Field Implementation of Compacted Concrete Pavement

May 2020
Final Report

Project number TR201919
MoDOT Research Report number cmr 20-004

PREPARED BY:

Kamal H. Khayat, PhD, P.Eng.

Nima Farzadnia, PhD

Missouri University of Science and Technology

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division, Research Section

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. cmr 20-004	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Field Implementation of Compacted Concrete Pavement		**5. Report Date** April 2020 Published: May 2020 **6. Performing Organization Code**
7. Author(s) Kamal H. Khayat, PhD, P.Eng. http://orcid.org/0000-0003-1431-0715 Nima Farzadnia, PhD, https://orcid.org/0000-0002-9396-4102		**8. Performing Organization Report No.** Project #00064824
9. Performing Organization Name and Address Center for Transportation Infrastructure and Safety/NUTC Program, Missouri University of Science and Technology 220 Engineering Research Lab Rolla, MO 65409		**10. Work Unit No.** **11. Contract or Grant No.** MoDOT project # TR201919
12. Sponsoring Agency Name and Address Missouri Department of Transportation (SPR-B) Construction and Materials Division P.O. Box 270 Jefferson City, MO 65102		**13. Type of Report and Period Covered** Final Report (June 1, 2019-April 30, 2020) **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at https://www.modot.org/research-publications.		

16. Abstract

The main objective of this research is to investigate the performance of Compacted Concrete Pavement (CCP) with special design features of surface texture that can reduce construction cost and secure safe and durable surface texture. This research was part of a larger project undertaken by the City of Mexico, Missouri in collaboration with Missouri Department of Transportation (MoDOT). The CCP mixture was evaluated for key fresh properties (unit weight, air content, and Vebe consistency), mechanical properties (compressive strength, flexural strength, and modulus of elasticity), drying shrinkage, and durability (air-void system, freeze thaw resistance, scaling resistance, bulk and surface resistivity). The results of this project aimed to add value to the current state of practice related to the use of CCP, synthesize current technical knowledge, study the potential problems associated with the use of CCP in pavement construction in Missouri, and propose guidelines for best practice related to CCP construction. Test results indicate the reliability of mechanical properties for the investigated CCP material. The compressive and flexural strengths and elastic modulus of the investigated concrete were approximately 4970 psi, 410 psi, and 4120 ksi for cast-in-field samples and 4470 psi, 450 psi, 3550 ksi for core samples, respectively. The drying shrinkage was limited to 60 $\mu\varepsilon$ after 70 d of testing, indicating low drying shrinkage. The durability tests showed that the CCP mixture can be classified as a mixture with moderate chloride ion permeability and acceptable resistance to de-icing salt scaling. However, the non-air entrained CCP showed poor resistance to freezing and thawing.

17. Key Words Compacted concrete pavement; Field implementation; Mechanical properties; Shrinkage; Durability		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified.	**20. Security Classif. (of this page)** Unclassified.	**21. No. of Pages** 42	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Field Implementation of Compacted Concrete Pavement

Project Number: TR201919

Final Report

PREPARED FOR THE

MISSOURI DEPARTMENT OF TRANSPORTATION

IN COOPERATION WITH THE

Missouri University of Science and Technology

Prepared by:
Kamal H. Khayat[1], Nima Farzadnia[2]

[1] Professor of Department of Civil, Architectural and Environmental Engineering, Director of Center for Infrastructure Engineering Studies, Missouri University of Science and Technology, Rolla, MO, USA (PI)
[2] Postdoctoral Fellow, Center for Infrastructure Engineering Studies, Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, USA

RE-CAST Project #00064824

April 2020

COPYRIGHT

DISCLAIMER

ACKNOWLEDGEMENTS

The authors would like to acknowledge several individuals and organizations that made this research project possible. First and foremost, the authors would like to acknowledge the financial support of Missouri Department of Transportation (MoDOT – Project 00064530, Task Order TR201904) and the collaboration of Ms. Jennifer Harper, Research Director with MoDOT, as well as the RE-CAST (REsearch on Concrete Applications for Sustainable Transportation) Tier-1 University Transportation Center (UTC) at Missouri University of Science and Technology (Missouri S&T – Project 00064824).

The authors would also like to thank the companies that provided materials required for the successful completion of this project, including Continental Cement Company, Audrain County concrete, Boone Quarry, Capital Sand Company, and ACEiT Industries, Inc.

The contribution of Le Teng, the PhD student, and support of Jason Cox, Senior Research Specialist of the Center for Infrastructure Engineering Studies (CIES), are greatly acknowledged.

