightweight aggregates. It should be noted that these materials were expected to be unique and were not necessarily expected to mirror the properties of natural or manufactured-lightweight aggregates. Pumice and expanded shale were identified as lightweight aggregates used commercially with similar physical density properties. The oxide compositions differ for the by-product-based materials. They all had significantly larger amounts of CaO than the pumice and expanded shale aggregates. The pumice and expanded shale aggregates had significantly larger amounts of SiO_2. The pumice also demonstrated the lowest values for MgO, K_2O, and TiO_2. The published values for the other mineral compounds found in pumice and expanded shale, with the exception of Fe_2O_3 which was sometimes higher, all fell within the range of the values found for the by-product materials tested. The oxides analysis and other chemical properties comparison of the by-product-based aggregates and commercial aggregates are shown on Table 11-11.

The by-product-based crushed aggregates range of values for physical properties are compared to published values for natural crushed gravel, two sources of pumice, and a source of manufactured expanded shale aggregate. An attempt was not made to optimize grain size distribution but rather to show the as-crushed condition for each of the new aggregate materials. Specific gradations could be managed with conventional commercial aggregate screening plant equipment.

Table 11-11: Oxides Analysis and Other Chemical Properties Comparison of By-Product-Based Aggregates to Commercial Materials (%) (91)

Oxides Analysis[1]	Range for By-Product Materials Tested	Pumice[3]	Volcanic Pumice[4]	Expanded Shale
SiO_2	9.5-39.2	70.3	60.8	>50
Al_2O_3	3.9-21.0	21.4	16.7	<20
Fe_2O_3	0.7-5.5	1.1	7.0	<10
CaO	20.3-49.8	0.5	4.4	<2
MgO	2.2-24.9	0.4	1.9	<5
K_2O	0.4-3.8	0.0	2.3	----
Na_2O	0.0-4.7	0.1	5.4	----
SO_3	0.3-12.3	0.8	0.1	----
TiO_2	0.0-1.4	0.0	----	----
LOI (750°C)[1,2]	-0.5-22.5	4.5	1.5	----
LOI (1000°C)[1,2]	-1.5-24.9	----	----	----
SUM	100.0	99.2	100.1	----
Available Alkali	0.2-6.8	----	----	----

Notes:

1. ASTM D- 4326, "Standard Test Method for Major and Minor Elements in Coal and Coke Ash by X-Ray Fluorescence" (101)
2. ASTM C-311, "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete" (99)
3. Witelite by Tarmac Catalog, www.witelite.com (98)
4. Volcanic Pumice from Papua and New Guinea (102)
5. Northeast Solite Corp., MSDS, http://www.nesolite.com/physicalcharac.htm
6. 1°F = 1.8°C + 32

The Witelite pumice physical properties fell within the ranges measured for the five by-product-based aggregates properties with the exception of absorption which was lower for this source of pumice at 16.3%. The volcanic pumice had a lower density of 37 lb/ft^3 (593 kg/m^3) and specific gravity of only 0.76. Staining was not reported for this aggregate source but is very important from an aesthetic perspective. Iron oxides that stain can provide unwanted black, brown, red, orange or pink discoloration in concrete and concrete products. The expanded shale properties shown in Table 11-12 for this source of lightweight aggregate fell within the ranges shown for the by-product-based aggregates with the exception of absorption which was slightly lower at 18% and the specific gravity was higher at a value of 1.73. The crushed gravel physical properties shown in Table 11-12 were significantly different when compared to the by-product aggregates with the highest density of 113 lb/ft^3 (1812 kg/m^3), absorption at only 1.6%, and a specific gravity of 2.57. Staining test performance was not reported. The physical properties comparison of by-product-based aggregates and commercial aggregates shown in Table 11-12 confirm that these aggregates are similar to expanded shale aggregates which fall in density below normal crushed gravel aggregate and just higher than pumice lightweight aggregate.

Table 11-12: Physical Properties Comparison of By-Product Mineral Based Aggregates to Commercial Materials (91)

	Density[1] (lb/ft^3)	Absorption[2] (%)	Specific Gravity[3]	Fineness Modulus[4]	Staining[5]
Pumice[6]	55.0	16.3	1.20	3.10	0
Volcanic Pumice[8]	37.0	32.1	0.76	2.55	----
Expanded Shale[7]	54.0	18.0	1.73	3.88	0
Crushed Gravel[9]	113.0	1.6	2.57	2.82	----
Range for By-Product Aggregates Tested	44.2-69.5	17.5-48.7	0.95-1.54	1.74-6.42	0

Notes:

1. Dry Bulk Density, ASTM C 29, "Standard Test Method for Bulk Density (Unit Weight) and Voids in Concrete" [10]
2. Absorption, ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity)" [11]
3. Relative Density (Specific Gravity) Oven Dry, ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity)" [11]
4. Fineness Modulus, ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" [8]
5. Staining-Visual Classification Method, ASTM C 641, "Standard Test Method for Iron Staining Materials in Lightweight Concrete Aggregates" [12]
6. Witelite by Tarmac Catalog, www.witelite.com
7. Northeast Solite Corp., #15 Block, http://www.nesolite.com/physicalcharac.htm
8. Volcanic Pumice from Papua and New Guinea[15]
9. Crushed Gravel Aggregate[15]
10. $1\ lb/ft^3 = 16.0356\ kg/m^3$

In summary the oxides analysis and physical properties of the by-product-based aggregates produced were determined, and shown to be similar to expanded shale and pumice aggregates as shown in Tables 11-11 and 11-12. All five of the by-product-based aggregates also did not show any iron staining effects. This information can be helpful in identifying potential construction uses for these new carbonated aggregate materials.

Feasibility Analysis of a Scaled Up Commercial Process

A carbonated-foamed material can most efficiently be manufactured at a site located adjacent to a by-product material producer. The following data indicates that the potential revenue from aggregate sales plus the estimated future value of CO_2 sequestration credits would be sufficient to support a further detailed evaluation of an actual commercial, carbonated-foamed slurry to aggregates manufacturing facility. The volumes of industrial by-products produced, which were used in this project, are large. Many producers incur an expense for disposal in an environment with increasing environmental regulations for landfill facilities. Landfills are unpopular and can be difficult to permit with an estimated lead time in some areas of seven years or longer. Landfills can also present industries with ongoing expenses for treatment of leachates, and property maintenance long after the by-products have been landfilled and the landfill is closed. The prospect of constructing a facility for a carbonate mineralization process with a valuable and useful end product adjacent to a coal-fly ash power plant, LKD, CKD, Slag, and/or RCF source, to recycle by-product materials, that may otherwise be destined for disposal can be environmentally, economically, and sociologically attractive. Depending on market pricing for these commodities, it is possible that a carbonate-mineralization to aggregate production process could become commercially attractive because the aggregates produced can be easily stockpiled and stored outdoors to meet seasonal demands for such aggregates. The advantages and disadvantages of a commercial by-product aggregate production process, from the social, environmental and financial perspectives are discussed below.

Benefits of Commercial By-Product Aggregates

Social Perspective:

- No loss of jobs. Existing landfill construction and disposal activities become carbonate-mineralization to sand/gravel/crushed stone stockpiling and material handling functions.
- Land use does not increase and existing dedicated property is converted to a higher value manufacturing use.
- If lightweight aggregates are manufactured and more widely used, there could be a safety benefit for workers with fewer injuries from lifting and handling lighter concrete blocks and other building materials.
- There would be lower fuel usage for delivering lower density materials conserving a valuable and dwindling energy resources for other societal purposes.
- There would be potential energy efficiency from the additional insulating value of lower density building materials.

Environmental Perspective:

- The need for additional landfills and associated environmental impacts could be reduced or eliminated for these industrial by-product materials.
- Existing natural mineral resources can be preserved for future generations.
- The process makes beneficial use of industrial by-products in producing carbonate mineralized aggregates.
- CO_2 is sequestered and stored for the geologic long term as carbonate at the amounts shown, see Table 11-13.
- A useful “green” building material becomes available at many new locations for a variety of purposes, such as: lower density geotechnical applications, insulating material, green roof rooting media, lightweight concrete and concrete products such as masonry units, and also provide potentially increased fire resistance and protection.

Table 11-13: Average CO_2 Sequestered by Percent Mass at 182 Day Age (91)

Material	Average % CO_2 by Mass at 182-Day Age	Starting % CO_2 by Mass at Day 0	Net % CO_2 Sequestered
CKD	20.3	9.5	10.8
LKD	25.7	22.2	3.5
RCF	13.8	14.6	0
CFA	2.4	0.1	2.3
Slag	5.0	1.4	3.6

Financial Perspective:

- The overall life cycle cost of industrial by-product disposal in a landfill in Wisconsin is estimated at approximately $35.00 to $45.00/ton.
- Lightweight aggregate pricing varies based on the quality and end-use application between $24.00 to $38.00/ton.
- Normal-weight aggregate pricing varies based on quality and processing requirements between $3.00 and $12.00/ton.
- CO_2 credits were valued in Europe at as much as $31.50/ton during 2006 (103) and are projected to increase in the future, as new laws regarding lowering CO_2 production become prevalent in the U.S.A.
- Aggregate is the largest volume ingredient in concrete, making up to 80% of the concrete volume. Therefore, the use of these by-product-based aggregates could significantly increase the recycled “green” content of concrete building materials

The following conservative economic assumptions for feasibility come from the author’s personal experience with other similar activities:

- Industrial by-product source manufacturing plants typically have an existing landfill, and space for production and storage of carbonate-aggregates on site.
- Dry fine powder industrial by-products can be moved from plant collection silos to an on-site batch plant silo for $5.00/ton (short haul or pneumatic transport line).
- Contractors can supply foaming agent, water and equipment to process industrial by-product materials at $30/ton.
- Hardened foamed material can be picked up, crushed and stockpiled, which provides additional surface area and pathways to absorb CO_2, for $15.00/ton.
- Normal material handling economics apply for supplying stockpiled materials to users, although a fuel savings may be possible if replacing normal weight materials with lightweight materials.
- CO_2 credits are available for sequestered CO_2 at $30.00/ton. Figure 11-19 was prepared as an example, to calculate the CO_2 credit in dollars per cubic yard, based upon percent CO_2 mass sequestered for an aggregate with a dry-rodded density of 55 lb/ft^3 (882 kg/m^3) (91). For example, if the manufactured aggregate has a density of 55 lb/ft^3 (882 kg/m^3), and CO_2 sequestration credits are valued at $30.00/ton, and the percentage by mass of CO_2 sequestered within the aggregate

are known, then a manufacturer could easily reference this chart to find the dollar value of the CO_2 sequestration credit available for each cubic yard of aggregate produced and sold. This information is important in establishing a competitive selling price for the manufactured aggregate product (91).

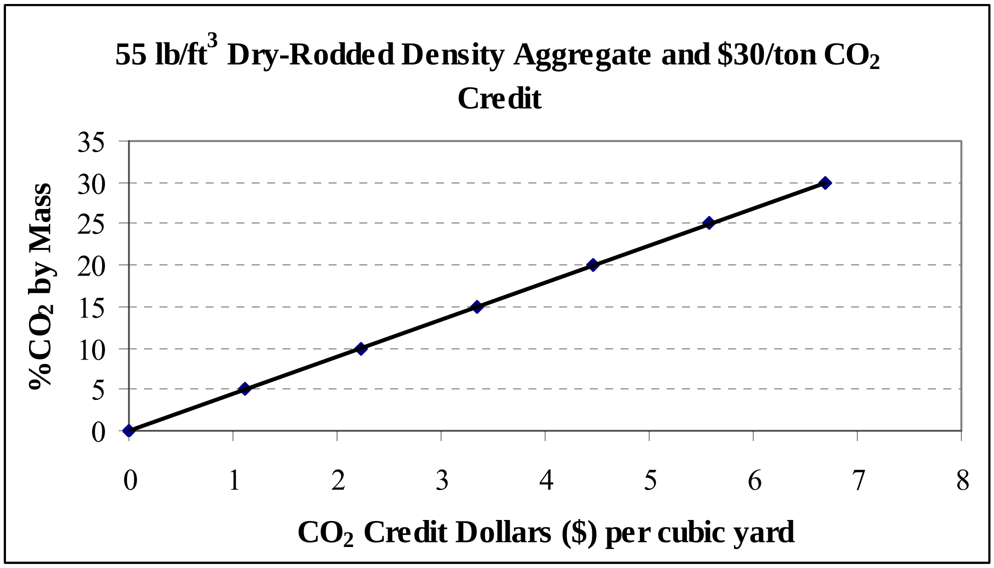


Figure 11- 19: CO_2 Credit Value Example for 55 lb/ft^3 Dry Density Aggregate (91)
Note: 1.00 lb/ft^3 = 16.0356 kg/m^3, 1.00 ton = 0.91 metric ton

Chapter 12

Sample Specifications

12.1 Specification for We Energies Cast-In-Place Concrete

Part 1 - General

1.01 Section Includes

A. Furnish and install all cast-in-place concrete.

1.02 References

A. American Concrete Institute (ACI):

1. *ACI 301 - Specifications for Structural Concrete for Buildings.*
2. *ACI 305 - Hot Weather Concreting.*
3. *ACI 306 - Cold Weather Concreting.*
4. *ACI 309 - Recommended Practice for Consolidation of Concrete.*

1.03 Submittals

A. Submit Portland cement and fly ash test reports at least 14 days prior to placement of concrete.

B. Submit manufacturer's data for concrete admixtures, liquid curing material, floor joint filler, finishing compounds, and bonding agents.

