

Advances in Ultra-High-Pressure Waterjetting

by Richard Schmid, *Flow International Corporation*

Abrasive blasting has dominated the surface preparation industry for most of this century, primarily because of its economic and performance benefits. High productivity rates, particularly for large area surfaces, have reinforced abrasive blasting's popularity with contractors. Industry-wide acceptance of a surface prepared by grit blasting and familiarity with the process were also factors.

However, external factors such as environmental and occupational regulations have prompted the surface preparation industry to seek alternatives. Concerns about the effects of air-borne dust on the public, the environment, and workers have resulted in the regulation of open abrasive blasting, especially for hazardous paint removal.

Contractors now must meet stringent requirements for containing abrasive and paint debris during blasting operations to protect the environment and the public, and they must assure that their workers have the proper training and protective equipment to reduce occupational exposures to lead, silica sand, and other dusts generated during blasting.

One alternative to abrasive blasting, ultra-high-pressure (UHP) waterjetting, has evolved as a viable tool for industrial applications. SSPC and NACE International define UHP waterjetting as 25,000 psi (172 MPa) or above; the present article defines it as above 35,000 psi (241 MPa).



Shipyards make up the largest group of users of UHP waterjetting for surface preparation. *Courtesy of Flow International and Todd Shipyards*

In the past 2 to 3 years, the acceptance of UHP waterjetting for surface preparation has grown rapidly. Before this period, waterjetting was used only on unique or very challenging applications. It is widely used today on many kinds of surface preparation projects, such as coating removal on bridges; ships; storage tanks; and large, complex steel structures.

This Maintenance Tip identifies advances in waterjetting equipment, coatings technology, and the understanding of chloride contamination that have made waterjetting a more viable option for surface preparation compared to several years ago. The article also identifies the 2 major uses of waterjetting today in maintenance coating operations.

Evolution in Waterjetting Technology *Developments in Pumps and Nozzles Increase Productivity*

Productivity levels of older, hand-held UHP lances were once one fourth to one third that of hand-held abrasive nozzles. For Near White (SSPC-SP 10) and White Metal (SSPC-SP 5), coating removal rates for UHP waterjetting generally fell into the range of 20 to 30 sq ft/hr (1.8 to 2.7 sq m/hr) per hand-held UHP tool, compared to productivity ranges of 90 to 120 sq ft/hr (8.1 to 10.8 sq m/hr) per nozzle for abrasive blasting. UHP productivity therefore limited the commercial viability of the method.

The 2 main reasons for the lower productivity of UHP were the limits of the hydraulic intensifier pump

and the limits of waterjet nozzle rotation rates. The intensifiers were not capable of achieving pressures above a range of 30,000 to 35,000 psi (206 to 241 MPa), which limited cleaning rates. Moreover, until recently, nozzle rotation rates were not attainable above 3,000 rpm, which also restricted cleaning rates.

However, technology has rapidly advanced between 1992 and 1996 to meet the production rates demanded by the surface preparation industry. Hydraulic intensifier pumps have been replaced by positive displacement (plunger) pumps capable of achieving pressures of 40,000 psi (276 MPa) in the field. Positive displacement pumps performing in the 10,000 to 20,000 psi (69 to 138 MPa) range had been available in the field for a number of years. The evolution in the capabilities of these pumps has been the most significant equipment advance in waterjetting technology in the past 4 years. Higher operating pressures mean faster coating removal rates. Nozzles have also improved in the past 4 years. Higher nozzle rotation speeds of 3,000 to 3,500 rpm are now possible. The higher the rotation speed of the multi jet nozzle means the faster the worker can move the wand across the surface to be cleaned and achieve full coating removal.

Higher pressures and nozzle advances have pushed productivity to rates comparable to hand-held abrasive blasting. For Near White and White Metal, typical removal rates are 80 to 100 sq ft/hr (7.2 to 9 sq m/hr) for UHP compared to 90 to 120 sq ft/hr (8.1 to 10.8 sq m/hr) for abrasive blasting and compared to earlier UHP rates of 20 to 30 sq ft/hr (1.8 to 2.7 sq m/hr).

Plunger Pumps Reduce Costs

In addition to their restrictions on pressure, hydraulic intensifier pumps were suited to shop work but not to

field work. They could not withstand the demands of harsh environments such as those found in shipyards and bridge sites. Attempts to convert hydraulic intensifier pumps from factory to field applications usually failed because the intensifiers were unreliable and complex, and they required clean operating conditions not generally possible in the field. If used in the field at all, they needed a well-trained staff to operate and maintain the equipment.

Not only do positive displacement pumps increase productivity, but they are also much easier to maintain and do not need the clean operating conditions that intensifiers require. Ease of maintenance makes positive displacement pumps a common choice for work in harsh industrial environments.

Operation of UHP systems now differs little from low pressure water blasting, a staple for decades in the automotive and marine industries. Users do not need to hire or train specialists to operate and maintain the equipment. Operators familiar with lower pressure water blasting procedures and safety requirements for waterjetting can now operate UHP systems.