ABSTRACT

The main objective of this research is to investigate the performance of Compacted Concrete Pavement (CCP) with special design features of surface texture that can reduce construction cost and secure safe and durable surface texture. This research was part of a larger project undertaken by the City of Mexico, Missouri in collaboration with Missouri Department of Transportation (MoDOT). The CCP mixture was evaluated for key fresh properties (unit weight, air content, and Vebe consistency), mechanical properties (compressive strength, flexural strength, and modulus of elasticity), drying shrinkage, and durability (air-void system, freeze thaw resistance, scaling resistance, bulk and surface resistivity). The results of this project aimed to add value to the current state of practice related to the use of CCP, synthesize current technical knowledge, study the potential problems associated with the use of CCP in pavement construction in Missouri, and propose guidelines for best practice related to CCP construction. Test results indicate the reliability of mechanical properties for the investigated CCP material. The compressive and flexural strengths and elastic modulus of the investigated concrete were approximately 4970 psi, 410 psi, and 4120 ksi for cast-in-field samples and 4470 psi, 450 psi, 3550 ksi for core samples, respectively. The drying shrinkage was limited to 60 $\mu\varepsilon$ after 70 d of testing, indicating low drying shrinkage. The durability tests showed that the CCP mixture can be classified as a mixture with moderate chloride ion permeability and acceptable resistance to de-icing salt scaling. However, the non-air entrained CCP showed poor resistance to freezing and thawing.

Keywords: Compacted concrete pavement; Field implementation; Mechanical properties; Shrinkage; Durability.

EXECUTIVE SUMMARY

This research project was undertaken to investigate the performance of Compacted Concrete Pavement (CCP) with special design features and durability of surface texture that can reduce construction cost and secure superior surface texture. CCP is an alternative form of Roller-Compacted Concrete (RCC) and is comprised of similar mixture proportioning; however, the CCP utilizes an admixture that enables better finishing and surface texture. The major difference in construction is that CCP has a longer "fresh" or "green" period and requires little or no rolling that makes the riding surface more uniform. The use of CCP technology is supposed to enable the use of conventional slip-form paving equipment and smaller roller compaction equipment in addition to power trowels to secure smooth texture during paving.

Table 1 shows the mixture proportioning of the CCP used in this project. The CCP had an optimum water-to-cement ratio of 0.52 and was designed to achieve a minimum compressive strength of 4000 psi at 28 days.

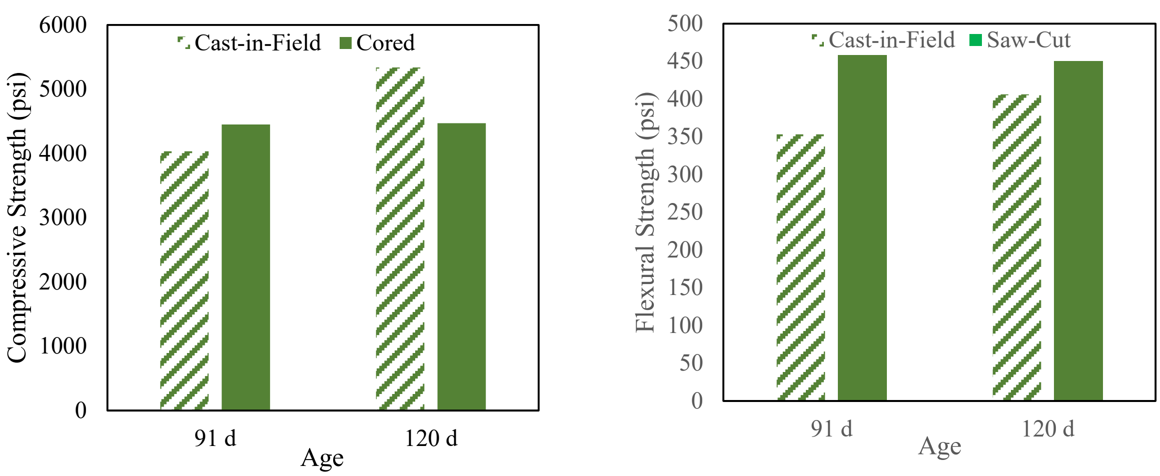
Table 1 - Mixture proportioning of the CCP

Mixture	Cement Type I/II (lb./yd^3)	Coarse Aggregate (MSA ½ in.) (lb./yd^3)	Water (lb./yd^3)	Sand (lb./yd^3)	Admixture-ACEiT Plus (oz/yd^3)
CCP	450	1843	235	1503	15.34

During the paving operation that took place on July 23, 2019, representative CCP mixture samples were cast into four prismatic molds measuring 6 × 6 × 24 in. to determine flexural strength. Furthermore, nine cylindrical samples measuring 6 × 12 in. were prepared to determine compressive strength and modulus of elasticity. The Vebe test was conducted to evaluate the consistency of the CCP. Furthermore, a slab measuring 2.5 × 7.5 ft was extracted from the

pavement by the City of Mexico 10 days after the paving operation. The slab was used to provide 12 saw-cut prisms and 15 core samples to determine in-situ mechanical properties, shrinkage, and durability of the concrete.