C. Submit concrete aggregate test reports and concrete mix designs at least 14 days prior to placement of concrete.

D. Submit results of concrete strength tests.

1.04 *Quality Assurance*

A. Comply with ACI 301, except as modified in this Section.

B. Hire an independent testing laboratory, approved by the Engineer, to perform the work listed below. All costs for this testing shall be paid by the Contractor.

1. *Test proposed aggregate.*
2. *Test proposed fly ash.*
3. *Design concrete mixes for each type of concrete specified*

4. *Cast concrete cylinders for strength tests.*
5. *Test concrete cylinders.*

C. Aggregate Tests:

1. *Test aggregates for compliance with ASTM C33.*

D. Concrete Mix Design:

1. *Prepare mix designs for each type of concrete specified.*
2. *Design concrete mixes in accordance with ACI 301.*

E. Concrete Strength Tests:

1. *Mold and cure three specimens from each sample in accordance with ASTM C31. Any deviations from the requirements of ASTM C31 shall be recorded in the test report.*
2. *Test specimens in accordance with ASTM C39. Two specimens shall be tested at 28 days for acceptance and one shall be tested at seven days for information. The acceptance test results shall be the average of the strengths of the two specimens tested at 28 days.*
3. *Make at least one strength test for each 100 cu. yds., or fraction thereof, of each mixture design of concrete placed in any one day.*
4. *A copy of the test results shall be furnished to the Engineer as soon as available.*
5. *All costs of concrete cylinder testing shall be paid by the Contractor.*
6. *Mold and field cure additional specimens for early form removal.*

F. Concrete Slump Tests:

1. *The Independent Testing Laboratory will determine slump of concrete from each truck in accordance with ASTM C143.*
2. *If the slump does not meet specifications, remove batch from work and return to supplier.*

G. Concrete Air Content Tests:

1. *The Independent Testing Laboratory will determine air content of concrete from each truck in accordance with ASTM C231.*
2. *If air content does not meet specifications, remove batch from work and return to supplier.*
3. *Air content will be tested prior to and after adding superplasticizer.*

H. Concrete Temperature:

1. *The Independent Testing Laboratory will determine temperature of concrete from each truck.*

1.05 Product Handling

A. Do not store forms, shores, reinforcing, equipment or other material on finished slab surfaces.

Part 2 – Products

2.01 Concrete Materials

A. Cement: Conform to ASTM C150, Type I. Provide cement from one source of supply.

B. Fly ash: Conform to ASTM C618, Class C from We Energies Oak Creek, Pleasant Prairie or Presque Isle Power Plants, or ASTM C618 Class F from We Energies Elm Road Generation Station.

C. Aggregate: Conform to ASTM C33. Provide aggregate from one source of supply.

D. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other foreign matter.

2.02 Admixtures

A. Air Entraining Admixture: Conform to ASTM C260.

B. Water Reducing Admixture: Conform to ASTM C494, Type A.

C. High Range Water-Reducing Admixtures (Superplasticizer): Conform to ASTM C494, Type F and contain no chlorides.

2.03 Miscellaneous Material

A. Burlap-Polyethylene Sheet: Burlap polyethylene sheeting shall consist of burlap weighing not less than 10 oz./linear yard, 40 in. wide impregnated on one side with white opaque polyethylene 0.006 in. thick. Sheeting shall conform to ASTM C171.

B. Liquid Curing Compound: Conform to ASTM C309, Type 1-D, Class B clear or translucent with fugitive dye. Not to be applied to floor slabs.

C. Expansion Joint Material: Bituminous fiber type conforming to ASTM D1751 with bituminous or paraffin binder.

D. Interior Joint Filler: One part, self-leveling, polymer reinforced joint filler, Everjoint manufactured by L&M Construction Chemicals, Inc., or approved equal.

E. Exterior Joint Sealant: Two part, self-leveling, polyurethane sealant, Sonolastic SL2 manufactured by Sonneborn, or approved equal.

F. Concrete Finishing Compound: Thoroseal cement based coating manufactured by Thoro System Products, or approved equal.

G. Bonding Agent: Acryl 60 manufactured by Thoro System Products, or approved equal.

2.04 Concrete Mix Proportions

A. 3000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	3000 psi
Minimum Cement Content	255 lbs/cu. yd.
Minimum Class C Fly ash Content	208 lbs/cu. yd.
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

B. 4000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	4000 psi
Minimum Cement Content	310 lbs/cu. yd.
Minimum Class C Fly ash Content	251 lbs/cu. yd.
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

C. 5000 PSI Concrete - 40% fly ash @ 1:1.25, cement to fly ash replacement ratio

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	5000 psi
Minimum Cement Content	367 lbs/cu. yd.
Minimum Class C Fly ash Content	265 lbs/cu. yd.
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

D. 6000 PSI Concrete - 40% fly ash @ 1:1.25 cement to fly ash replacement ratio.

Coarse Aggregate Size	ASTM C33 No. 67
Minimum Compressive Strength at 28 days	6000 psi
Minimum Cement Content	445 lbs/cu. yd.
Minimum Class C Fly ash Content	239 lbs/cu. yd.
Slump	6½ in.
Superplasticizer	Compatible with cement and as needed for workability
Air Entraining Agent	Compatible with cement and as needed for air content to provide required air for exposure condition

Part 3 – Execution

3.01 Concrete Production

A. Batch, mix, and transport ready-mixed concrete in accordance with ASTM C94.

B. Mix concrete only in quantities for immediate use. Discard concrete which has set. Do not retemper.

C. Discharge concrete from truck within 60 minutes after cement is added to the mix.

D. Do not add water at the site without the permission of the Engineer.

E. Add superplasticizer to the concrete at the project site. Add superplasticizer and mix concrete in accordance with manufacturer's recommendations.

3.02 Embedded Items

A. All sleeves, inserts, anchors, and embedded items required for adjoining work or for its support shall be placed prior to placing concrete.

B. All embedded items shall be positioned accurately and supported against displacement.

C. Voids in sleeves, inserts and anchor slots shall be filled temporarily with readily removable material to prevent the entry of concrete into the voids.

3.03 Preparation Before Placing

A. Formwork shall be completed and all reinforcement and embedded items shall be secured in place.

B. All snow, ice, and mud shall be removed prior to placing concrete.

C. Do not place concrete on frozen ground.

D. Do not place concrete on ground with standing water or when upper 2" of ground is saturated.

E. Do not place concrete during rain, sleet, or snow.

3.04 Concrete Conveying

A. Handle concrete from the mixer to the place of final deposit as rapidly as practical by methods, which will prevent segregation or loss of ingredients.

3.05 Concrete Depositing

A. Deposit concrete continuously or in layers of such thickness that no concrete will be deposited on concrete which has hardened sufficiently to cause the formation of seams or planes of weakness within the section.

B. Place concrete at such a rate that the concrete which is being integrated with fresh concrete is still plastic.

C. Concrete, which has partially hardened or has been contaminated by hardened materials, shall not be deposited.

D. Remove rejected concrete from the site.

E. Deposit concrete as nearly as practicable to its final position to avoid segregation due to handling or flowing.

F. Free fall of concrete shall not exceed five feet. Use chutes equipped with hopper heads for placing where a drop of more than five feet is required.

3.06 Placing Concrete Slabs

A. Deposit and consolidate concrete slabs in a continuous operation.

B. Consolidate concrete placed in slabs by vibrating bridge screeds, roller pipe screeds or other methods acceptable to the Engineer. Bring slab surfaces to the correct level with a straight edge and then strike off. Use bullfloats or darbies to smooth the surface, leaving it free from bumps and hollows.

C. Do not leave screed stakes in concrete.

D. Do not sprinkle water on the plastic surface. Do not disturb the slab surfaces prior to start of finishing operations.

3.07 Cold Weather Placing

A. Do not place concrete when the air temperature is less than 40°F without the specific approval of the Engineer.

B. Comply with ACI 306 to protect all concrete work from physical damage and reduced strength caused by frost or low temperatures.

C. The temperature of the concrete delivered at the site shall conform to the following limitations.

Air Temperature	Minimum Concrete Temperature
30° to 45°F	60°F
0° to 30°F	65°F
Below 0°F	70°F

D. If water or aggregate is heated above 100°F, the water shall be combined with the aggregate in the mixer before cement is added. Cement shall not be mixed with water or with mixtures of water and aggregate having a temperature greater than 100°F.

E. When the mean daily temperature is less than 40°F, the temperature of the concrete shall be maintained between 50°and 70°F for the required curing period.

F. Arrangements for heating, covering, insulation, or housing the concrete work shall be made in advance of placement and shall be adequate to maintain the required temperature without injury due to concentration of heat.

G. Combustion heaters shall not be used during the first 24 hours unless precautions are taken to prevent exposure of the concrete to exhaust gases.

3.08 Hot Weather Placing

A. Comply with ACI 305 when hot weather conditions exist.

B. Maintain concrete temperature at time of placement below 90°F.

C. When the temperature of the steel is greater than 120°F, steel forms and reinforcement shall be sprayed with water prior to placing concrete.

D. Keep all surfaces protected from rapid drying. Provide windbreaks, shading, fog spraying, sprinkling, ponding, or wet covering in advance of placement.

3.09 Consolidation

A. Consolidate all concrete in accordance with provisions of ACI 309.

B. Consolidate each layer of concrete immediately after placing, by use of internal concrete vibrators. Maintain a frequency of not less than 8,000 vibrations per minute for each internal vibrator.

C. Provide adequate number of units and power source at all times. Use a minimum of two vibrators for all work and maintain spare units to ensure adequacy.

D. Insert the vibrator so as to penetrate the lift immediately below the one being placed. Do not insert the vibrator into lower courses, which have begun to set.

E. Spacing between insertions of the vibrator shall generally be from 12" to 18" and shall not exceed twice the radius of action as shown in ACI 309 or eighteen (18) inches.

F. Do not use vibrators to transport concrete inside the forms.

G. Vibration shall be adequate and properly carried out to minimize entrapped air and surface voids on formed surfaces.

3.10 Concrete Slab Finishing

A. Float Finish:

1. *Apply float finish to all slab surfaces.*
2. *After placing and screeding concrete slabs, do not work the surface until ready for floating. Begin floating when the surface water has disappeared and when the concrete has stiffened sufficiently to permit operation of a power-driven float.*
3. *Consolidate the surface with power-driven float, or by handfloating if the area is small or inaccessible to power units.*
4. *Check and level the surface plane to a tolerance not exceeding 1/4 inch in ten (10) feet when tested with a ten-foot straight-edge placed on the surface at not less than two different angles.*
5. *Immediately after leveling, refloat the surfaces to a smooth, uniform, granular texture.*

B. Trowel Finish:

1. *Apply steel trowel finish to all interior floor slabs, topping, and stair treads.*
2. *Apply float finish to slabs as described above in part 3.10.A.*
3. *After floating, begin the first trowel finish operation using a power-driven trowel. Begin final troweling when the surface produces a ringing sound as the trowel is moved over the surface.*

4. *Consolidate the concrete surface by the final hand troweling operation, free from trowel marks, uniform in texture and appearance, and with a surface plane tolerance not exceeding 1/8 inch in 10 feet when tested with a ten foot straight-edge.*

C. Broom Finish:

1. *Apply non-slip broom finish to all exterior sidewalks and aprons.*
2. *Apply float to slabs as described above in part 3.10A.*
3. *Immediately after floating, slightly roughen the concrete surface by sweeping in the direction perpendicular to the main traffic route. Use a fiber-bristle broom.*

3.11 Finishing Formed Surfaces

A. Smooth Form Finish: Provide a smooth formed surface to all formed surfaces not exposed to view unless otherwise noted in paragraph B. Smooth formed finish shall consist of the following:

1. *Construct formwork in exact dimension of the concrete member poured.*
2. *Patch all tie holes and defects.*
3. *Remove all fins, concrete "buttons", and protrusions completely.*

B. Special Wall Finish: Provide a special wall finish to all formed surfaces exposed to view.

1. *Provide a smooth form finish in accordance with paragraph 3.11.A.*
2. *Thoroughly clean wall surface and remove all dirt, loose mortar particles, paint, films, protective coatings, efflorescence and other foreign material.*
3. *Dampen surface with clean water just prior to application of finishing compound.*
4. *Mix one part bonding agent to three parts clean water for mixing liquid.*
5. *Mix concrete finish compound with mixing liquid as specified by the manufacturer.*
6. *Apply first coat to concrete with brush at 2 lbs. per square yard.*
7. *Apply second coat to concrete with brush at 2 lbs. per square yard after the first coat has set.*
8. *When the second coat has set, float it to a uniform texture with a sponge float.*
9. *Prepare three test samples of various textures for approval by the Engineer. Each sample shall be approximately 6' x 6' in size and located on an unexposed wall surface as directed by the Engineer.*

3.12 Curing

A. Immediately after placement, all concrete shall be damp cured for a minimum of seven days.

B. All slabs shall be covered with approved burlap-polyethylene film and kept in place throughout the curing period.

C. Walls, beams, columns, and other formed surfaces shall be covered with burlap-polyethylene film or sprayed with an approved curing compound.