Advances in the Coatings

Industry

Understanding of Chloride Contamination, Cleaning, and Coating Adhesion

An abrasive blasted surface is impacted with many small, discreet abrasive particles that flatten out the sharp peaks created from original profile and also create new peaks.¹ On a microscopic level, abrasive particles will actually fold over and trap contaminants such as chlorides and sulfates, affecting the quality of the finished product. Chloride levels as low as 10 µg/sq cm and sulfate levels higher than 20 µg/sq cm on

an abrasive blasted surface can cause blistering of coating films after a few weeks of exposure to condensing humidity.¹ It has been well known for many years that soluble salts still remain at these levels on steel surfaces after abrasive blasting.^{2,3}

UHP is capable of removing soluble salts. One coating manufacturer found that if potable water is used for UHP waterjetting, surface salt levels below 7 µg/sq cm can be obtained on old rusted and pitted steel.⁴ SSPC and NACE have published this level in their joint standard, SSPC-SP 12/NACE 5, "Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Waterjetting Prior to Recoating." Furthermore, following upon the work of a major coating manufacturer that published visual standards for waterjetted surfaces, SSPC and NACE are developing consensus visual standards for coated steel surfaces prepared by wet methods.

Coatings Developed for Flash-Rusted Surfaces

A waterjetted surface will show signs of light flash rusting shortly after preparation. Until recently, owners and coating manufacturers have been hesitant to apply coatings over a flash-rusted surface. It is usually the coating manufacturer who takes final responsibility or warranty for the long-term performance of the coating. Recognizing the benefits of UHP waterjetting, major coating manufacturers have developed surface-tolerant coatings that can be applied directly over a waterjetted surface.⁵ The draft NACE/SSPC visual standards for surfaces prepared by wet methods also provide reference photos for degrees of flash rusting.

Most generic types of surface-tolerant coatings on the market can be

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applied over tightly adhered flash rust. These coatings are specifically designed to go over less than optimum surfaces and still provide excellent adhesion.

Major Types of UHP Waterjetting Applications

Drydocks and Shipyards

Environmental attributes of UHP have broadened markets for the equipment. Shipyards, with their proximity to environmentally sensitive areas, make up the largest group of users of UHP surface preparation equipment.

For paint removal and surface preparation on ships, water is typically allowed to flow down the side of the ship and drop into the bottom of the dry-dock, where it is collected and pumped to a central filtration system that is in place to process run-off waters from rain and washing operations.

Compared to dry blasting, there is no risk of abrasive contamination to neighboring residential or industrial areas. Also, there is no risk of abrasive contamination to surrounding areas of a ship repair project, which allows for other repair processes to be conducted simultaneously. For example, repainting or equipment repair work can go on adjacent to a waterjetting project. Concurrent repair work significantly reduces the time in dry dock, contributing to cost savings for both the vessel owner and the shipyard.

Waterjetting provides several other cost savings benefits to the shipyard owner and vessel owner. Because abrasive is not used, there is no cost of grit, nor cost to collect and dispose of grit. The water used in the process generally can be filtered and disposed of through the sewer system while the paint chips are disposed of as a separate waste. Waterjetting can be

used adjacent to sensitive deck equipment, such as winches, electric motors, and cranes, without the need for masking or tarping.

Lead-Based Paint Removal from Steel Structures

The second largest application of UHP waterjetting is removal of lead-based paint from steel structures. UHP surface preparation generates no air-borne dust, eliminating the necessity to construct costly containment systems. It reduces worker protection costs and improves worker efficiency. Blasters can often wear lightweight face masks in place of cumbersome and expensive air-supplied respiratory equipment.

In fact, UHP waterjetting has actually simplified containment. Most UHP waterjetting projects, even lead-based paint removal, are done without the use of negative air containment.

Typical to a project is a simple tarp laid out just below the removal area with an earth or timber berm to work as a collection "pond." Water is pumped from the simple poly tarp pond to settling tanks where paint chips and water are separated. In some cases, additional tarps are used to shroud structures like a curtain and direct the water to the tarped area on the ground.

Waterjetting also eliminates the cost of disposing of lead-contaminated abrasive. Abrasive blasters use 4 to 10 lbs of abrasive/sq ft (5 to 9 kg/sq m). In contrast, waterjetting uses approximately 2 to 3 gal. of water/sq ft (83 to 124 L/sq m). This small amount of water is easily collected and treated if necessary for disposal or recycling. The amount of solid or hazardous waste is greatly reduced; without spent abrasive, only the paint debris needs to be disposed of as a solid or hazardous waste.

Limitations of Waterjetting

Despite advances in the technology and in the industry, waterjetting is not suited for every type of project. It is not appropriate for projects such as the following.

- Maintenance projects requiring a profile of the steel: Waterjetting alone will not profile the steel structure like dry abrasive blasting. Therefore, UHP waterjetting is not typically used when removing paint from non-profiled steel such as that on many bridges built before 1975. In some instances, however, such as with lead-based paint, the paint is removed with waterjetting, and dry abrasive blasting is used as a secondary process to profile the steel. This combination of methods eliminates the disposal of grit contaminated with lead-based paint.
- New construction: Waterjetting is typically not used in new steel construction because it is not capable of

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providing a surface profile. Surface preparation is typically done in production plants with large recycling shot blasters.

- Areas where there are no environmental regulations: In some areas, open air abrasive blasting is still viable. Dry abrasive blasting projects are being drastically reduced, but on those projects where it can still be done, abrasive blasting is sometimes more cost effective than waterjetting, especially if collection and disposal of grit are not issues.