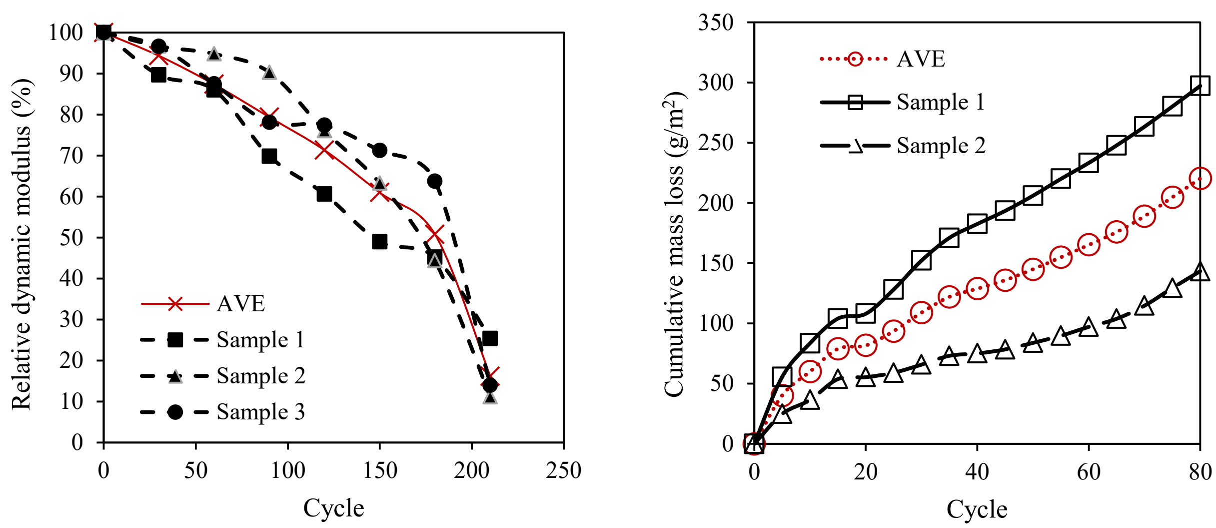
Figure 1 shows the mean compressive and flexural strengths of the cast-in-field and cored/saw-cut samples determined at 91 and 120 d. The results indicate that the concrete developed adequate compressive and flexural strengths as specified in the project. The results are indicative that prolonged curing after 91 d did not significantly affect the mechanical properties. In this project, the cast-in-field and cored/saw-cut samples exhibited comparable compressive and flexural strengths, indicating that similar compaction energy was applied during the molding of the test samples and those exerted by the paving machine.



(a) (b)

Figure 1 - Mechanical properties of CCP: (a) compressive strength and (b) flexural strength at 91 and 120 d

The examination of core samples indicated that the average air void volume, chord length, paste-to-air ratio, and spacing factor were 4.3%, 0.005 in., 6.05, and 0.006 in. (150 μm), respectively. Figure 2 shows the results of the freezing and thawing and deicing salt scaling tests. The freezing and thawing test was discontinued after 210 cycles, instead of the standard 300 cycles, given the sharp reduction in the dynamic elastic modulus. The relative dynamic modulus of 60% was obtained after 150 cycles of freezing and thawing, resulting in a durability coefficient of 30%. This indicates that the non air-entrained CCP had low frost durability. On the other hand, the concrete exhibited an excellent resistance to deicing salt scaling tests where mass loss was recorded for 80 cycles instead of the standard 50 cycles. The mass loss due to the deicing salt scaling test after 80 cycles was significantly below the acceptable range of 0.20 lb./ft^2 (1000 g/m^2) after 50 cycles. This is mainly attributed to the high surface density of the mixture resulting from the compaction of the CCP. The concrete exhibited moderate chloride ion permeability that was determined using the bulk electrical resistivity test. The drying shrinkage was limited to 60 με after 70 d of drying, which is considered to be low shrinkage.