D. All burlap-polyethylene film shall be adequately anchored at the edges to prevent moisture loss.

E. Rewet all slab surfaces at least once a day during the curing period.

3.13 Patching

A. Repair honeycomb and other defective areas, fill surface voids and fill form tie holes and similar defects in accordance with Chapter 9 of ACI 301.

B. Reinforce or replace deficient work as directed by the Engineer and at no additional cost to the Owner.

3.14 Cleaning

A. Upon completion and prior to any painting, all exposed or painted concrete surfaces shall be thoroughly cleaned of all concrete spatters, from oil or other foreign material detrimental to appearance or painting.

END OF SECTION

12.2 Specification for We Energies Bottom Ash Structural Backfill

Part 1 – General

1.01 Section Includes

A. Furnish bottom ash structural fill material and backfill excavation (for bridges, culverts, retaining walls, structural plate pipes, pipe anchors, and/or around building basements).

1.02 References

A. WDOT - Standard Specifications for Highway and Structure Construction Section 210.

B. ASTM E1861 - Standard Guide for Use of Coal Combustion By-Products in Structural Fills.

1.03 Submittals

A. Submit Sieve Analysis Test and Reports.

1.04 Quality Assurance

A. Chapter NR 538 - Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code).

B. Comply with ASTM E1861, except as modified in this section.

C. Hire an independent testing laboratory, approved by the Engineer to perform the work listed below. All costs for the testing shall be paid by the Contractor.

   1. *Perform Sieve Analysis Test on the bottom ash.*
   2. *Measure field density of the bottom ash.*

Part 2 – Products

2.01 Bottom Ash Structural Fill

A. Bottom Ash: Meet ASTM E1861 requirements.

B. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other foreign matter.

Part 3 – Execution

3.01 Bottom Ash Material

A. Bottom ash used for backfill shall be of a quality acceptable to the Engineer and free from frozen lumps, wood or other extraneous or deleterious material.

3.02 Limitations on Placing Backfill

A. Bottom ash shall not be placed against concrete masonry retaining wall or abutment until the masonry has been in place 14 days or until tests show the strength of masonry strong enough to take lateral pressure from the fill.

B. Structural backfill shall not be placed against any portion of any substructure until the required curing and protection, surface finishing, damp proofing and waterproofing of the work to be covered by structural fill has been completed.

C. When backfilling against retaining walls, fill uniformly and simultaneously on both sides to the elevations of the front ground surface immediately after removal of the forms.

D. Abutments for rigid frame structures and abutments not designed as self-sustaining shall not be backfilled until concrete in the superstructure has been poured and cured.

E. Backfill only after the area has been cleared of all false work, sheet piling, cribbing, shoring, bracing, forms and rubbish.

3.03 Bottom Ash Transporting and Placing

A. Bottom ash shall be transported in a truck or other vehicle and shall be so unloaded such that contents of each vehicle are gradually deposited instead of simultaneously emptying the entire content as one mass.

B. Backfill shall be placed in continuous horizontal layers not more than eight inches thick and brought up uniformly. Compact each layer to at least 95% of proctor density or 90% of modified proctor density (ASTM D1557) before the next layer is placed, by means of approved rollers or portable mechanical or pneumatic tampers or vibrators.

C. Backfilling along front face of abutments, retaining walls and wing walls shall extend to within six inches of weep holes, unless otherwise specified.

3.04 Cleaning

A. Upon completion of placing structural fill, the area shall be thoroughly cleaned of all foreign material.

END OF SECTION

12.3 Specification for We Energies Bottom Ash as Granular Backfill

Part 1 – General

1.01 Section Includes

A. Furnish bottom ash granular material and backfill trenches for pipe culverts, storm sewers, under drains and similar structures.

1.02 References

A. WDOT - Standard Specifications for Highway and Structure Construction-Section 209.

B. ASTM D422 - Test Method for Particle Size Analysis of Soils

C. Chapter NR 538 - Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code).

1.03 Submittals

A. Submit Sieve Analysis Test Results

1.04 Quality Assurance

A. Comply with WDOT - Standard Specification for Highway and Structure Construction Section 209.2 for particle size distribution, except as modified in this section.

B. Hire an independent testing laboratory, approved by the Engineer to perform the work listed below. All costs for the testing shall be paid by the Contractor.

1. *Perform Sieve Analysis Test on the aggregate.*
2. *Measure field density of the backfill.*

Part 2 – Products

2.01 Bottom Ash Granular Fill

A. Bottom Ash: Particle size distribution shall meet job requirements.

B. Water: Clean potable and free from deleterious amounts of oil, acid, alkali or other foreign matter.

Part 3 – Execution

3.01 Bottom Ash Material

A. Bottom ash used for backfill shall be of a quality acceptable to the Engineer and free from frozen lumps, wood or other extraneous or perishable material.

3.02 Bottom Ash Placing and Compacting

A. Bottom ash shall be unloaded from the truck or other vehicles so that the contents of each vehicle are gradually deposited instead of emptying the entire contents as one mass.

B. The bottom ash shall be spread and leveled in layers generally not exceeding eight inches in thickness before compaction.

C. Compact each layer to the degree that no further appreciable consolidation is evident under the actions of the compaction equipment. The required compaction shall be attained before any material for a succeeding layer is placed thereon.

D. Compaction shall be performed by specialized compaction equipment in addition to hauling and leveling equipment routed and distributed over each layer of the fill.

E. The fill material shall be compacted to at least 90% of modified proctor maximum density (ASTM D1557) for their full depth.

3.04 Cleaning

A. Upon completion of placing granular fill, the area shall be thoroughly cleaned of all foreign material. The compaction area shall be free from bottom ash debris and suitable for placement of topsoil or next course of road construction.

END OF SECTION

12.4 Specification for We Energies Flowable Fly Ash Slurry Controlled Low Strength Material (CLSM)

Part 1 - General

1.01 Section Includes

A. Furnish and place controlled low strength material as backfill in trenches for culverts, conduit, storm sewers, utilities or similar structures, as a backfill behind bridge abutments or as a fill for retirement of sewers, tunnels, tanks, culverts or pipes.

1.02 References

A. ACI 229R-99 Report: Controlled Low Strength Materials (CLSM)

B. ACI 304 - Guide for measuring, mixing, transporting and placing concrete.

C. Chapter NR 538 - Beneficial use of industrial by-products - Department of Natural Resources (Wisconsin Administrative Code).

1.03 Submittals

A. Submit fly ash test results.

B. Submit CLSM flow and compressive strength test results.

C. Submit documentation that the fly ash used in this mixture meets the requirements of Industrial By-Products Categories 1, 2, 3 or 4 in NR 538 of the Wisconsin Administrative Code for use as a confined geotechnical fill.

1.04 Quality Assurance

A. Comply with ACI 229R, except as modified in this section.

B. Hire an independent testing laboratory, approved by the Engineer, to perform the work listed below. All costs for testing shall be paid by the Contractor.

   1. *Design CLSM mixes for each type of CLSM specified.*
   2. *Cast CLSM cylinder for compressive strength test.*
   3. *Measure flow of CLSM.*
   4. *Test CLSM cylinders.*

C. CLSM Mix Design

   1. *CLSM shall consist of a designed mixture of cement and We Energies bituminous coal fly ash and sometimes aggregate.*
   2. *The designed mixture shall be self-leveling and shall be essentially free from shrinkage after hardening. The mixture shall be designed to reach a state of hardening such that it can support the weight of a person in no more than 24 hours.*

3. *The CLSM shall meet the following criteria:*

Test	Method	Valve
Flow	ASTM D6103	10” (250 mm) ± 3”
Compressive Strength	ASTM D4832	20-200psi @ 28 days (140 - 1400 kPa)

(The compressive strength values shown are guideline targets and actual cylinder breaks may vary considerably while still providing an acceptable and re-excavatable fill material. 100psi is 14,400 psf in soil terms, which is comparable to very compacted gravel to hard pan material.)

D. CLSM Strength Tests

1. *Mold and cure three specimens from each sample in accordance with ASTM D4832. Any deviations from the requirements of ASTM D4832 shall be recorded in the test report.*
2. *Test specimens in accordance with ASTM D4832. Two specimens shall be tested at 28 days for acceptance and one shall be tested at seven days for information. The acceptance test results shall be the average of the strength of the two specimens tested at 28 days.*
3. *Make at least one strength test for each 100 cu. yd., or fraction thereof, of each mixture design of CLSM placed in any one day.*
4. *A copy of the test results shall be furnished to the Engineer as soon as possible.*
5. *The Contractor shall pay all costs of CLSM cylinder testing.*

E. CLSM Flow Tests

1. *The testing laboratory will determine the flow of CLSM from each truck in accordance with ASTM D6103.*
2. *If flow does not meet specifications, remove batch from work and dispose of off-site.*
3. *The Contractor will pay all costs of flow testing.*

F. Hardening Time

1. *On projects where hardening time is critical, the Owner/Engineer may at his/her discretion measure the hardening time in accordance with ASTM C403.*
2. *When measured in accordance with ASTM C403, the CLSM shall give a penetration number in the range of 500 to 1500.*
3. *All costs for measuring hardening time shall be paid by the Contractor.*

Part 2 – Products

2.01 CLSM Material

A. Cement: Conform to ASTM C150, Type 1. Provide cement from one source.

B. Aggregate: Conform to ASTM C33 unless approved by the Engineer.

C. We Energies Fly Ash: Not necessarily conforming to ASTM C 618.

D. Water: Clean, potable, and free from deleterious amounts of oil, acid, alkali or other matter.

2.02 CLSM Mixture Proportions

A. CLSM mixtures shall be proportioned to meet project requirements. The following mixture proportions shall be considered as a guideline for CLSM mixtures. The mixture proportions shall be modified to meet specific project requirements.

1. *Flo-Pac 1 – (Excavatable) trench backfill applications:*
    Portland Cement : 100 lb/cu. yd.
    Class F Fly ash : 1450 lb/cu. yd.
    Water : 950 lb/cu. yd.
    Total Weight : 2500 lb/cu. yd

2. *Flo-Pac 2 (Excavatable)*
    Portland Cement : 70 lb/cu. yd.
    Class F Fly ash : 925 lb/cu. yd.
    Sand (SSD) : 1175 lb/cu. yd.
    Added Water : 785 lb/cu. yd.
    Total Weight : 3002 lb/cu. yd.

3. *Flo-Pac 5 (Not easily excavatable)*
    Portland Cement : 200 lb/cu. yd.
    Class F Fly ash : 700 lb/cu. yd.
    Stone (SSD) : 1500 lb/cu. yd.
    Sand (SSD) : 750 lb/cu. yd.
    Added Water : 480 lb/cu. yd.
    Total Weight : 3683 lb/cu. yd.

4. *Flo-Pac 6 (Excavatable)*
    Portland Cement : 50 lb/cu. yd.
    Class C Fly ash : 50 lb/cu. yd.
    Sand (SSD) : 3100 lb/cu. yd.
    Added Water : 500 lb/cu. yd
    Total Weight : 3700 lb/cu. yd.

Part 3 – Execution

3.01 CLSM Production and Conveyance

A. CLSM shall be batched, mixed and transported in accordance with ACI 229.

B. CLSM shall be mixed only in quantities for immediate use. CLSM, that has set, shall be discarded and shall not be retempered.

C. Discharge CLSM from truck within 90 minutes after cement and fly ash is added to the mix.

D. CLSM shall be handled from the mixer to the place of final deposit as rapidly as practical by methods, which will prevent segregation or loss of ingredients.

3.02 CLSM Depositing

A. CLSM shall be placed to the lines and grades as shown on the plans.

B. Materials shall be proportioned in accordance with the specified mix design. The product shall be of consistent texture and flow characteristics. The Engineer may reject any materials exhibiting a substantial change in properties, appearance or composition.

C. CLSM, which has partially hardened or has been contaminated by hardened material, shall not be deposited.

D. Deposit CLSM as soon as practical, so it can flow to any irregular area and fill completely.

E. CLSM shall be placed in accordance with Wisconsin DNR Chapter NR538 and no CLSM material shall be allowed to enter any stream, lake, or storm sewer system.

F. If the official Weather Bureau forecast for the construction site predicts temperatures at or below freezing within the next 24 hours after placement of CLSM, the Contractor shall protect the material placed from freezing during that time period. If the temperature is not forecast to rise above 40°F (4°C) for 72 hours after placement, the Engineer may require protection from freezing for up to 72 hours.

G. When CLSM is used for pipe bedding, it shall be placed in lifts to prevent floating the pipe.

H. When backfilling existing basement walls, or walls not designed for full lateral pressure from CLSM, CLSM shall be placed in lifts to prevent overstressing.