Conclusion

Advances in waterjetting equipment, coatings technology, and environmental protection have made UHP waterjetting a more viable option than it has been in the past. Its use need not be inhibited by equipment that is difficult to use and maintain in the field or by flash rusting over clean steel.

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How Water Transmission Affects Slab-on-Grade Flooring Systems

by Charles Hall and Scott O'Connor, Phoenix Engineering Services, Inc.

Two types of water transmission problems are associated with failures of slab-on-grade flooring or topping systems:

- hydrostatic water pressure, which is the static condition of moisture in a slab; and
- water vapor pressure, which is the dynamic condition of moisture in the form of vapor emanating from a slab.

This article explains hydrostatic and water vapor pressures, describes their adverse effects on coated concrete, identifies corrective measures, and describes methods of detecting and measuring moisture in concrete.

Two Types of Water Transmission Problems

Hydrostatic water pressure is derived from water in the liquid phase.^{1,7} It is sometimes known as head pressure (Fig. 1). Hydrostatic pressure is the result of force exerted by a column (head) of water. The pressure is equal to 0.43 psi per linear foot of water height (9.76 kPa per linear meter).

This force is the result of the differential between the highest elevation of a water column and the lowest physical point of a structure. Hydrostatic water pressure problems are generally associated with below-grade slab or areas subjected to high water tables. Other water liquid phase pressures and dynamic forces associated with hydrostatic pressure result from

- capillary pressures developed within the concrete matrix pore spaces and up through the subsoil (Fig. 2), and
- osmotic pressures developed within the concrete matrix and across

the coating membrane to its top surface (Fig. 3).

Water vapor pressure, or water in a vapor (gaseous) phase, acts and responds in an entirely different way than water in a liquid phase, i.e., hydrostatic water.^{1,7} Water vapor has a density of only 1/250,000 that of water in a liquid phase. Vapor can readily pass through most concrete substrates that have capillary spaces as small as 5 micrometers.

Water vapor pressure is the combined result of the dynamic effects of ambient environmental parameters:

- the amount of available liquid phase water (moisture content) present to become vaporized,
- temperature, and
- relative humidity.

Water vapor movement through concrete requires the development of pressure as the driving force due to a differential in vapor pressure between the above- and below-slab ambient environments, i.e., temperature and humidity (Fig. 4). Vapor pressure differentials are developed due to differences of relative humidity and temperature above and below the slab (Fig. 5). Water vapor pressures are related to changes in temperature and relative humidity differentials.

Adverse Effects of Hydrostatic and Water Vapor Pressure

Hydrostatic and water vapor pressures have a variety of detrimental effects on slabs on grade, coatings, and flooring systems.^{2,4,7}

Effects on Slabs on Grade

Hydrostatic and water vapor pressures may transport water-soluble

minerals from both the subsoil and the slab concrete towards the slab surface. Concentrations of the minerals at or near the slab's surface occur when the water/moisture has evaporated, thereby recrystallizing the minerals in place. Crystallization of

minerals is an expansive physical reaction that can exert strong disruptive forces within the concrete matrix, causing weakening or disintegration and subsequent break-up of the slab itself. Waterproofing prevents water in its liquid phase

from entering into and through concrete from hydrostatic pressures. Moisture vapor controls are used to prevent water escaping in its gaseous state and emanating from a slab's surface.

Effects on Coatings and Flooring Materials

Hydrostatic and vapor pressures build up on the negative side of an impermeable (non-breathing) membrane, coating, or flooring material. There are positive and negative sides to all membranes with respect to moisture vapor pressures. The positive side refers to the side in which contact from the moisture source is being made. The negative is opposite the moisture source. Higher pressures are found on the positive side. If the pressures are allowed to accumulate, or are not dissipated or relieved by venting, they may develop sufficiently to disbond the coating or flooring system from the slab. Bond failure will occur when the hydrostatic or vapor pressures exceed the adhesive bond strength of the coating or flooring system to the parent concrete substrate.

Breathable (high permeance) coatings and flooring systems are far less susceptible to the effects of hydrostatic or vapor pressures than non-breathing coatings or flooring systems. Breathable materials typically exhibit U.S. perm ratings of greater than 3.0 perms. (Perm = grains of moisture per hour per sq ft per inches of mercury [P=1 gr/hr/sq ft/in. Hgl.])* Concrete (3,000 psi [21 kPa]