(a) (b)

Figure 2 - Frost durability of CCP: (a) Variations of relative dynamic modulus of elasticity and (b) Mass loss of saw-cut slabs after different de-icing salt scaling cycle

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Problem statement and research objectives

There are trending interests in exploring the application of cost-effective and rapid pavement construction techniques due to the increasing budget constraints and decreasing time in pavement construction. Roller-compacted concrete (RCC) is a stiff mixture of aggregate, cementitious materials, and water, that is compacted by vibratory rollers (ACI 325, 1995). Compacted concrete pavement (CCP) is an advanced form of RCC and is comprised of similar mixture proportions as that of RCC. However, CCP utilizes an admixture that enables better finishing and supposedly a more durable surface texture. The major difference in construction is that CCP has a longer "fresh" or "green" period and requires little or no rolling that makes the riding surface more uniform and consistent. The use of CCP technology is supposed to secure smooth texture during paving.

Past research at Missouri University of Science and Technology (Missouri S&T) in collaboration with the Missouri Department of Transportation (MoDOT) was carried out to investigate in-situ properties of a non-air-entrained RCC used for the construction of a pavement shoulder on Route 160 in Missouri. The results demonstrated the superior performance of RCC in rapid pavement construction (Khayat and Libre, 2014). Another work is underway at Missouri S&T in collaboration with MoDOT and the Minnesota Department of Transportation (MnDOT) to evaluate the performance of CCP pavement construction used for a service road construction in Cape Girardeau, MO. However, limited experience exists with CCP.

The main objective of the project presented in this report was to assess the feasibility of using the CCP technology to facilitate rapid pavement construction and secure high-quality surface finish without the need to apply a riding surface. The modified RCC was used for the paving of a city street in Mexico, MO. The implementation project was undertaken to investigate the engineering properties and durability of the novel RCC design. The concrete was sampled to evaluate key fresh and hardened concrete properties, and core and saw-cut specimens were extracted to evaluate in-situ performance of the CCP.

2. EXPERIMENTAL PROGRAM

The study presented in this report aimed at evaluating the performance of the modified RCC mixture used for the CCP construction. The paving took place on July 23, 2019 on Holt Street in Mexico, MO, shown in Figure 2-1.