I. Allow CLSM to self-level. Barricade the site or protect by other means, till CLSM hardens to avoid accidental entry.

3.03 Construction Cautions

A. CLSM is placed as a liquid. Hence, it exerts fluid pressure. If CLSM is placed against basement walls or other structures, verify that the structure is capable of taking this lateral pressure. If the structure is not capable of handling this pressure, it can be braced externally until the CLSM slurry solidifies, or the CLSM slurry may be placed in multiple lifts so that one lift hardens before the next is placed.

B. Fresh CLSM flowable fly ash slurry that is placed in deep excavations behaves like “quick-sand” and must be protected from accidental entry until it hardens.

C. Low strength CLSM material (where re-excavation may be required at a later age) should be specified with a maximum strength (or a range of strength) that will allow for easy re-excavation with normal equipment. The addition of coarse aggregate to the mixture generally makes re-excavation more difficult.

D. When transporting CLSM flowable slurry in a ready-mix truck, the driver should be aware of the liquid nature of the material being transported. CLSM may spill out of the back of a ready mix truck with quick stops or traveling up hills. It is better to transport CLSM stiff and add water at the job site for high flow requirements.

3.04 Cleaning

A. Upon completion of placing CLSM, clean the surrounding area of all CLSM spatters, or other foreign material detrimental to appearance.

END OF SECTION

12.5 Sample Specification for We Energies Class C Fly Ash Stabilized Cold In-place Recycled (CIR) Asphaltic Concrete Pavement also known as Full Depth Reclamation

Part 1 - General

1.01 Section Includes

A. Pulverize and relay the existing asphaltic surface and stabilize the recycled materials with Class C fly ash.

1.02 References

A. WisDOT – Standard Specifications for Highway and Structure Construction-Section 325.

B. ASTM C-618 – Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

C. Chapter NR 538 – Beneficial Use of Industrial By-Products - Department of Natural Resources (Wisconsin Administrative Code)

D. ASTM D-698 – Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort

E. ASTM D-5239 – Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization

1.03 Submittals

A. Submit fly ash test results.

1.04 Quality Assurance

A. Comply with WisDOT - Standard Specification for Highway and Structure Construction Section 325 for particle size distribution, except as modified in this section.

B. Required moisture contents will be established by the Engineer based on laboratory tests with the site materials and specific fly ash to be used for the treatment.

Part 2 – Products

2.01 Materials

A. Fly Ash

Fly ash shall comply with the physical requirements of ASTM D-5239 6.4 maintaining a minimum compressive strength of 3.45 MPa (500 psi) at 7 days and the chemical requirements of ASTM C-618. Table 1, for Class “C” fly ash. Self-cementing ashes not meeting the above requirements can be used provided that the sulfur trioxide content does not exceed

10% and the self-cementing properties have been demonstrated to provide the required degree of stabilization. The source of the ash shall be identified and approved in advance of stabilization operations so that laboratory tests can be completed prior to commencing work.

B. Water

The water used in the stabilized mixture shall be clean, clear, free of sewage, vegetable matter, oil, acid and alkali. Water known to be potable may be used without testing. All other sources shall be tested in accordance with A.A.S.H.T.O. T-26 and approved by the Engineer.

Part 3 – Execution

3.01 Reprocessed Asphaltic Base

A. Description

The work under this item shall consist of cutting out, grading and windrowing the existing gravel shoulders and pulverizing and relaying the existing asphaltic surface as shown on the plans and as hereinafter provided.

B. Construction Methods

The milling machine used shall be capable of pulverizing the existing asphaltic surface to a width of 12’6”. The milling machine shall be equipped with a spray bar capable of adding 8% by volume of water to the pulverized material. The amount of water added shall be determined by the Engineer.

The existing asphaltic surface shall be pulverized to a depth as shown on the plans and to a maximum size of 1-1/2 inches. A milling machine intended for this pulverizing operation shall be utilized. The milling machine shall be self-propelled and equipped with electronic devices which will provide accurate depth, grade and slope control. Contractor shall furnish necessary extra trucks, loaders and graders to transfer reprocessed material where needed and to balance the material.

Surplus reprocessed material from the project shall remain the property of the Owner.

Contractor shall grade the pulverized material to a width and slope as shown on the plans.

The grader used to distribute the reprocessed material shall be equipped with an approved automatic control system capable of automatically controlling the elevation and slope of the blade. Crown slope shown in the typical section is after compaction. Slope at lay down or rolling technique shall be adjusted to achieve desired final cross slope.

C. Method of Measurement

This item will be measured as provided in the contract by the area in square yards. The quantity to be measured for payment shall be the area of the pavement before being removed and then redistributed, graded and compacted. Crushed Aggregate Base Course added shall be measured by the ton, delivered and spread prior to the reprocessing operation.

D. Basis of Payment

This item, measured as provided above, will be paid for at the contract unit price per square yard, which price shall be full compensation for removing, redistributing, adding moisture and blending aggregate, shaping and compacting the materials and for furnishing all labor, equipment, water, tools and incidentals necessary to complete the work.

3.02 Specifications for Stabilization of Pavement Subgrades with Self-Cementing Coal Fly Ash

A. Description

This item shall consist of the addition of self-cementing fly ash to the reprocessed asphaltic base, mixing, and compacting the material to the required density to develop a stabilized subgrade section. This item shall be constructed as specified herein and in conformity with the typical sections, lines, and grades as shown on the plans or as established by the Engineer.

B. Equipment

1. The machinery, tools and equipment necessary for proper execution of the work shall be on the project and approved by the Engineer prior to beginning construction operations. Blending of the reprocessed asphaltic base-fly ash mixture shall be accomplished by a Bomag MPH 100 pulvamixer or equivalent. Compaction shall be achieved using a vibratory padfoot roller. Rubber-tired rollers will not be permitted except for finish rolling of the stabilized section.

   All machinery, tools and equipment used shall be maintained in a satisfactory and workmanlike manner.

2. Fly ash shall be stored and handled in closed weatherproof containers until immediately before distribution.
3. Fly ash is furnished in trucks, each truck shall have the weight of fly ash certified on public scales or the Contractor shall place a set of standard platform truck scales or hopper scales at a location approved by the Engineer.

C. Construction Methods

1. General

   It is the primary purpose of this specification to secure a completed section of treated material which contains a uniform fly ash/reprocessed asphaltic base mixture with no loose or segregated areas; which has a uniform density and moisture content; and which is well bound for its full depth. It shall be the responsibility of the Contractor to regulate the sequence of work; to process a sufficient quantity of material to provide a completed section as shown on plans; to use the proper amounts of fly ash; to achieve final compaction within the specified time; to maintain the work; and to rework the lifts as necessary to meet the approved requirements. Soil temperature shall be at or above 35ºF at the time ash is incorporated.

2. Preparation of Subgrade

Before other construction operations are begun, the area where the fly ash stabilized material will be placed shall be cut and shaped in conformance with the lines and grades shown on the plans.

All areas shall be firm and able to support, without displacement, the construction equipment and the compaction hereinafter specified. Soft or yielding subgrade shall be corrected and made stable by scarifying, adding fly ash, and compacting until it is of uniform stability.

Where the stabilized section is to extend below the cut surface, the ash shall be distributed uniformly across the surface in a quantity sufficient to provide the specified ash content. The ash shall be incorporated with a pulvamixer with water being added to achieve the specified moisture content.

3. Moisture Control

Moisture control shall be achieved through use of a pulvamixer equipped with a spray bar in the mixing drum capable of applying sufficient quantities of water to achieve the required moisture content for the soil-fly ash mixture. The system shall be capable of being regulated to the degree necessary to maintain moisture contents within the specified range.

Required moisture contents will be established by the Engineer based on laboratory tests with the site reprocessed asphaltic base and specific fly ash to be used for the treatment. Final moisture content of the mix immediately prior to compaction shall not exceed the specified range of moisture contents. If moisture contents exceed the specified limits, additional fly ash may be added to lower moisture contents to the required limits. Lowering moisture contents by aeration following addition of fly ash will not be allowed.

4. Application of Fly Ash

Immediately prior to application of fly ash, the area shall be bladed to provide uniform distribution of fly ash.

The fly ash shall be spread in an approved manner at the rates shown on the plans or as directed by the Engineer.

The fly ash shall be distributed at a uniform rate and in such manner to reduce the scattering of fly ash by wind to a minimum. Fly ash shall not be applied when wind conditions, in the opinion of Engineer, are such that blowing fly ash will become objectionable to adjacent property owners.

Mixing operations shall commence within one hour after distribution of the fly ash.

5. Mixing

The RAB and fly ash shall be thoroughly mixed by approved mixers or other approved equipment, and the mixing continued until, in the opinion of the Engineer, a homogeneous, friable mixture of reprocessed asphaltic base and fly ash, free from all clods or lumps, is obtained. If the reprocessed asphaltic base-fly ash mixture contains clods, they shall be reduced in size by additional pulverization.

6. Compaction

Compaction of the mixture shall begin immediately after mixing of the fly ash and be completed within two hours, (one or two hours depending upon the degree of stabilization required and experience level of the stabilization contractor), following incorporation of fly ash. Compaction of the mixture shall begin at the bottom and shall continue until the entire depth of mixture is uniformly compacted to the specified density using padfoot or similar rollers.

All non-uniform (too wet, too dry or insufficiently treated) areas which appear shall be corrected immediately by scarifying the areas affected, adding or removing material as required and remixing and recompacting.

The stabilized section shall be compacted to a minimum of 95% of the material's maximum dry density as determined by ASTM D-698 (Standard proctor compaction). Moisture content of the reprocessed asphaltic base fly ash mixture shall be in the range developed from the laboratory compaction and strength tests.

In addition to the requirements specified for density, the full depth of the material shown on the plans shall be compacted to the extent necessary to remain firm and stable under construction equipment. After each section is completed, tests will be made by the Engineer. If the material fails to meet the density or moisture content requirements, the Engineer may require it be reworked as necessary to meet those requirements or require the Contractor to change his construction methods to obtain required density on the next section. Additional fly ash will be added to areas that are reworked and amount required will be established by the Engineer. Should the material, due to any reason or cause, lose the required stability, density and finish before the work is accepted, it shall be reprocessed, recompacted and refinished at the sole expense of the Contractor. Reprocessing shall follow the same pattern as the initial stabilization including the addition of fly ash.

7. Finishing and Curing

After the stabilized layer has been compacted, it shall be brought to the required lines and grades in accordance with the typical sections.

a. After the fly ash treated course has been finished as specified herein, the surface shall be protected against rapid drying by either of the following curing methods for a period of not less than three (3) days or until the pavement is placed :

1) Maintain in a thorough and continuously moist condition by sprinkling.

2) Binder course shall be applied within three to seven calendar days.

D. Measurement

Fly ash will be measured by the ton (2,000 pounds), dry weight. Mixing reprocessed asphaltic base and fly ash will be measured by the square yard in place.

E. Payment

Work performed and materials furnished as prescribed by this item and measured as provided under “Measurement” will be paid for as follows:

Fly ash will be paid for at the unit price bid per ton (2,000 pounds) which price shall be full compensation for furnishing all fly ash.

Mixing reprocessed asphaltic base and fly ash will be paid for at the unit price per square yard in place, which shall include placing of fly ash, mixing reprocessed asphaltic base, fly ash, and water, compacting the mixture, grading to required cross slope, and final compaction. Contractor shall supply water necessary to achieve optimal density and the cost shall be incidental to this item.

3.03. Temporary Pavement Marking, 4 inch, Removable Tape

A. This work shall be in accordance with the pertinent requirements of Section 649 of the Standard Specifications and as hereinafter provided.

B. General

This item of work shall consist of furnishing and application of temporary pavement marking to all intermediate courses or layers and final surfaces of asphaltic pavement on the same day that such course, layers, or surfaces are placed, in order to delineate the traffic centerline.

C. Basis of Payment

The item of Temporary Pavement Marking, 4 inch removable tape will be considered incidental to the item Asphaltic Concrete Pavement.

END OF SECTION

12.6 Specification for Self-Consolidating Concrete Using We Energies Class C Fly Ash

Part 1 - General

1.01 Section Includes

A. Furnish and install all self-consolidating concrete.

1.02 References

A. Comply with the latest currently applicable standards and specifications published by the ACI, and the ASTM.

1.03 Submittals

A. Manufacturer's Literature: Submit to the Engineer for review, three copies of manufacturer's specifications and installation instructions for each item of proprietary material used (admixtures, bonding agents, etc.), showing compliance with these specifications

B. Design Mixtures: Submit to the Engineer for review, three copies of mixture proportions

C. Materials: Submit to the Engineer for review, three copies of test reports prepared by an independent testing laboratory certifying that the materials to be used in the manufacture of concrete meets the requirements of these specifications at least 14 days prior to placement of concrete. This includes, but is not limited to, aggregates, Portland cement and fly ash test reports.

D. Submit results of concrete strength tests.

1.04 Quality Assurance

A. Comply with the applicable requirements specified by ASTM and ACI.

B. A Contractor shall submit a mixture proportioning report prepared by an independent testing laboratory meeting the requirements of these specifications

C. Complete mixture proportions shall be submitted at least one week before the concreting operations are to start. The final mixture proportion is to include compressive strength test results, slump/flow, and other relevant information.