* Current metric formula for reporting permeance is

$$57.2 \cdot 10^{-12} \text{ kg/sec} \cdot \text{sq m} \cdot \text{Pascals.}$$

Previously used (S.I.) formula for reporting permeance is

$$57.2 \text{ nanograms/sec} \cdot \text{sq m} \cdot \text{Pa.}$$

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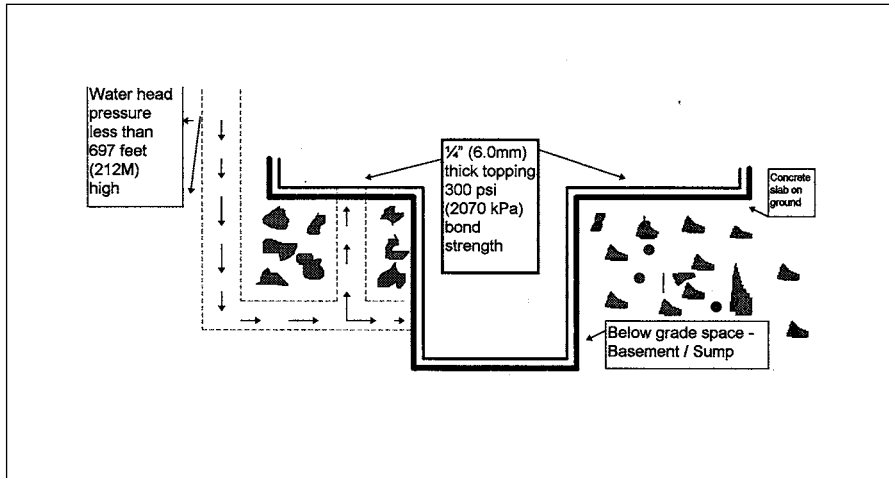


Fig. 1 - Hydrostatic pressure as exerted by a column of water. Formula: an arbitrary column height of 700 ft (212 m) head x 0.43 psi (2.9 kPa)/ft (m) head = 300 psi (2,070 kPa) head pressure. In this example, the bond strength of the topping exceeds the head pressure of the column of water.

Figures courtesy of Phoenix Engineering Services, Inc.

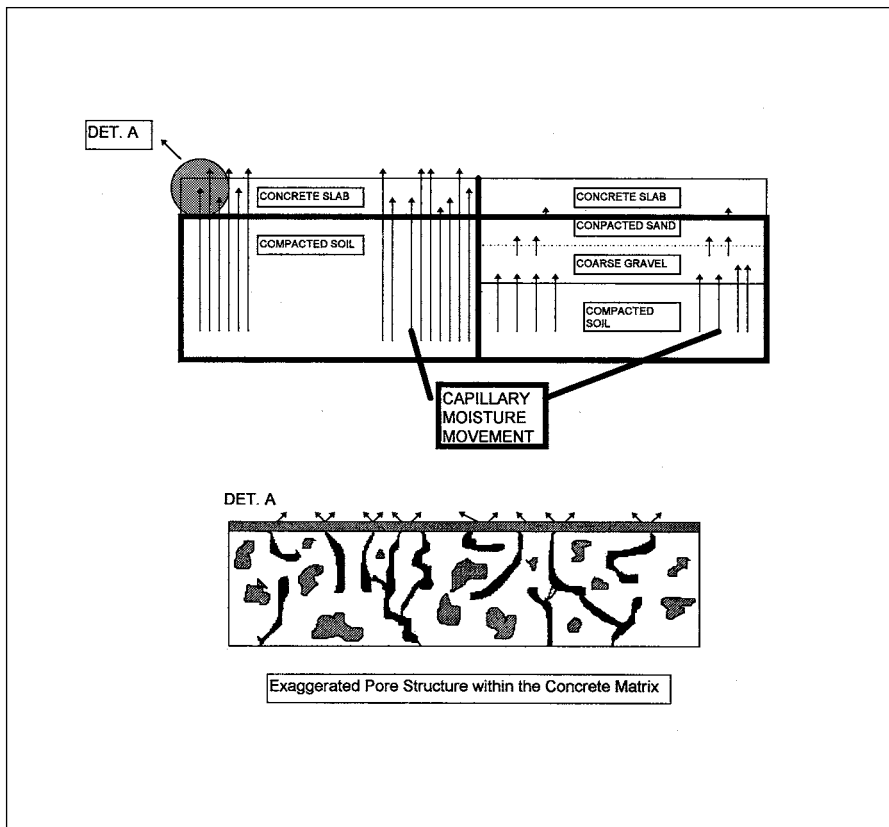


Fig. 2 - Capillary pressure moisture transmission. The dark spots represent aggregate.

compressive) typically exhibits perm ratings of 20 to 30. Cross-linked, chemically cured epoxy coating and flooring systems typically exhibit very low perm ratings of 0.15 perms.

Moisture emission from slab-on-grade concrete is quantified as the

up capillary pressures due to liquid phase moisture transmission from wet or damp subsoil to the concrete itself.

Unlike concrete itself, coarse sand, fine sand, and fine silt and clay subsoils, gravel completely lacks

250 micrometers]), polyvinyl acetate-reinforced polyethylene (4 to 10 mils [100 to 250 micrometers]), roofing felt (55 lbs [25 kg]), asphalt-impregnated fiberglass, and polymer-modified paper. Reinforced 10-mil (250-micrometer) thick polyvinyl acetate sheet seems to offer the best overall physical properties for slab-on-grade moisture control.

Construction damage (punctures), unsealed seams, pipes, and other obstructions breach the monolithic quality of vapor barrier sheets and significantly reduce their effectiveness. Some proprietary coating and flooring manufacturers offer a "complete systems approach" by providing integrated seam seals and boots to seal around pipe and conduit slab penetrations.

Empirical testing has shown that the thickness of the membrane sheet has little or no significant impact on its effectiveness. The inherent permeability of the membrane material itself is the determining factor. Thicker films are, however, less likely to puncture or tear.