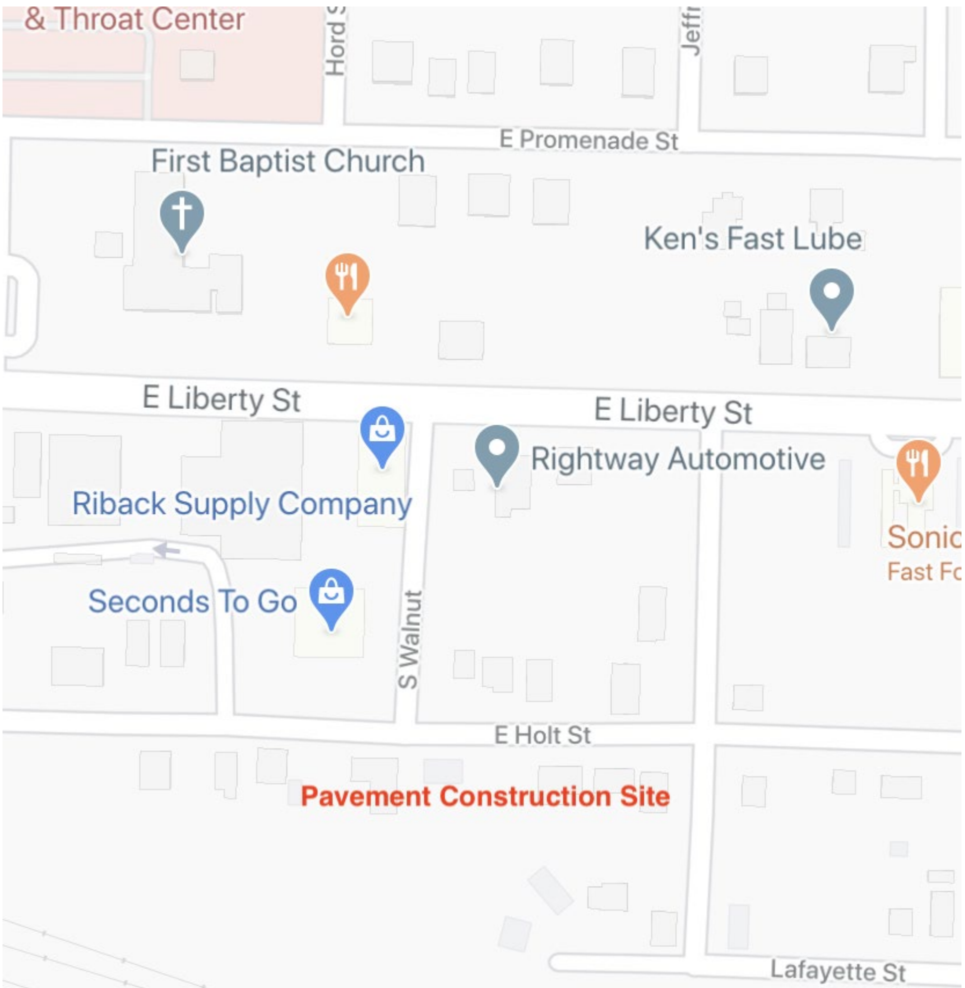


Figure 2-1 - Project location on Holt Street, Mexico, MO

The paving process was implemented using a concrete slip-form paver, roller compactor, and power trowels. A photo of the concrete paver is shown in Figure 2-2. Figure 2-3 shows the roller compactor that was used to consolidate the concrete and expedite the compaction operations. Figure 2-4 shows the final surface finishing operations carried out with the power trowels. The photo also shows the application of the ACEiT Blue that was used as a finishing aid.

Figure 2-2 - CCP pavement construction

Figure 2-5 shows the RCC / CCP paving surface after the paving operation and thereafter at the conclusion of the finishing operations. The final finish is clearly adequate and resembles that of a conventional concrete paving operation, which is not possible to achieve with conventional RCC construction.

Figure 2-3 - Smaller compactor used to consolidate the concrete

Figure 2-4 - Surface finishing operations and application of ACEiT Blue finishing aid

Figure 2-5 - Surface finish at end of paving operations (top) and conclusion of finishing (bottom)

The mixture proportioning of the concrete used in this implementation project is reported in Table 2-1. The mixture is proportioned without any fly ash and has an optimum water-to-cement ratio of 0.52 to achieve a minimum compressive strength of 4000 psi at 28 days. The RCC mixture uses a powdered form ACEiT® Plus additive. According to the material's manufacturer, the ACEiT® Plus is a cement hydration stabilizer designed to retain a significant amount of water that can be released to cement particles incrementally through the cement setting period, which can lead to lower heat of hydration.

Table 2-1 - Mixture proportioning of the CCP

Mixture	Cement Type I/II (lb./yd^3)	Coarse Aggregate (MSA ½ in.) (lb./yd^3)	Water (lb./yd^3)	Sand (lb./yd^3)	ACEiT® Plus (oz/yd^3)
CCP	450	1843	235	1503	15.34

During the paving operation, representative concrete samples were taken at the jobsite to test fresh properties and cast control specimens. The concrete samples were covered with plastic sheet until the end of the sampling time in order to avoid evaporation of water. The concrete was sampled to determine the Vebe consistency and density. Four prismatic molds measuring 6 × 6 × 24 in. were cast to determine flexural strength, and nine cylindrical samples measuring 6 × 12 in. were prepared to determine compressive strength and modulus of elasticity (Figure 2-6).

Figure 2-6 - Cast in field sampling process

A slab measuring approximately 2 × 7 ft was extracted from the pavement by the City of Mexico

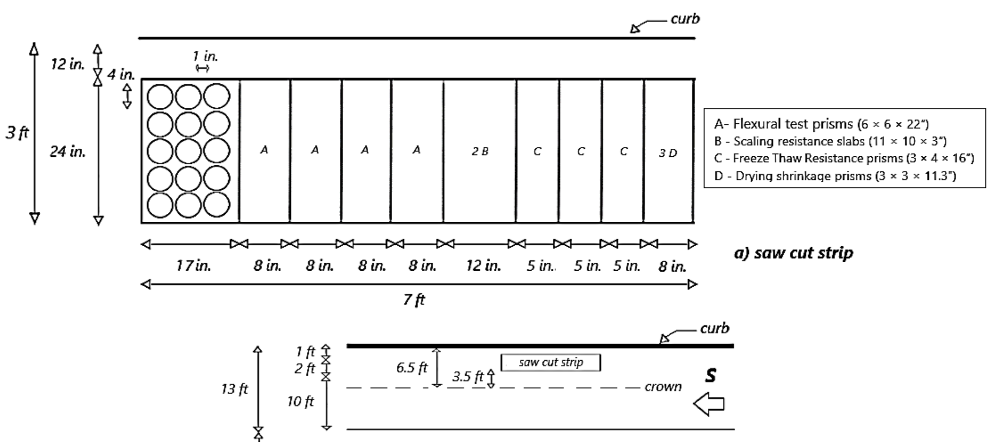


Figure 2-7 - Cutting plan

10 days following the paving operation. Figure 2-7 shows the saw cutting/coring plan.