D. Mixture Proportioning Requirements:

1. *Verify the adequacy of the mixture proportions. Make a minimum of nine cylinders per test mixture, 3 tested at 3-day age, 3 tested at 7-day age and 3 tested at 28-day age. Mixture proportioning shall be in accordance with ACI and sampling and testing shall be in accordance with ASTM.*
2. *Submit for approval to the Engineer the complete compressive test data on the test mixture, including mixture proportions used, actual slump/flow, actual air*

content, air temperature at the time of test, concrete temperature, weight of concrete per cubic feet and other pertinent information.

3. *In lieu of new mixture proportions, as required by these specifications, the Contractor may submit test results for a mixture, used in construction within the previous six months, indicating performance in accordance with these specifications*
4. *Adjustment of mixture proportions that prove unsatisfactory in use, shall be subject to the Engineer's review. Concrete that does not exhibit the specified control characteristics will be considered unsatisfactory.*

E. Use materials from the same source from start to finish of the job unless the Engineer has approved changes in writing.

F. Admixtures, other than air entraining agent and plasticizing agent shall not be used without the written approval of the Engineer.

G. Specimens for compression, slump/flow, and air content tests shall be secured in accordance with ASTM Test Designation C-172.

H. Slump flow and Visual Stability Index Tests:

1. *Conduct accordance with the Interim Guidelines for the Use of Self-Consolidating concrete in PCI Member Plants, April 2003.*

I. Air Entraining Content Test:

1. *Test shall be made in accordance with ASTM Test Designation C-231.*

J. Compression Test:

1. *Concrete cylinders for compression test shall be made and cured in accordance with ASTM Test Designation C-31.*
2. *Cylinders shall be tested for compression in accordance with ASTM Test Designation C-39.*
3. *The average strength of the laboratory cured specimens representing strength of each concrete shall be equal to or greater than the specified 28-day compressive strength, and not more than one 28-day strength test in a ten shall have a value less than 90% of the specified strength.*
4. *If the laboratory cured cylinders fail to meet the above requirement, change the proportions of the concrete ingredients sufficiently to increase the strength to the specified value. The concrete strength shall be evaluated in accordance with ACI 214R.*

Part 2 – Products

2.01 Concrete Materials

A. Portland cement: Conform to ASTM, Test Designation C-150, Type I. Provide cement from one source of supply.

B. Fly Ash: Conform to ASTM, Test Designation C-618 from We Energies Oak Creek, Pleasant Prairie , Presque Isle, or Elm Road Power Plants

C. Fine Aggregate: Natural sand conforming to ASTM, Test Designation C-33. Provide aggregate from one source of supply.

D. Course Aggregate: Gravel conforming to ASTM, Test Designation C-33, maximum size of aggregate to be ¾ "

E. Water: Drinkable, fresh, clean, and free from sediments and other deleterious substances.

2.02 Admixtures

A. Plasticizing Admixture: Conform to ASTM C494 for high range water reducer (superplasticizer) and viscosity modifying admixtures. The type of admixture shall be subject to the Engineer's review.

B. Air Entraining Admixture: Conform to ASTM, Test Designation C-260.

2.03 Miscellaneous Material

A. Calcium chloride and other chlorides shall not be used except in accordance with ACI.

B. Heated water must be used when the outside temperature during concreting operations drops below 40ºF. Temperature of the concrete leaving the truck mixer, at the time of discharge, shall be between 80ºF and 90ºF.

C. During the hot weather, when the outside temperature during concreting operations reaches 100ºF, or above, cool the concrete to 80ºF or lower using ice (50 lbs. ice equals 6 gallons of water).

2.04 Mixture Proportioning

A. Concrete shall be composed of Portland cement (maximum 300 lbs./ cu. yd.), Class C fly ash, fine aggregate, coarse aggregate, water, and plasticizing admixture(s). Concrete shall have an additional ingredient of air entraining admixture.

Concrete shall be proportioned in such manner that it is homogeneous, readily placeable, and uniformly workable, and shall be proportioned in accordance with ACI Standards.

Minimum Compressive Strength at 28 days (In lieu of the standard 28-day test results, accelerated strength test results will be acceptable)	3500 psi
Minimum Class C Fly ash Content	200 lbs./cu.yd.
Slump/flow	26±2"
Visual Stability Index	1.5 or less
Air Entraining Agent	Be 5.5% ± 1% Higher air content will be allowed if other requirements of this section are met
Water to Cementitious ratio	Not more than 0.35

B. The minimum amount of concrete proportioned per truckload shall be three cubic yards.

C. Concrete proportions shall be measured, mixed, transported, and placed in accordance with the ACI requirements.

Part 3 – Execution

3.01 Concrete Mixing

A. Batch, mix and transport ready-mixed concrete in accordance with ASTM C-94.

B. Adding water to unworkable concrete upon delivery end is not permitted unless:

1. *The Engineer accepts procedure and observes addition of water.*
2. *Concrete is still unworkable after adjustments to mixture proportions.*

C. Concrete will be considered unacceptable if it undergoes initial set or if not deposited within 90 minutes of the time the water is introduced. If the concrete is to be transported long distance, than the “90 minute requirement” could be modified with the proper use of a set retarding admixture as approved by the Engineer.

D. No admixtures shall be added to the concrete at the job site unless approved by the Engineer.

E. When the concrete is delivered to the job site, the Engineer will make additional tests as deemed necessary.

3.02 Embedded Items

A. All sleeves, inserts, anchors, and embedded items required for adjoining work or for its support shall be placed prior to placing concrete.

B. All embedded items shall be positioned accurately and supported against displacement.

C. Voids in sleeves, inserts and anchor slots shall be filled temporarily with readily removable material to prevent the entry of concrete into the voids.

3.03 Preparation Before Placing

A. Formwork shall be completed and all reinforcement and embedded items shall be secured in place.

B. All snow, ice, and mud shall be removed prior to placing concrete.

C. Do not place concrete on frozen ground.

D. Do not place concrete on ground with standing water or when upper 2” of ground is saturated.

E. Do not place concrete during rain, sleet, or snow.

3.04 Concrete Conveying

A. Handle concrete from the mixer to the place of final deposit as rapidly as practical by methods, which will prevent segregation or loss of ingredients.

3.05 Concrete Depositing

A. Deposit concrete continuously or in layers of such thickness that no concrete will be deposited on concrete which has hardened sufficiently to cause the formation of seams or planes of weakness within the section.

B. Place concrete at such a rate that the concrete which is being integrated with fresh concrete is still plastic.

C. Concrete, which has partially hardened or has been contaminated by hardened materials, shall not be deposited.

D. Remove rejected concrete from the site.

E. Deposit concrete as nearly as practicable to its final position to avoid segregation due to handling or flowing.

F. Free fall of concrete shall not exceed five feet. Use chutes equipped with hopper heads for placing where a drop of more than five feet is required.

3.06 Placing Concrete Slabs

A. Deposit and consolidate concrete slabs in a continuous operation.

B. Consolidate concrete placed in slabs by vibrating bridge screeds, roller pipe screeds or other methods acceptable to the Engineer. Bring slab surfaces to the correct level with a straight edge and then strike off. Use bullfloats or darbies to smooth the surface, leaving it free from bumps and hollows.

C. Do not leave screed stakes in concrete.

D. Do not sprinkle water on the plastic surface. Do not disturb the slab surfaces prior to start of finishing operations.

3.07 Cold Weather Placing

A. Do not place concrete when the air temperature is less than 40°F without the specific approval of the Engineer.

B. Comply with ACI 306 to protect all concrete work from physical damage and reduced strength caused by frost or low temperatures.

C. The temperature of the concrete delivered at the site shall conform to the following limitations.

Air Temperature	Minimum Concrete Temperature
30° to 45°F	60°F
0° to 30°F	65°F
Below 0°F	70°F

D. If water or aggregate is heated above 100°F, the water shall be combined with the aggregate in the mixer before cement is added. Cement shall not be mixed with water or with mixtures of water and aggregate having a temperature greater than 100°F.

E. When the mean daily temperature is less than 40°F, the temperature of the concrete shall be maintained between 50°and 70°F for the required curing period.

F. Arrangements for heating, covering, insulation, or housing the concrete work shall be made in advance of placement and shall be adequate to maintain the required temperature without injury due to concentration of heat.

G. Combustion heaters shall not be used during the first 24 hours unless precautions are taken to prevent exposure of the concrete to exhaust gases.

3.08 Hot Weather Placing

A. Comply with ACI 305 when hot weather conditions exist.

B. Maintain concrete temperature at time of placement below 90°F.

C. When the temperature of the steel is greater than 120°F, steel forms and reinforcement shall be sprayed with water prior to placing concrete.

D. Keep all surfaces protected from rapid drying. Provide windbreaks, shading, fog spraying, sprinkling, ponding, or wet covering in advance of placement.

3.09 Concrete Slab Finishing

A. Float Finish:

   1. *Apply float finish to all slab surfaces.*
   2. *After placing and screeding concrete slabs, do not work the surface until ready for floating. Begin floating when the surface water has disappeared and when the concrete has stiffened sufficiently to permit operation of a power-driven float.*
   3. *Consolidate the surface with power-driven float, or by hand-floating if the area is small or inaccessible to power units.*
   4. *Check and level the surface plane to a tolerance not exceeding 1/4 inch in ten (10) feet when tested with a ten-foot straight-edge placed on the surface at not less than two different angles.*
   5. *Immediately after leveling, refloat the surfaces to a smooth, uniform, granular texture.*

B. Trowel Finish:

   1. *Apply steel trowel finish to all interior floor slabs, topping, and stair treads.*
   2. *Apply float finish to slabs as described above in part*

3.09.A.

3. *After floating, begin the first trowel finish operation using a power-driven trowel. Begin final troweling when the surface produces a ringing sound as the trowel is moved over the surface.*
4. *Consolidate the concrete surface by the final hand troweling operation, free from trowel marks, uniform in texture and appearance, and with a surface plane tolerance not exceeding 1/8 inch in 10 feet when tested with a ten foot straight-edge.*

C. Broom Finish:

1. *Apply non-slip broom finish to all exterior sidewalks and aprons.*
2. *Apply float to slabs as described above in part 3.10A.*
3. *Immediately after floating, slightly roughen the concrete surface by sweeping in the direction perpendicular to the main traffic route. Use a fiber-bristle broom*.

3.10 Finishing Formed Surfaces

A. Smooth Form Finish: Provide a smooth formed surface to all formed surfaces not exposed to view unless otherwise noted in paragraph B. Smooth formed finish shall consist of the following:

1. *Construct formwork in exact dimension of the concrete member poured.*
2. *Patch all tie holes and defects.*
3. *Remove all fins, concrete “buttons”, and protrusions completely.*

B. Special Wall Finish: Provide a special wall finish to all formed surfaces exposed to view.

1. *Provide a smooth form finish in accordance with paragraph 3.10.A.*
2. *Thoroughly clean wall surface and remove all dirt, loose mortar particles, paint, films, protective coatings, efflorescence and other foreign material.*
3. *Dampen surface with clean water just prior to application of finishing compound.*
4. *Mix one part bonding agent to three parts clean water for mixing liquid.*
5. *Mix concrete finish compound with mixing liquid as specified by the manufacturer.*
6. *Apply first coat to concrete with brush at 2 lbs. per square yard.*
7. *Apply second coat to concrete with brush at 2 lbs. per square yard after the first coat has set.*

8. *When the second coat has set, float it to a uniform texture with a sponge float.*
9. *Prepare three test samples of various textures for approval by the Engineer. Each sample shall be approximately 6’ x 6’ in size and located on an unexposed wall surface as directed by the Engineer.*

3.11 Curing

A. Immediately after placement, all concrete shall be damp cured for a minimum of seven days.

B. All slabs shall be covered with approved burlap-polyethylene film and kept in place throughout the curing period.

C. Walls, beams, columns, and other formed surfaces shall be covered with burlap-polyethylene film or sprayed with an approved curing compound.

D. All burlap-polyethylene film shall be adequately anchored at the edges to prevent moisture loss.

E. Rewet all slab surfaces at least once a day during the curing period.

3.12 Patching

A. Repair honeycomb and other defective areas, fill surface voids and fill form tie holes and similar defects in accordance with Chapter 9 of ACI 301.

B. Reinforce or replace deficient work as directed by the Engineer and at no additional cost to the Owner.

3.13 Cleaning

A. Upon completion and prior to any painting, all exposed or painted concrete surfaces shall be thoroughly cleaned of all concrete spatters, from oil or other foreign material detrimental to appearance or painting.