Secondary Capillary Breaks

A secondary capillary break consisting of coarse sand 4 in. (100 mm) deep may prove beneficial when placed on top of the sheet barrier material. This break may prevent the capillary wicking of moisture into the concrete slab where the integrity of the sheet barrier has been compromised. The synergistic combination of capillary break gravel, vapor barrier sheet, and secondary capillary break sand has proven to afford the highest resistance to moisture and vapor transmission into slabs on grade.

Insulation To Reduce Condensation

The use of insulation under a slab and around its perimeter edge greatly reduces water condensation on the slab surfaces. Insulation materi-

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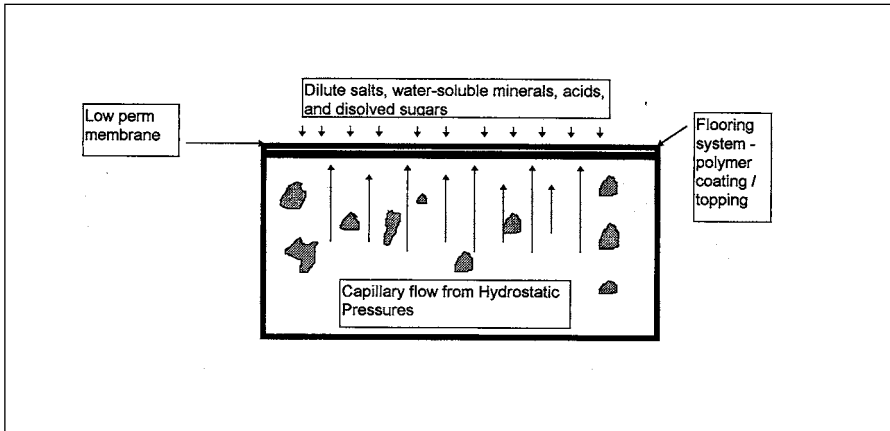


Fig. 3 - Osmotic pressure

pounds of water emitted per 1,000 sq ft (90 sq m) per 24-hour period. Moisture emissions are the combined total of moisture from hydrostatic and water vapor pressures. Moisture emissions as dictated and recommended by industry associations should not exceed 3.0 lbs/1,000 sq ft/24 hrs (1.5 kg/100 sq m/24 hrs).¹⁰

Corrective Measures and Remedial Actions

Design and Construction

Corrective measures may be included during the design and construction phases of slab-on-grade concrete.^{3,4,7,9} Some easily controlled design and construction parameters and practices used to curtail or eliminate slab-on-grade moisture problems are listed below.

Gravel Capillary Breaks

The use of ¼ to ¾ in. (6 to 10 mm) of gravel is effective as a capillary break between the concrete slab bottom and the underlying subsoil. Gravel layers may be 8 to 12 in. (200 to 300 mm) deep. Gravel breaks

the interconnected network of microscopic size pore spaces needed to effectively transport water up by capillary pressure. Subsoil is an excellent medium for capillary transfer. Moisture content of soils is proportional to the fineness of the soil particles.

Fine soils less than 0.002 mils (0.05 micrometers) particle diameter at a 55 percent concentration may give off 12 gal. of water or 99 lbs/1,000 sq ft/24 hrs (51 L [50 kg]/100 sq m/24 hrs). Capillary water from the water table may rise 2.5 ft (0.8 m) through coarse sand, 7.5 ft (2.3 m) through fine sand, and 11.5 ft (3.5 m) for fine silt and clay subsoils. Capillary transfer of water through clean, graded gravel is negligible.

Low Perm Vapor Barriers

The use of low perm vapor barriers (sheet materials) under the slab and over the gravel or subsoil layer is effective for hydrostatic and vapor pressure. Commonly used sheet stock vapor barrier materials are polyethylene (4 to 10 mils [100 to

als must not be damaged by contact with water. The insulating properties must be capable of withstanding cyclic wetting and drying, and should be highly resistant to pests, termites, fungus, and mildew.

Condensation is defined as water

lower the w/c ratio, the denser the concrete. The denser the concrete, the higher its resistance to moisture transmitted from hydrostatic and water vapor pressures. High w/c ratios produce porous concrete. Low w/c ratio concrete slabs reduce the

newly placed “green” concrete are most likely due to the excess water of convenience not used up in the hydration process. Only 0.3 lbs of water is required to completely hydrate 1.0 lbs of Portland cement.

A w/c ratio of 0.57 requires approximately 135 wet cure days to obtain impermeable cement paste. A w/c ratio of 0.52 requires only 50 wet cure days. A w/c ratio of 0.45 requires fewer than 14 days. The remaining water is for the convenience of placement flowability.

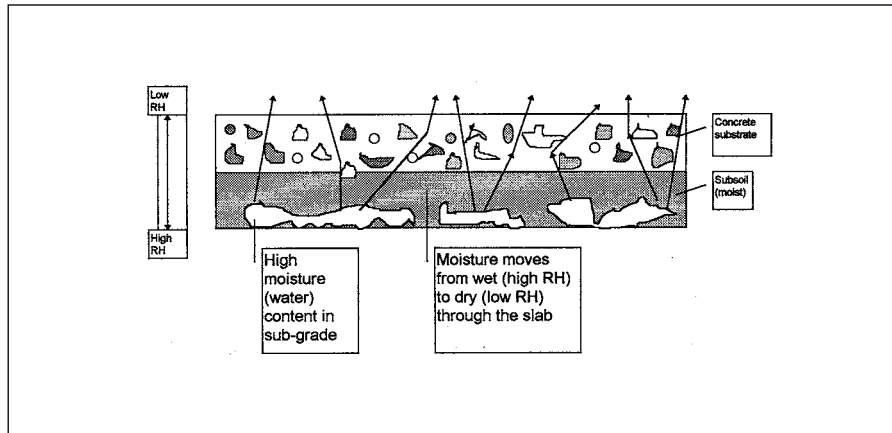


Fig. 4 - Moisture vapor transmission (MVT)