The following procedure was taken during the cutting:

- A strip of 2 ft in width by 7 ft in length was cut out of the pavement parallel to the paving direction of the south lane (Figure 2-7).
- Samples were cut perpendicular to the paving direction.
- All cut samples were of full depth (8 in.) of pavement.

During saw cutting operations, however, the slab was broken into different segments. The segments were transported to Missouri S&T for the extraction of cores samples and prismatic samples. The slab was used to provide 12 saw-cut prisms and 15 core samples to determine in-situ mechanical properties, drying shrinkage, and durability characteristics of the concrete. The testing program used to evaluate concrete performance is summarized in Table 2-2.

Table 2-2 - Concrete test methods and protocols

Property	Test Methods	Cast-in-field		Cored/Saw-cut	
		No	Size	No	Size
Fresh Properties					
Unit weight	ASTM C 138				
Air content	ASTM C 231				
Consistency	ASTM C1170				
Mechanical Properties					
Compressive strength (91 and 120 d)	ASTM C 39	6	6 × 12″ (cylinders)	6	4× 8 in. (cores)
Flexural strength (91 and 120 d)	ASTM C 78	4	6 × 6 × 22″ (beams)	4	6 × 6 × 22 in. (prisms)
Modulus of elasticity (91d)	ASTM C 469	3	6 × 12″ (cylinders)	3	4 × 8 in. (cores)
Shrinkage and Durability					
Drying shrinkage	ASTM C 157			3	3 × 3 × 11.3 in. (prisms)
Freeze-thaw resistance	ASTM C 666, Proc. A			3	3 × 4 × 16 in. (prisms)
Air-void system	ASTM C 457			1	4 ×1 in. (3 disks)
Scaling resistance	ASTM C 672			2	11 × 10 × 3 in. (slabs)
Bulk and surface resistivity (91 d)	AASHTO T95/ ASTM C1760			2	4 × 8 in. (cores)
Total		13	Cylinder: 9 Beam: 4	24	Core: 12 Saw-cut: 12

3. TEST METHODS

3.1 Vebe test

The Vebe consistency time and density of freshly compacted concrete were measured for two representative concrete deliveries during the paving operation. The test was performed according to ASTM C 1170. Figure 3-1 shows the Vebe test apparatus. The procedure consisted of placing a representative sample of CCP mixture of approximately 29.5 lb. in a standardized cylindrical steel mold. The mold was fixed on a vibrating table, and a circular plastic plate was placed on top of the concrete sample. In order to consolidate the concrete, a removable mass of 50 lb. was applied to the plate, and the vibrating table was turned on. For Vebe consistency time, the time of consolidation is recorded as the consistency time until a mortar ring is observed around the plastic plate. In the absence of mortar ring formation within 60 seconds from the start of vibration, the Vebe consistency time is reported to be greater than 60 seconds.

The density of fresh compacted concrete is calculated after the Vebe consistency time test. The mold was overfilled with more concrete and was properly consolidated using a jack hammer device. The density of the fresh compacted concrete was measured using the mass of the mold with concrete and the mass and volume of the empty mold.

3.2 Compressive strength and modulus of elasticity

The 91-d and 120-d compressive strengths of cast-in-field and core samples were determined using 6 × 12 in. cylinders according to ASTM C39. Figure 3-2 shows the setup for compressive strength test. The modulus of elasticity (MOE) of cast-in-field and core samples was conducted in accordance to ASTM C 469. The samples were maintained in saturated conditions prior to testing.

Figure 3-1 - Vebe test apparatus for determining consistency/density of fresh CCP

All cylinders were capped one day before the testing using high strength sulphur capping compound according to ASTM C 617. They were then returned to a moist curing room until the testing. The stress rate was 35 ± 7 psi/s during the loading process.

Figure 3-2 - Test setup for compressive strength measurement

3.3 Flexural strength

The flexural strength testing was conducted on prismatic samples measuring 6 × 6 × 24 in. (span of 18 in.) according to ASTM C1609. The loading rate was maintained at displacement control of 0.0035 in./min until failure of the beam samples. Figure 3-3 shows the test set-up for the flexural test.