END OF SECTION

Chapter 13

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Appendix A

Product Data Sheets

Ash; We Energies Coal Combustion Products – Fly Ash or Bottom Ash

We Energies Gypsum; FGD Gypsum; OCPP, PPPP, and ERGS FGD Process Gypsum; FGD Produced Gypsum

FGD Wastewater Filter Cake

NFPA
F 0
R 0
H 1
S

Wisconsin Energy Corporation

C.H.E.S. - Chemical Hazard Evaluation System

PRODUCT DATA SHEET

CHES#: 14468
REVISION: 11
DATE: 07/31/12
SUPERCEDES: 1/30/2012

I General Information

Trade Name:	ASH; WE ENERGIES COAL COMBUSTION PRODUCTS - FLY ASH OR BOTTOM ASH
Chemical Name:	Mixture
Manufacturer:	We Energies 333 W. Everett St. Milwaukee, WI 53201
Information Phone No.:	414-221-2345
Emergency Phone:	262-542-1440
Identical Products:	Fly Ash (Eastern/Western Coal), BITUMINOUS AND SUB-BITUMINOUS ASH (ALL PLANTS)
Container:	Various
Use:	Fly Ash: Pozzolans in concrete; cementious material; soil amendment; sorbents Bottom Ash: Construction aggregates; soil amendment
Locations:	PIPP, PPPP, OCPP, VAPP, MCPP, FO, ERGS

II Ingredients

CHEMICAL	%	CAS	TLV	PEL	STEL	CEIL	TRI
AMORPHOUS SILICA	20 - 60	7631-86-9		80 mg/m3/%SiO			☐
ALUMINUM OXIDE	10 - 33	1344-28-1	10 mg/m3	10 mg/m3			☑
IRON OXIDE	4 - 30	1309-37-1	5 mg/m3	10 mg/m3			☐
CRYSTALLINE SILICA**	0 - 10	14808-60-7	0.05 mg/m3	10 mg/m3/(%SiO + 2)			☐
CALCIUM OXIDE	1 - 30	1305-78-8	2 mg/m3	5 mg/m3			☐
AMMONIA (PPPP/ERGS Ash only)	0 - 300 ppm	7664-41-7	25 ppm		35 ppm		☐
MAGNESIUM OXIDE	0 - 4	1309-48-4	10 mg/m3	15 mg/m3			☐
TITANIUM DIOXIDE	0 - 3	13463-67-7	10 mg/m3	10 mg/m3			☐
SODIUM OXIDE	0 - 10	12401-86-4					☐
POTASSIUM OXIDE	0 - 3	12136-45-7					☐
CARBON	0 - 50	7440-44-0					☐
MANY TRACE METALS	ALL <.1						☐
SULFUR TRIOXIDE	2.61	7446-11-9					☐

III Health Hazard Data

Routes/Effects of Acute Overexposure

Skin	May be abrasive and or irritating.
Eyes	May be irritating and abrasive.
Inhalation	Little hazard produced by normal operations in open or well ventilated areas. Dust may irritate the mucous membrane.
Ingestion	Mild irritation of throat and G.I. tract.

Chronic Overexposure Effects

Lung damage. Specifically silicosis/**also see section IX**

Warning Properties

Eye, nose, and/or throat irritation. Skin redness or burning.

First Aid

Skin	Wash with mild soap and water.
Eyes	Flush with large amount of water for at least 15 minutes -- Seek medical attention.
Inhalation	Remove to fresh air -- Seek medical help promptly -- Use artificial respiration, if necessary. See http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf for more information during emergencies.
Ingestion	Give milk or water - DO NOT induce vomiting - Seek medical attention promptly.

IV Exposure Controls / Personal Protection

Engineering Controls

Consider on a case-by-case basis/usually not required. Local exhaust above the TLV/PEL limits.

Personal Protective Equipment

Eyes/Face	Safety glasses or dust goggles recommended.
Skin	Gloves recommended if irritating to skin. Appropriate for the task-e.g. cloth/leather/synthetic.
Respiratory	Lot No. 742-5848/6135 (Magenta) HEPA filter if needed with full/half respirator
Special Clothing or Equipment	Cover skin areas as needed/flyash can be irritating. Avoid creating dust, vacuum or dampen area if possible.

V Fire/Explosion Data

Flash Point	NONE
Auto Ignition	N/A

Extinguishing Media

Suitable for surrounding fire.

VI Physical Data

Boiling Point	N/A	N/A	**Appearance**	Fine tan or gray colored powder
Melting Point	N/A	N/A	**Odor**	Odorless
Vapor Density	N/A		**Vapor Pressure (mmHg)**	N/A
Specific Gravity	2 - 3		**Percent Volatile**	N/A
Bulk Density	N/A		**pH**	N/A
Solubility (H2O)	Slight		**Corrosivity on Metal**	N/A

VII Reactivity

Chemical Stability

Stable.

Hazardous Polymerization

May not occur.

Hazardous Decomposition

None established.

VIII Environmental/Handling/Storage

Spill Or Leak Procedure

Collect and dispose per local, state and fed. regs.

Storage Procedures

Contain as appropriate to minimize dusting. Label all unlabeled containers with a CHES label (L/N 138-2010).

Is This Product Listed Or Does It Contain Any Chemical Listed For The Following:

1. Disposal Of Product Or Any Residue A Hazardous Waste? No
   Hazardous Waste Code:
2. An Extremely Hazardous Substance Under Emergency Planning And Community Right-To-Know?

Substance Name:	Threshold Planning Quantity (lbs.):
No	N/A

3. An EPA Hazardous Substance Requiring Spill Reporting?

Listed Substance:	Reportable Quantity (lbs.):
No	N/A

4. An OSHA Hazardous Chemical? Chemical Name: AMMONIA
   AMORPHOUS SILICA
   CRYSTALLINE SILICA**

Does It Contain Any Materials Regulated As Hazardous Materials Or Hazardous Substances By The Department Of Transportation?

Proper Shipping Name:	Not Regulated		
Hazard Class:	None	Packing Group:	N/A
UN/NA Code:	N/A	Quantity Required for Placarding:	N/A
Labels Required:	N/A		

IX Other

**LISTED BY IARC As A Possible Human Carcinogen Based On Laboratory Animal Test DATA-No Evidence Of Human Carcinogenicity.

Note: PIPP = Presque Isle Power Plant; PPPP= Pleasant Prairie Power Plant; OCPP= Oak Creek Power Plant;VAPP= Valley Power Plant; MCPP= Milwaukee County Power Plant; ERGS=Elm Road Generating Station

This information was based upon current scientific literature. Information may be developed from time to time which may render this document incorrect; therefore, the Wisconsin Energy Corporation nor any of its subsidiaries makes any warranties to its agents, employees, or contractors as to the applicability of this data to the user's intended purpose.

NFPA

Wisconsin Energy Corporation

C.H.E.S. - Chemical Hazard Evaluation System

PRODUCT DATA SHEET

CHES#: 16721
REVISION: 10
DATE: 07/31/12
SUPERCEDES: 2/29/2012

I General Information

Trade Name:	**WE ENERGIES GYPSUM; FGD GYPSUM; PPPP, OCPP and ERGS FGD PROCESS GYPSUM; FGD PRODUCED GYPSUM**
Chemical Name:	Mixture
Manufacturer:	We Energies 333 W. Everett St. Milwaukee, WI 53201
Information Phone No.:	414-221-2345
Emergency Phone:	8004518346
Locations:	FO, ERGS, PPPP, OCPP

II Ingredients

CHEMICAL	%	CAS	TLV	PEL	STEL	CEIL	TRI
GYPSUM (CA(SO4).2H2O) (CaSO4-2H20)	> 90	13397-24-5		15 mg/m3			☐
CALCIUM SULFITE HEMIHYDRATE (CaSO3-1/2H20)	< 5	N/A					☐
CALCIUM CARBONATE (CaCO3)	< 5	1317-65-3	10 mg/m3	15 mg/m3			☐

III Health Hazard Data

Routes/Effects of Acute Overexposure

Skin	Little hazard from intermittent contact. May cause slight irritation to the skin.
Eyes	May cause mild irritation and a burning sensation. Particles may cause irritation.
Inhalation	May cause respiratory irritation or other pulmonary effects.
Ingestion	Mild irritation of throat and G.I. tract.

Chronic Overexposure Effects

Chronic overexposure unlikely. May aggravate pre-existing skin conditions (i.e. dermatitis). May aggravate pre-existing respiratory conditions

Warning Properties

Eye, nose, and/or throat irritation. Skin redness or burning. Coughing, sneezing.

First Aid

Skin	Wash with mild soap and water.
Eyes	Flush with large amount of water for at least 15 minutes -- Seek medical attention, if irritation persists
Inhalation	Remove to fresh air -- Seek medical help promptly -- Use artificial respiration, if necessary. See http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf for more information during emergencies.
Ingestion	Not expected to be a problem when ingested. If uncomfortable, seek medical assistance.

IV Exposure Controls / Personal Protection

Engineering Controls

Local exhaust if uncontrolled dusting occurs.

Personal Protective Equipment

Eyes/Face	None normally required other than safety glasses. Dust goggles if necessary.
Skin	Work gloves as needed. Barrier creams.
Respiratory	Lot No. 742-5848/6135 (Magenta) HEPA filter if needed with full/half respirator.
Special Clothing or Equipment	Wash after use/handling. Change/wash contaminated clothing before reuse.

V Fire/Explosion Data

Flash Point	None
Auto Ignition	N/A

Extinguishing Media

Suitable for surrounding fire.

VI Physical Data

Boiling Point	N/A	N/A	**Appearance**	White to off white powder

Melting Point	N/A	N/A	**Odor**	Low
Vapor Density	N/A		**Vapor Pressure (mmHg)**	N/A
Specific Gravity	2.3 - 2.5		**Percent Volatile**	0
Bulk Density	45 - 150 Lb/Ft3		**pH**	7 @25C
Solubility (H2O)	0.21 g/100 g Solution		**Corrosivity on Metal**	N/A

VII Reactivity

Chemical Stability

Stable.

Hazardous Decomposition

CaO, SO2.

Hazardous Polymerization

May not occur.

VIII Environmental/Handling/Storage

Spill Or Leak Procedure

Control dust, dispose of residue with general refuse.

Storage Procedures

Keep dry, avoid contact with water. Label all unlabeled containers with a CHES label (L/N 138-2010)

Is This Product Listed Or Does It Contain Any Chemical Listed For The Following:

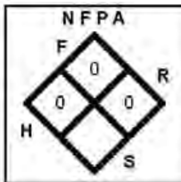
1. Disposal Of Product Or Any Residue A Hazardous Waste? No
   Hazardous Waste Code:
2. An Extremely Hazardous Substance Under Emergency Planning And Community Right-To-Know?
   Substance Name: No
   Threshold Planning Quantity (lbs.): N/A
3. An EPA Hazardous Substance Requiring Spill Reporting?
   Listed Substance: No
   Reportable Quantity (lbs.): N/A
4. An OSHA Hazardous Chemical? Chemical Name: None

Does It Contain Any Materials Regulated As Hazardous Materials Or Hazardous Substances By The Department Of Transportation?

Proper Shipping Name: Not Regulated
Hazard Class: N/A
UN/NA Code: N/A
Labels Required: N/A
Packing Group: N/A
Quantity Required for Placarding:

IX Other

This information was based upon current scientific literature. Information may be developed from time to time which may render this document incorrect; therefore, the Wisconsin Energy Corporation nor any of its subsidiaries makes any warranties to its agents, employees, or contractors as to the applicability of this data to the user's intended purpose.



Wisconsin Energy Corporation

C.H.E.S. - Chemical Hazard Evaluation System

PRODUCT DATA SHEET

CHES#: 17268
REVISION: 06
DATE: 07/31/12
SUPERCEDES: 10/8/2009

I General Information

Trade Name:	**FGD WASTEWATER FILTERCAKE**
Chemical Name:	Mixture
Manufacturer:	We Energies 333 W. Everett St. Milwaukee, WI 53201
Information Phone No.:	414-221-2345
Emergency Phone:	262-542-1440
Locations:	FO, ERGS, PPPP, OCPP

II Ingredients

CHEMICAL	%	CAS	TLV	PEL	STEL	CEIL	TRI
GYPSUM (CA(SO4).2H2O) (CaSO4-2H20)	30 - 40	13397-24-5		15 mg/m3			☐
QUARTZ (CaSO3-1/2H20)	5 - 10	14808-60-7	0.05 mg/m3	10 mg/m3/(%SiC + 2)			☐
CALCIUM CARBONATE	< 10	1317-65-3	10 mg/m3	15 mg/m3			☐
K-FELDSPAR (KAISi3O8)	0 - 5	N/A					☐
MAGNESIUM SULFATE TRIHYDRATE (15320-30-6)	0 - 5	N/A					☐
PARTICULATES	0 - 5 (i.e. flyash)	N/A					☐
MANY TRACE METALS	< 0.2						☐
MERCURY; METALLIC MERCURY (INORGANIC MERCURY)	< 200 ppm	7439-97-6	0.025 mg/m3	0.05 mg/m3		0.1 mg/m3	☐
NONHAZARDOUS BLEND:	(Balance)						☐

III Health Hazard Data

Routes/Effects of Acute Overexposure

Skin	Little hazard from intermittent contact. May cause slight irritation to the skin.
Eyes	May cause mild irritation and a burning sensation. Particles may cause irritation.
Inhalation	May cause respiratory irritation or other pulmonary effects.
Ingestion	Mild irritation of throat and G.I. tract.