vapor changing from a gas to a liquid state. Condensation occurs when the surface temperature of the slab is equal to or below the dew point temperature of the ambient air. Insulation aids in keeping the slab’s surface temperature above the ambient dew point temperature. Insulation will reduce or eliminate the condensation (sweating) or water vapor on the perimeter or underside base of the concrete slab. Water condensation on a base concrete surface will be transmitted into, and through, the concrete primarily by capillary pressure.

Reduced Water-to-Cement Ratios

Water-to-cement (w/c) ratios in concrete slab mix design play an important part in controlling moisture problems.⁴ Concrete mixes having w/c ratios greater than 0.50 require substantially and progressively longer wet curing times to form relatively impermeable cement paste. The longer curing time lengthens the waiting time required to install low permeability flooring systems over new (green) concrete. The

evaporable mixing water (waters of convenience), the curing period, and the moisture permeance of the concrete.

The use of high range water-reducing agents or super plasticizers in the concrete mix greatly aids in achieving low w/c concrete of less than 0.40 while maintaining flowability and slump characteristics. Pozzolans have also proved very effective. These materials—such as fly ash, silica fume, and some metakaolin clays—can be mixed with water in the presence of Portland cement to form additional high quality calcium silicate hydrate cement paste. This paste can result in concrete with higher densities, better physical properties, and lower water/gas permeability.

New concrete slabs on grade should be allowed sufficient time to form impermeable cement paste before flooring materials are installed. Usually 2 or more months are needed for cure before the application of coatings or finished flooring (28-day absolute minimum).

Flooring problems occurring over

Grading to Improve Drainage

Grading the site to achieve surface water drainage away from the slab will reduce the potential for hydrostatic problems.³ Site grading should be performed to carry water away from the slab in all directions. Finished grades away from the slab should be a 12-inch (300-millimeter) drop for every 25 ft (7.5 m) in all directions. This is equal to a 4.0 percent slope. Finished grades at outside walls should be a minimum of 8 in. (200 mm) below the top surface of the slab. Finished grades next to slab-on-grade concrete should also have a 12-inch (300-millimeter) drop for every 25 ft (7.5 m) in all directions, i.e., a 4 percent slope.

Corrective and Remedial Measures on Existing Slabs

Corrective and remedial measures may be required on existing slabs on grade after design, construction, and concrete placement. Some common materials and practices are provided below.

Liquid Silicate Penetrants

There are 2 basic types of liquid silicate penetrants. The first type are penetrants that clog and plug up concrete slab capillaries to physically block water vapor transmission.

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The second type are penetrants that restrict (plug up) capillaries only at the concrete's slab surface. These types are different chemically but similar in terms of performance.

Penetrants that clog and physically block capillaries are based upon potassium and sodium silicates. The potassium silicates are applied directly to clean, dampened concrete surfaces by means of low pressure spray.

These proprietary formulas react *in situ* with available calcium hydroxide to form insoluble carbonate compounds that fill in and block the concrete's capillaries. Both potassium and sodium silicates are usually applied at rates between 200 and 250 sq ft/gal. (4.9 to 6.1 sq m/L). The rate depends on the porosity of the concrete.

Neither the potassium nor the sodium silicate is effective enough by itself to completely eliminate the higher vapor or hydrostatic pressures sometimes incurred; however, each has been used effectively with other methods. ACI publication 212.3-91 states that the use of chemical admixtures such as sodium silicate is "detrimental to concrete strength" and is "not effective or acceptable in controlling moisture migration through slabs on grade."⁵ This statement is in reference to its use as an admixture and not as a topical surface treatment.

Surface Coatings

Polymer materials may include various deck paints, epoxies, urethane acrylics, and other surface-applied liquid films. Chemically cured materials such as epoxies and some two-part urethanes have extremely low perm rates with respect to high perm (high breathability) coatings such as water-borne acrylics. Alkyd and oil-based coatings should be avoided at all costs because of saponification problems on concrete.

Breathable (High Perm) Coatings

Coatings exhibiting high perm ratings of 3 or more have the ability to "breathe" and let the moisture vapor pass through, thereby maintaining their bond to the concrete and allowing the release

of greater than 6.0 lbs (3.0 kg) would exceed the 50 percent reduction requirement. The resultant back pressure development and sometimes the surface pH increase can lead to disbondment or spalling on the surface of the concrete slab.