Figure 3-3 - Test setup for flexural strength measurement of beam specimens

3.4 Electrical resistivity

The electrical resistivity measurement was used to classify the concrete according to the corrosion rate. The measurement of electrical resistivity was determined using two different methods. As shown in Figure 3-4, the direct two-electrode method (ASTM C1760) and the four-point Wenner probe method (AASHTO TP 95-11) were utilized, corresponding to bulk electrical conductivity and surface resistivity, respectively. The electrical resistivity was measured using cored cylindrical samples measuring 4 × 8 in. at the age of 91 d. Four samples were tested, and each sample was tested four times to get more reliable results.

a) b)

Figure 3-4 - Testing apparatus for: (a) surface resistivity and (b) bulk resistivity

3.5 Air-void system

Samples measuring 4 in. × 1 in. cut from cores were prepared to determine the air-void system according to ASTM C 457. Figure 3-5 shows sample preparation for air-void system analysis. Two samples were tested with each sample tested four times, rotating the sample by 90° each time. The average of the four results was calculated as the air-void system parameters. By this means, the variations in the results would be averaged out, and more reliable values can be obtained.

a) b)

Figure 3-5 - Sample preparation for air-void system: (a) surface polishing and (b) surface treatment

3.6 Freeze-thaw resistance

The freeze-thaw resistance of saw-cut samples was evaluated in accordance with ASTM C666, Procedure A. The test procedure consisted of subjecting concrete samples to up to 300 cycles or until failure due to rapid freezing and thawing in water at temperatures varying between 41 to -0.4 °F. For the investigated concrete, three samples were tested, and the average was used to interpret the results. The samples were placed in metal containers and surrounded by approximately 0.2 in. of clean water in a specified chamber. Freezing was generated with a cooling plate at the bottom of the apparatus, whereas thawing was produced by heating elements placed between the containers. The dynamic modulus of elasticity was measured at the end of each series of 30 cycles. Figure 3-6 shows the freeze-thaw chamber and test setup.

The durability coefficient was calculated as the square of the ratio of the pulse velocities of P waves in the concrete at the end of the testing period to the value recorded at the beginning of the test, multiplied by the number of cycles at the termination of the test and was divided by 300. The test was terminated soon after the relative dynamic modulus of elasticity decreased to a level lower than 60%.

a) b)

Figure 3-6 - Freeze-thaw test: (a) chamber and (b) test setup

3.7 Drying shrinkage

Drying shrinkage of mixtures was determined for saw-cut prisms measuring 3 × 3 × 11.3 in. according to ASTM C157, using a digital type extensometer (DEMEC gauge). The saw-cut prisms were stored in a temperature of 70 ± 3 °F and relative humidity of 50% ± 4%. The measurement of shrinkage started at 91 d after casting. The samples were kept in a lime saturated curing tank prior to exposure to drying. Figure 3-7 shows the test setup for drying shrinkage.

Figure 3-7 - Drying shrinkage testing

3.8 Deicing salt-scaling resistance

Deicing salt-scaling test was carried out using two saw-cut slabs measuring 11×10×3 in. in accordance with ASTM C672. Figure 3-8 shows the freeze-thaw chamber. The test was conducted on two samples representing the CCP mixture at 91 d. During this test, the surface of the concrete was covered with approximately 0.24 in. of 4% sodium chloride solution (i.e., 0.14 oz. of NaCl for each 3.4 fl. oz. of water). The samples were subjected to 80 freezing and thawing cycles (instead of the standard 50 cycles). The samples were alternately placed in a freezing environment (-0.08 ± 3.02 °F) and a thawing environment (73.4 ± 3.1 °F). At the end of each series of 5 cycles, the salt solution was renewed, and the scaling residues were recuperated, dried, and weighed. The extent of surface scaling was also assessed visually. The visual rating of zero means no scaling of the concrete surfaces and five for severe scaling with coarse aggregates visible over the entire surface.

Figure 3-8 - Freeze-and-thaw chamber for deicing salt-scaling test

4. TEST RESULTS AND DISCUSSION

4.1 Vebe test

As mentioned earlier, the Vebe consistency time is recorded as the consistency time until a mortar ring is observed around the plastic plate. In the absence of mortar ring formation within 60 seconds from the start of vibration, the Vebe consistency time was reported to be greater than 60 seconds. Table 4-1 presents the Vebe test results for mixtures associated with two readings. Accordingly, the representative mixtures are categorized as having extremely dry consistency, as per ASTM C1170.