Chronic Overexposure Effects

Silicosis, lung cancer and pulmonary tuberculosis

Warning Properties

Eye, nose, and/or throat irritation. Skin redness or burning. Coughing, sneezing. Conjunctivitis, rhinitis, laryngitis, pharyngtis, bleeding from the nose.

First Aid

Skin	Wash with mild soap and water.
Eyes	Flush with large amount of water for at least 15 minutes -- Seek medical attention, if irritation persists.
Inhalation	Remove to fresh air -- Seek medical help promptly -- Use artificial respiration, if necessary. See http://hazmat.dot.gov/pubs/erg/erg2008_eng.pdf for more information during emergencies.
Ingestion	Not expected to be a problem when ingested. If uncomfortable, seek medical assistance.

IV Exposure Controls / Personal Protection

Engineering Controls

Local exhaust if uncontrolled dusting occurs.

Personal Protective Equipment

Eyes/Face	None normally required other than safety glasses. Dust goggles if necessary.
Skin	Work gloves as needed. Barrier creams.

Personal Protective Equipment

Respiratory	Lot No. 742-5848/6135 (Magenta) HEPA filter if needed with full/half respirator.
Special Clothing or Equipment	Wash after use/handling. Change/wash contaminated clothing before reuse.

V Fire/Explosion Data

Flash Point	None
Auto Ignition	N/A

Extinguishing Media

Suitable for surrounding fire.

VI Physical Data

Boiling Point	N/A	N/A	**Appearance**	Dark colored semi-solid/solid
Melting Point	N/A	N/A	**Odor**	Slight sulfur like odor
Vapor Density	N/A		**Vapor Pressure (mmHg)**	N/A
Specific Gravity	N/A		**Percent Volatile**	(Low)
Bulk Density	45 - 150 Lb/Ft3		**pH**	8 - 10
Solubility (H2O)	Slight		**Corrosivity on Metal**	N/A

VII Reactivity

Chemical Stability

Stable.

Hazardous Polymerization

May not occur.

Hazardous Decomposition

CaO, SO2.

VIII Environmental/Handling/Storage

Spill Or Leak Procedure

Control dust, dispose of residue with general refuse.

Storage Procedures

Keep dry, avoid contact with water. Label all unlabeled containers with a CHES label (L/N 138-2010).

Is This Product Listed Or Does It Contain Any Chemical Listed For The Following:

1. Disposal Of Product Or Any Residue A Hazardous Waste? No

   Hazardous Waste Code:

2. An Extremely Hazardous Substance Under Emergency Planning And Community Right-To-Know?

Substance Name:	Threshold Planning Quantity (lbs.):
No	N/A

3. An EPA Hazardous Substance Requiring Spill Reporting?

Listed Substance:	Reportable Quantity (lbs.):
No	N/A

4. An OSHA Hazardous Chemical? Chemical Name: CALCIUM CARBONATE

   GYPSUM (CA(SO4).2H2O)

   QUARTZ

Does It Contain Any Materials Regulated As Hazardous Materials Or Hazardous Substances By The Department Of Transportation?

Proper Shipping Name:	Not Regulated		
Hazard Class:	N/A	Packing Group:	N/A
UN/NA Code:	N/A	Quantity Required for Placarding:	
Labels Required:	N/A		

IX Other

This information was based upon current scientific literature. Information may be developed from time to time which may render this document incorrect; therefore, the Wisconsin Energy Corporation nor any of its subsidiaries makes any warranties to its agents, employees, or contractors as to the applicability of this data to the user's intended purpose.

Appendix B

Radioactivity in Coal and Fly Ash

by Kjell Johansen, Ph.D.*

*Dr. Johansen is a Sr. Nuclear Chemistry Analyst at NextERA Energy Point Beach in Two Rivers, Wisconsin, where he is responsible for air and water related effluent compliance issues including the Radiological Environmental Monitoring Program (REMP), Groundwater Protection Program (GWPP), and the Offsite Dose Calculation Manual (ODCM). Additionally Dr. Johansen prepares the annual monitoring report that is sent to the Nuclear Regulatory Commission. This report presents all the monitoring results and discusses their relationship to current and historical plant operations. Dr. Johansen received an MS in Radiological Health Physics from North Dakota State University, an MS in Environmental Health Sciences from the University of Michigan, and a PhD in Oceanography from the University of Michigan. He spent 12 years at the UM Great Lakes Research Division as a radiolimnologist measuring NORM and fallout radionuclides in Great Lakes' sediments to determine the fate and historical inputs of pollutants to the Great Lakes. While a Radiological Engineer at We Energies from 1983 - 2000, he was responsible for Point Beach's radiological effluent and environmental monitoring programs. During that time, he also served as the Radiation Safety Officer for the use of radioactive level gauges at We Energies fossil plants.

Radioactivity in Coal and Fly Ash

A. We live in a radioactive world. The naturally occurring radioactive atoms, or radionuclides, in the earth, the air, the vegetation, and our bodies constantly irradiate us. Each second naturally occurring radioactive atoms in the earth bombard us with 15,000 photons. Photons are a form of electromagnetic radiation given off by the radioactive atoms as they transform into stable atoms. When the nuclear transformations occur in the form of emitted particles, the original atom is transformed into a different element, which also may be radioactive. These radioactive transformations or decays continue until a stable element is formed. The earth contains two main classes of natural radioactive elements: primordial and cosmogenic.

B. Primordial radionuclides have been present since the formation of the earth. Uranium and thorium, the most well-known primordial radionuclides, have no stable isotopes. (Isotopes are atoms of the same element that have the same chemical property but differ slightly in atomic weight due to the number of neutrons in the nucleus.) In contrast, normal, non-radioactive potassium has one radioactive, primordial isotope, potassium-40 or K-40. Out of every one million potassium atoms, 119 will be primordial K-40 atoms. Whereas K-40 decays directly to a stable element, uranium and thorium decay to stable lead isotopes via a series of decays that produce numerous other radioactive elements, such as radium and radon, in the process.

C. Cosmogenic radionuclides are continually being made by the cosmic ray bombardment of the earth's atmosphere. There are 22 different cosmogenic radionuclides that become incorporated into plants and other living material to varying degrees based upon their chemical properties. The most important cosmogenic radionuclides are carbon-14 (C-14), hydrogen-3 (H-3), and beryllium-7 (Be-7).

D. The common unit for the decay rate, or transformations per unit time, is the curie or Ci (named for the Polish scientist, Marie Curie). One curie equals 2.22 trillion decays (2,220,000,000,000) per minute. Not all radionuclides decay at the same rate. The more unstable the nucleus, the faster the decay rate. Two properties directly follow from the variation in decay rates. One, it takes more atoms of a low decay rate radionuclide to produce one curie than it does for a high decay rate radionuclide to produce one curie. Two, atoms with a high decay rate will disappear faster than atoms with a low decay rate. Therefore, just because there are equal curie amounts of radionuclides present does not mean that there are an equal number of atoms present

E. Inversely related to the decay rate is the atoms half-life. One half-life is the time it takes the initial number of atoms to decay to half that number. The C-14 half-life is 5760 years where as that of Be-7 is 53.3 days. The half-life of H-3 is in between these two, 12.28 years. By comparison, the half-lives of the primordial radionuclides uranium, thorium, and K-40 are the order of a billion years. One of the radionuclides formed by the decay of uranium has a half-life on the order of microseconds.

F. Based on their known cosmic ray production rates, atoms per unit area per unit time (National Council on Radiation Protection and Measurements, Report #94, p. 39. 1987) and their known decay rates, we calculate the annual number of curies of each of the major cosmogenic radionuclides produced in the air over Wisconsin (56,154 square miles) to be as follows: 11.9 Ci of C-14, 552 Ci of H-3, and 15,100 Ci of Be-7.

G. While you may remember NORM as a character from the TV sitcom "Cheers," in the field of environmental radioactivity NORM is an acronym for **N**aturally **O**ccurring **R**adioactive **M**aterial. The air, soil, water, vegetation, and even our bodies are NORM because they contain varying amounts of naturally occurring radioactive atoms. The most common NORM radionuclides are uranium, thorium, radium, potassium-40, and carbon-14. Because of the low radionuclide concentrations in NORM, the unit used to express these values is the picoCurie or pCi. A pCi is a very small number, one-trillionth of a curie. As mentioned above, a curie is 2.22 trillion disintegrations per minute. Hence, one pCi equals 2.22 disintegrations per minute.

H. The standard 70 kilogram (154 pound) adult contains the following amounts of the aforementioned radionuclides: 30 pCi of uranium, 3 pCi of thorium, 30 pCi of radium, 110,000 pCi of K-40, and 400,000 pCi of C-14 (International Commission of Radiation Protection – Publication 39 and National Council on Radiation Protection and Measurements –Report No. 94).

I. Radioactive elements enter our bodies through the food we eat and the air we breathe. C-14 and K-40 react chemically in the same manner as the stable or non-radioactive isotopes of these elements and are continually being incorporated into the plants and animals in the food chain. Because the chemical composition of our bodies is internally regulated with respect to the amount of stable carbon and potassium present, the concentrations of C-14 and K-40 are regulated as well. Uranium, thorium, and radium also enter our bodies through the food chain, but to a lesser extent as evidenced by the pCi quantities of NORM in our bodies mentioned in the preceding paragraph. Because radium is chemically similar to calcium, long-lived radium-226 (half-life = 1600 years) will build up in the skeleton. Uranium and thorium exhibit a lesser degree of build-up. Because of the relative chemical inactivity of Ra, Th, and U compared to the C and K, it takes a longer time to remove the Ra, Th, and U once they are incorporated in our bodies.

J. The amount of NORM you consume each day depends upon the foods you eat. Norm has been measured in many food items. Foods high in potassium have a correspondingly higher amount of K-40. For example, a serving of dried apricots has 409 pCi of K-40; a fresh banana, 368 pCi; a glass of orange juice, 409 pCi; bran flakes, 155 pCi; a glass of skim milk, 285 pCi; a medium potato, 690 pCi; spinach, 97 pCi; substituting lite salt (potassium chloride) for 1.2 grams of common table salt, 499 pCi; and 3 oz. of chicken breast, 180 pCi. (If you know the grams of potassium in your food, multiply by 818 to get the number of pCi of K-40). Because the body's K-40 is chemically regulated along with non-radioactive potassium, K-40 will not build up in the body but vary as stable potassium varies as a function of muscle mass and age.

K. The most common mode of radium ingestion is via drinking water. As recently noted in the Journal-Sentinel, 53 Wisconsin communities will have to reduce the radium content of their drinking water because it contains more than the EPA allowable concentration of 5 pCi/liter, (about 19 pCi per gallon).

A person drinking the recommended 8 glasses of water a day would consume about 10 pCi of radium per day, of which about 30% would be absorbed into the body (International Commission on Radiation Protection, Report of Committee 2, 1963). The food highest in radium is the Brazil nut. Brazil nuts selectively concentrate calcium family elements such as barium and radium (R. L. Kathren, 1984, Radioactivity in the Environment, Harwood Academic Publishers, p. 67). This concentration process gives Brazil nuts a radium concentration of 1-7 pCi per gram or, in a comparison to water on a weight basis, 1000 – 7000 pCi per liter. All other foods contain, on average, 1/1000th of the radium found in Brazil nuts. The US Nuclear Regulatory Commission sets the annual ingestion limit for Ra-226 at 2,000,000 pCi/yr (Title 10, Code of Federal Regulations, Part 20, Appendix B).

L. Radon, a chemically inert, radioactive gas produced by the decay of radium, is a normal constituent of air and enters the body by breathing. Radon generated by the decay of radium diffuses into the soil pore water where it can reach concentrations of 100 – 1000 pCi/liter. The pore water radon then diffuses out of the ground into the air to yield concentrations on the order 0.1 – 0.2 pCi/liter in the northern hemisphere (NCRP Report No. 94). The amount and rate of radon entering the air from the ground depends not only upon the amount of radium in the soil but also on the physical condition of the soil containing the radium. Frozen soil and snow cover slow down the transfer of radon to the air. Radon diffuses out of porous soils more quickly than out of rock or compacted soil. Meteorological conditions like wind speed and the air pressure also affect the transfer of radon from the soil to the air. Unlike the other elements, radon does not react chemically with the body and so is readily exhaled as well as inhaled. The concentration of radon in our lungs is normally in equilibrium with the concentration in the air that we breathe.

M. The energy released by radioactive elements can be measured. The amount of energy deposited in the human body from radioactive decay is called dose. As mentioned above, radionuclides enter the body through air and foods we eat. Energy deposited in our bodies from the radioactive isotopes in our bodies is called internal dose. External doses result from gamma rays emitted by terrestrial NORM sources such as the ground and building materials and from cosmic rays. Roughly 1,000,000 photons per minute are responsible for the terrestrial component of the total NORM dose. About 500,000 decays per minute in our bodies contribute to our internal NORM dose (M. Eisenbud, Environment Vol.26 (10): 6-33, 1984). This internal NORM acts as an external radiation source to people around us. Based on the amount of K-40, the standard 154-pound adult emits about 24,400 photons per minute, which contributes dose to nearby individuals.