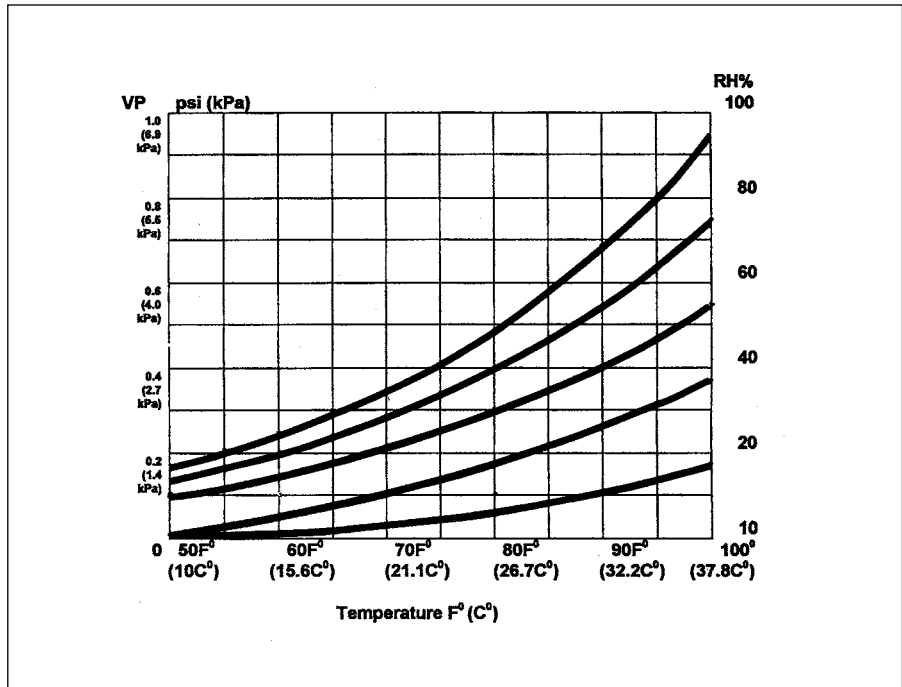


Fig. 5 - Moisture vapor pressure (VP) at different temperatures and relative humidities (RH)

of vapor pressures. High perm breathable coatings are not very good moisture vapor barriers and are still susceptible to loss of adhesion due to hydrostatic liquid phase water pressures.

The overall effectiveness of surface coatings is highly dependent on their tensile and bond strengths to the concrete slab. They must also have good resistance to the high pH alkalinity of concrete. Generally speaking, low perm coatings such as epoxies and two-part urethanes should not be used where they have to reduce more than 50 percent of the moisture transmission as quantified and measured by instrumental techniques. Given a standard of 3.0 lbs of water/1,000 sq ft/ 24 hrs (1.5 kg/100 sq m/24 hrs) as a maximum amount permitted, a measurement

Surface coatings should not be used alone to reduce or eliminate moisture transmission through slabs. Applied to concrete slabs, surface coatings are usually used to protect the concrete from its immediate environment, which may include chemical attack and physical damage. Considering the above, surface coatings may become part of the moisture problem rather than a remedy.

Moisture Barrier (Low Perm)

For surface-applied coatings to be effective moisture barriers, they must have the following characteristics:

- low perm ratings (less than 0.5 U.S. Perms);
- high resistance to the effects of

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high pH (alkalinity), which may lead to saponification;

- adhesive bond strengths to the concrete slab greater than the combined pressure effects of hydrostatic and vapor pressures; and
- adequate chemical resistance and physical properties to perform in their intended service environment.

Membrane Moisture

Dispersion Systems

These materials include any surface-applied material that allows for and accommodates moisture vapor emission absorption, wicking, expansion, and subsequent evaporation. Two basic systems are presented below.

Cement-based coatings may be polymer modified. The cementitious coating material is usually brushed on or applied by broom directly to the cleaned concrete slab surface. Application may be followed by placement of an impervious low perm vapor barrier sheet material, itself followed by another coat of cementitious coating. The use of an acrylic polymer in the cementitious coating increases the physical properties, bond strength, and vapor pressure resistance of the coating.

Fiberglass wicking systems are made with woven strand fiberglass matting impregnated with an acrylic resin binder to create a membrane-like sheet. The fiberglass is capable of transporting moisture through wicking (capillary pressure) from the concrete slab. The moisture is transferred laterally throughout its surface, to be dissipated and evaporated into the ambient air.

The system is effective only for the control of moisture in its vapor phase and only up to the moisture saturation threshold of the fiberglass membrane itself. This system is, however, highly effective up to its saturation threshold limit.

Detection and Measurement of Moisture^{6,7,8,10}

This discussion must be prefaced with the warning that contractors planning to install low permeance (non-breathing) flooring or coating systems to slab-on-grade substrates should perform slab moisture emission tests only when the environmental conditions

closely approximate the anticipated in-service conditions. Moisture vapor and hydrostatic pressures are not constants and are therefore subject to significant change at any time.

The amount of water in a liquid phase within a slab is measured and quantified in percentage factors.

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Moisture content in slabs is quantified as a direct percentage of the water weight of the concrete.

Water vapor emanating from a slab's surface in its gaseous state is measured and quantified in weight/area/time. Flooring industry consensus is that moisture vapor emissions from slabs on grade should not exceed 3.0 lbs of mois-

ture/sq ft/24 hours (14.7 kg/sq m/24 hours).¹⁰ Moisture emission is quantified by the weight of water emanating from 1,000 sq ft (90 sq m) of slab surface over a 24-hour period.

Moisture detection and measurement techniques performed as pre- and post-installation testing include the following.