N. The standard dose unit in the United States is the rem. Because doses from NORM are small, these doses are reported in millirem (mrem), or 1/1000th of a rem. In the US, the average annual NORM dose is 300 mrem. The largest part of this dose, 200 mrem, comes from the radon in the air. When we say the dose is from the radon in air, this actually is shorthand for radon and the radionuclides to which the radon decays. It is the decay products that produce most of the dose because these decay products, as opposed to a noble gas, are particulates that remain in the lungs for a longer period of time. Two of these decay products, lead-210 (22.3 yr half-life) and polonium-210 (138 day half-life) contribute most of the dose. The remaining 100 mrem is divided among cosmic (30 mrem), internal (40 mrem), and terrestrial sources (30 mrem). In the case of human-to-human irradiation mentioned above, the K-40 dose from spending 8 hours a day at 1 foot from an adult emitting 24,400 photons per minute is about 0.4 mrem/yr.

O. Cosmic ray doses increase with elevation above sea level. Typical doses in Wisconsin are around 27 mrem/yr. In Denver, the mile-high city, the cosmic ray dose is 50 mrem/yr. The highest cosmic ray dose in the US, 125 mrem/year, occurs in Leadville, CO. La Paz, Bolivia has a cosmic ray dose of 202 mrem/yr. A passenger in a New York to Los Angles flight at an altitude of 39,000 feet would get 2.5 mrem for the 5-hour flight.

P. The major contributor to the annual internal dose is K-40 (18 mrem). Lesser contributions result from two radon decay products, Pb –210 and Po-210 (14 mrem), from Ra-226 (1 mrem), and from C-14 (0.1 mrem). Note that even though the human body contains 400,000 pCi of C-14, roughly four times the pCi content of K-40, the resulting dose is very much less than that from K-40. This happens because the energy emitted per decay of C-14 is much less than that per disintegration of K-40. [United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1993; NCRP Report #94; Medical Effects of Ionizing Radiation, F.A. Mettler and R.D. Mosely, 1985; D.C. Kocher, Radioactive Decay Data Tables, Dept. of Energy TIC-11026, 1981]

Q. Scientists have determined the NORM terrestrial doses in many parts of the world. These doses vary depending upon the geology of the area. Regions with high amounts of uranium and thorium in the soil and bedrock also have higher radium and radon concentrations. The US average is 30 mrem. The highest US terrestrial dose is 88 mrem. The highest measured terrestrial dose, 26,000 mrem/yr, occurs in Ramsar, Iran. Other high annual terrestrial doses occur in areas of Brazil and India (3,500 mrem), China (1,000 mrem), Norway (1,050 mrem), and Italy (438 mrem). The areas in Iran, India, and Brazil are associated with high concentrations of uranium and thorium in the soil. Epidemiological studies of the people in these areas have been made to determine, what, if any, affect these high radiation dose levels have on health. To date, no radiation related health effects have been found. [UNSCEAR 1993; NCRP Report #94]

R. Consumer products also generate NORM radiation exposures. The most common and highest consumer product exposure results from cigarettes. Smoking 30 cigarettes a day for a year delivers a lung dose of 16,000 mrem/yr, which is equivalent to a whole body dose of 1,300 mrem. By comparison to cigarettes, a chest X-ray delivers 20-30 mrem to the same tissues. Masonry buildings typically contribute 13 mrem/yr to its occupants from the uranium, thorium, and K-40 in the building material. Some electrodes used for arc welding contain thorium in order to produce greater arc stability and less weld metal contamination. Using these rods on an occasional basis results in less the 1 mrem/yr, most of which is in the form of external radiation (NCRP Reports #94 & 95).

S. Carbon based fuels also are NORM. Natural gas contains 10 – 20 pCi of radon per liter. [A liter is slightly larger than a quart with 1 gallon = 3.785 liters.] As a result, cooking with natural gas produces a dose of 0.4 mrem/yr (NCRP Reports #94 & 95). Coal contains numerous radionuclides. The US

Geological Survey maintains a large database of uranium and thorium data on coal from various US coal fields. Based on more than 5000 coal samples from all the major coal regions in the US, the average U content of 1.3 parts per million (ppm) equals 0.44 pCi/g. The average thorium (3.32 ppm) concentration is 0.37 pCi/g. These concentrations are not that much different from soil: 1.0 pCi/g for uranium (range 0.12 – 3.8 pCi/g) and 0.98 pCi/g for thorium (range 0.1 – 3.4 pCi/g). Both uranium and thorium decay to stable Pb and along the way produce radioactive isotopes of uranium, thorium, radium, radon, bismuth, lead, and polonium. Ra-226 analyses of coal indicate concentrations in the range of 0.2 – 3 pCi/g [J. Tadmore, J. of Environmental Radioactivity 4(1986) 177-204]. Lignite, a low-grade coal, has slightly higher concentrations: U-238, 8.26 pCi/g; Ra-226, 9.34 pCi/g; Th-232, 0.51 pCi/g; K-40, 4.67 pCi/g [Rouni *et. al.*, Sci. Total Environment 272(2001) 261-272]. In coal-fired power plants, some of the NORM is released via the stack whereas most is trapped in the resulting ash. Studies in Great Britain (K. R. Smith et. al., Radiological Impact of the UK Population of Industries Which Use or Produce Materials Containing Enhanced Levels of Naturally Occurring Radionuclides, Part I: Coal-fired Electricity Generation, National Radiation Protection Board report, NRPB-R327, 2001) and the United States (EPA, Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generating Units – Final Report to Congress, EPA-453/R-98-004a, Feb. 1998) conclude that NORM emissions from coal-fired plants do not pose a health problem. A United Nations group of experts reached a similar conclusion (UNSCEAR, 1993).

T. The NORM concentration in coal ash is higher than in the coal because most of the radionuclides stay in the ash as compared to being released to the air during the combustion process. Therefore, burning off the organic content of the coal results in about a 10-fold increase in U, Th, and Ra concentrations in the ash as compared to the coal (UNSCEAR, 1993; USGS Fact Sheet FS-163-97). Based on the concentration process, the Ra-226 concentrations in ash could be on the order of 1-30 pCi/g. Analyses of various ashes and ash products produced at WE-Energies plants in 1993 and 2003 found Ra-226 concentrations in the range of 1 – 3 pCi/g. This is comparable to the concentrations in soil (0.2 – 3 pCi/g) and within the range of 1 – 8 pCi/g found in ash from analyses of other fly ash in the US (Cement and Concrete Containing Fly Ash, Guideline for Federal Procurement, Federal Register, Vol 48 (20), January 28, 1983, Rules and Regulations; Zielinski and Budahn, Fuel Vol.77 (1998) 259-267).

U. Given that the ash may be land filled or may be used in building materials as a cement substitute, the doses resulting from these applications have been studied to determine if there is any risk. The British Nuclear Radiation Protection Board (Smith *et. al*. 2001) conducted a detailed evaluation "Radiological Impact on the UK Population of Industries Which Use or Produce Materials Containing Enhanced Levels of Naturally Occurring Radionuclides, Part I: Coal-fired Electricity Generation" (NRBP-R327) of the doses from fly ash released to the air to people living within 500 meters (547 yards) of a plant stack, to landfill workers burying fly ash, to workers manufacturing building products from fly ash, and to people living in a house built with fly ash building products. The maximum doses determined from this evaluation were 0.15 mrem/yr for the person living near the plant, 0.13 mrem/yr from releases from the ash landfill, 0.5 mrem/yr for workers manufacturing building products, and 13.5 mrem/yr to a resident of a home constructed with fly ash building materials. The latter is not that different from the 13 mrem/yr from living in a brick/masonry house mentioned earlier.

V. Based on the preceding discussion, the radioactivity levels in coal and the slightly enhanced levels in coal ash do not constitute a safety hazard. The levels of radioactivity are within the range found in other natural products. The doses resulting from using the ash in various products are comparable to doses from other human activities and from other natural sources. These doses from the radionuclides in ash are much less than the 300 mrem/yr received from normal background radiation.

Appendix C

Field Guide for Recycling HMA Pavement (CIR) with Self-Cementing Class C Fly Ash

Prepared in cooperation with Lafarge North America and Bloom Consultants, LLC.

What is Fly Ash Stabilization?

Enhancing the strength of recycled asphalt pavement is simply applying controlled amounts of class ‘C’ fly ash to the CIR surface, thoroughly blending the ash with the recycled material and water, usually with a reclaimer or pulverizer, grading the material blend and compacting it. The stabilized material is then ready for paving.

Why is stabilization done?

Stabilizing CIR materials with fly ash makes them dryer, stronger, very stable and easy to grade. The self-cementing fly ash makes the recycled asphalt hard, strong and allows for interim traffic operations. Subsequent construction operations can proceed.

What types of equipment are required?

Essential pieces of equipment include a distributor truck, a reclaimer [pulverizer] for blending, a grader, a pad-foot roller, a drum roller and a water truck. A bucket loader is also helpful.

Who controls the work activities?

Ideally, the recycling contractor is in charge of operations and controls the work flow. Others involved are the fly ash supplier, engineers and contractors who are in charge of related work such as storm sewer or other utility work. The stabilizing contractor in any case is in charge of the operation and controls work flow.

Is the process difficult?

Stabilizing CIR materials with self-cementing Class ‘C’ fly ash is easy, but there are several very critical elements in the operation.

Is the sequence of work activities important?

The success of any stabilizing project depends on having the component activities planned and closely controlled throughout the process. The preferred sequence of activities follows:

- Prepare the site either by pre-pulverizing the existing HMA pavement and base course.
- Spread the fly ash in predetermined concentrations on the prepared surface.
- The preferred distributor is a vane feeder truck.

- Blend the fly ash and prepared materials with the reclaimer and add a pre-determined amount of water to the mixture. A reclaimer equipped with an injection manifold is ideal for the addition of water.
- Compact the blended material with a pad-foot roller in vibratory mode if the site will tolerate it and grade the surface to comply with design requirements.
- Complete final grading and roll with the drum roller. The surface is now ready for paving.

Are there any cautions to be aware of in the process?

Plan the work and layout the site before the work starts. Make sure all equipment operators understand the importance of controlling the operation. Control the distribution of fly ash so the vane feeder does not get too far ahead of the blending operation. Be sure to have an adequate supply of ash on site and in delivery. Control the transfer of ash to the distributor truck.

During ash material transfer operations and other activities, it is crucial to keep trucks and equipment from running through the newly placed ash. The material will not be influenced too much by wind unless it is disturbed. Preserving environmental integrity during construction is critical.

Since fly ash undergoes a change through hydration [much like cement does in concrete] it is very important to begin grading operations as soon as the fly ash is distributed and blended. Open time during warm weather is less than one hour. After that, achieving good surface results becomes more difficult. Keep in mind, Class C fly ash enhanced materials will get hard and gain strength.

The contractor should carefully watch the yield of the fly ash during distribution. Pace or measure the remaining work and estimate volume requirements. Compare the data with fly ash supply. Avoid over or under treating any of the work areas.

The reclaimer operator must assure that areas where ash is distributed are mixed or blended. Some overlap is better than leaving strips or other areas unmixed. Care needs to be taken to keep fly ash out of roadside ditches and off adjacent private property.

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Bruce W. Ramme

Bruce W. Ramme is Vice President Environmental at We Energies in Milwaukee, Wisconsin. He is a registered Professional Engineer in Wisconsin and has BS, MS, Ph.D., and EMBA degrees from the University of Wisconsin—Milwaukee. He has worked as an engineer and manager for over 30 years in various design engineering, project management, operations, and research positions. He has worked to develop high value uses and maintain full utilization of We Energies' coal combustion products. Prior to joining We Energies, Bruce worked in plant engineering at A.O. Smith's Powder Metallurgy Division, and as a structural engineer at Industrial Consulting Engineers, Inc. and Lakeside Bridge and Steel Company.

Bruce is a member of ACI Committees: 229 Controlled Low Strength Materials, 213 Lightweight Aggregates, 230 Soil Cement, and 232 Fly Ash and Natural Pozzolans, and 555 Recycled Materials. Bruce is also a past president of the ACI Wisconsin Chapter and the Southeast Branch of the Wisconsin section of ASCE.

Mathew P. Tharaniyil

Mathew P. Tharaniyil is the President of Bloom Companies, LLC headquartered in Milwaukee, WI. He holds a Bachelor's Degree in Civil Engineering from the University of Calicut, India and a Master's Degree in Structural Engineering from the University of Wisconsin, Milwaukee. He has over 23 years of experience in the Civil Engineering industry, and is a registered Professional Engineer in Wisconsin, Illinois, Michigan and Minnesota. His experience includes working in the public and private consulting and construction sectors, delivering projects in the domestic and international markets.

He is a member of the Wisconsin Society of Professional Engineers and has served as President and Secretary/Treasurer of the Greater Milwaukee Chapter. He served as a Public Member on the Accounting Examination Board of the Wisconsin Department of Regulation and Licensing. Additionally, Mathew is the member of the Heavy Movable Structures, Inc and the American Society of Civil Engineers.