Methods for Measuring Moisture Content

Gravimetric Testing

Gravimetric testing is currently the most accurate and reliable technique for determining the actual percentage by weight of water (moisture) in concrete, slabs or otherwise. This method may be used to verify the 3 percent maximum moisture content. Concrete samples are hermetically sealed, weighed, and oven dried at 248 F (120 C) until a constant weight is achieved. The difference between the weights before and after oven drying is expressed as the percentage of moisture of the total mass. Gravimetric testing is suitable for both pre- and post-installation moisture measurements, i.e., plastic and hardened. This method measures static moisture contained in the slab but is not suited to measurement of moisture vapor. The method is destructive.

Newly placed concrete of 3,000 to 5,000 psi (21 to 35 kPa) compressive strength exhibits moisture content between 5 percent and 10 percent by weight.

Nuclear Density

Nuclear density is highly accurate but not as practical or easy as the first method described. This method utilizes nuclear tagging of the hydrogen (H) atoms in water (H₂O) with the isotope Americium 241 (beryllium neutrons). A commercial instrument known as the Troxler Gage utilizes this nuclear technology. This method provides the percentage of static water in the slab by weight relative to concrete density. Density instrumentation requires careful calibration and correction for other hydrogen compounds that may be in the concrete.

Radio Frequency

Like nuclear density, radio frequency is accurate but not as practical or

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easy as the first 2 methods described. Several proprietary, affordable instruments use radio frequency energy (RFE) as moisture detection and measurement techniques.

RFE is propagated several inches into the concrete. The resultant reflected RFE power loss or RFE absorption levels are measured. The power loss is directly proportional to the moisture content. The instrumentation must be calibrated against a known concrete moisture content. Many readings can be taken over a large surface area in very little time. This method is also helpful in detecting and tracing moisture intrusion sources. This method does not measure moisture vapor.

Both the nuclear density and RFE measurement techniques are non-destructive.

Electro-conductive

This measurement technique indirectly measures moisture content of concrete by directly measuring the concrete's (dc) electrical conductance, or, reciprocally, its (dc) electrical resistance. The moisture content of concrete is related to the concrete's electrical conductance. The conductance is measured by the instruments in millimeters over a range of 0 to 32. An electrical current is passed between 2 pin-like electrodes pushed into the concrete surfaces. The resultant reading is the concrete's conductance between the electrodes.

There is no direct correlation between the measured current and absolute percentage of moisture, but comparisons are useful. In addition, this technique is falsely affected by the presence of ionic salts such as sodium and calcium chlorides. The higher the level of ionic salts, the higher the conductance will be, resulting in erroneously high moisture readings. A moisture meter is available based on this principle.

The coatings industry and instrument manufacturers have collectively through job site experience and testing reached a consensus that readings greater than 16 are not conducive to proper coating or flooring material application.

This technique is the least accurate method. The method does not measure moisture vapor.

Methods for Measuring Moisture Emitted from Concrete

Calcium Chloride Desiccant Test

This method is the most reliable test for moisture content. It is easy and practical to perform. It has been adopted by the flooring industry to be the standard for determining the amount, by weight, of moisture

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emitted. The technique requires little training and can usually be conducted by field technicians. Unlike the gravimetric method, this test measures dynamic moisture (vapor) emanating from the concrete. Anhydrous calcium chloride is weighed to the nearest tenth of a gram and hermetically sealed to the concrete surface for 60 hours. It is then removed

and weighed to determine the amount of moisture absorbed. This determination is based upon the weight before and after placement, as in the gravimetric method.

The information provided by this method is the water moisture weight in lbs/1,000 sq ft/24hrs (kg/90 sq m/24 hrs). This method is non-destructive.

Calcium chloride test frequencies are based upon the total surface area requiring evaluation. Recommended test frequencies are as follows:

- 500 to 1,000 sq ft (45 to 90 sq m) = 3 tests minimum,
- 1,000 to 5,000 sq ft (90 to 450 sq m) = 4 tests minimum, and
- 1 test for each additional 5,000 sq ft (450 sq m).

Proprietary Variation of Calcium Chloride Test

A proprietary method has been developed by which the calcium chloride test units are placed on the slab's surface in a measured grid pattern. The data are then automatically collected and downloaded into a computer to perform transform analysis. The transform data are computer generated into color-coded map representations of the moisture vapor emissions.

This technique is currently the most accurate and economical method to evaluate large surface areas. The calcium chloride desiccant test and the gravimetric method are judged by the industry to be the most accurate practical methods used to quantify moisture content in or emanating from concrete slabs on grade. Other methods may be quicker and easier to perform but do not provide the accuracy of quantification.

Plastic Sheet Test (ASTM D 4263)

This ASTM test method utilizes a 4.0-mil thick (200-micrometer) transparent polyethylene sheet cut to 18 in. square (457 mm square).⁶ The plastic sheet is tightly taped to the concrete's surface around its perimeter with two-inch (50-millimeter) wide duct tape, with the edges carefully sealed. The sheet is left in place a minimum of 16 hours and then visually evaluated for the presence of moisture condensation on the un-

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derside. One sheet test should be conducted every 500 sq ft (45 sq m) of horizontal surface. The plastic sheet method provides only qualitative information for go/no-go flooring application. It may be used to indicate moisture vapor emission from a slab's surface, but only on a qualitative basis. **JPCL**

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