Table 4-1 - Vebe test results

Mixture properties	Reading 1	Reading 2
Vebe consistency time	> 60 s	> 60 s
Density of fresh compacted concrete	138 lb./ft^3 (2,213 kg/m^3)	141 lb./ft^3 (2,251 kg/m^3)

4.2 Compressive strength and modulus of elasticity

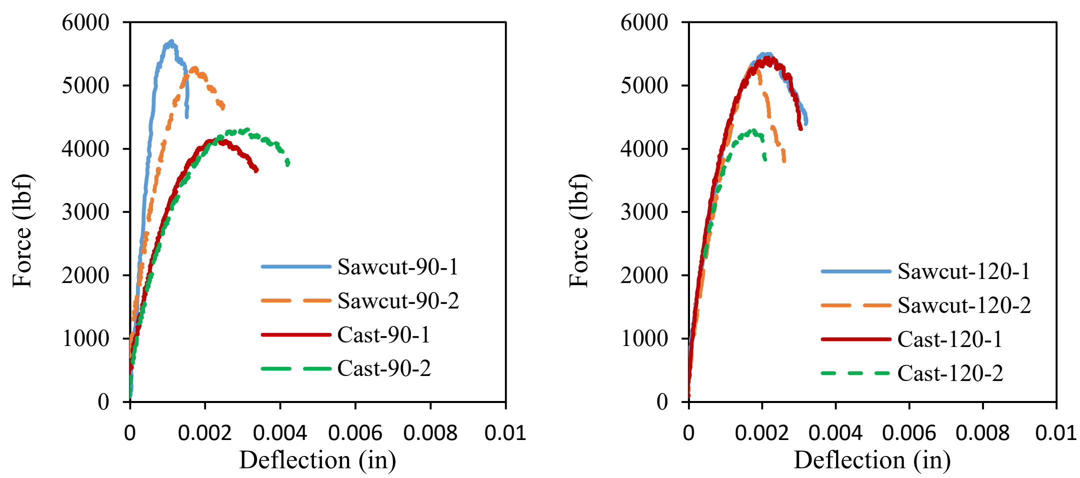
Table 4-2 reports the compressive strength of the cast-in-field and core samples at 91 and 120 d and elastic modulus (MOE) at 91 d. The recorded values for cast-in-field and core samples were similar, that agrees well with the results of density recorded for associated samples. This indicated that sufficient consolidation was applied during the field casting, which was comparable to consolidation energy applied by the paver. All the tested samples obtained compressive strength greater than the specified strength value of 4000 psi required for the CCP construction. Comparing to the previous project (Khayat and Libre, 2014) on RCC, similar compressive strength and modulus of elasticity values were obtained for the CCP samples of the same age. Likewise, the increase of curing time had limited influence on the development of compressive strength. The mean compressive strength of core samples at 91 and 120 d were 4450 and 4470 psi (30 and 31 MPa), respectively.

Table 4-2 - Compressive strength and MOE results

Sample	Curing age (d)	Compressive strength (psi)					Elastic modulus (ksi)					Density (lb./ft^3)
		1	2	3	Mean	COV	1	2	3	Mean	COV	
Cast-in-field sample	91	4140	4200	3760	4030	5%	3915	4310	4150	4120	4%	153
	120	5030	4240	5640	4970	11%	-	-	-	-	-	
Core sample	91	4570	4140	4640	4450	5%	4655	3395	2595	3550	24%	147
	120	4280	3920	5190	4470	12%	-	-	-	-	-	

4.3 Flexural strength

The load-deflection results of cast-in-field and saw-cut samples at 91 and 120 d are reported in Figure 4-1. Table 4-3 summarized the flexural strength of the cast-in-field and saw-cut samples at 91 and 120 d. It was observed that all samples exhibited brittle failure behavior. The flexural strength of saw-cut samples was slightly higher than that of cast-in-field specimens. For example, the flexural strength of cast-in-field and saw-cut samples at 120 d were 405 and 450 psi, respectively. The increase in curing time had limited effect on the development of flexural strength. For example, the flexural strengths of saw-cut samples at 91 and 120 d were 460 and 450 psi, respectively. These results are consistent with those of compressive strength.



(a) 91 d (b) 120 d

Figure 4-1 - Load-deflection curves of cast-in-place and saw-cut samples at 91 and 120 d

Table 4-3 - Flexural and residual strength results

Sample	Curing age (d)	Flexural strength (psi)		
		1	2	Mean
Cast-in-field	91	350	360	355
	120	450	360	405
Saw-cut	91	480	440	460
	120	460	440	450

4.4 Electrical resistivity

The bulk and surface resistivity values of the investigated mixture are shown in Tables 4-4 and 4-5, respectively. The average values of bulk and surface electrical resistivity were 12.3 and 14.9 KΩ.cm, respectively, which is in good agreement with results of RCC from the previous project (Khayat and Libre, 2014). According to the correlation of surface resistivity and chloride ion permeability, this mixture can be classified with moderate chloride ion permeability (Mehdipour, 2017). It should be noted that the corrosion is not critical because RCC pavements are constructed without reinforcement. However, this test provides information on the impermeability of the material, which is an important parameter in characterizing durability and service life of the concrete.

Table 4-4 - Bulk electrical resistivity of cores (KΩ.cm)

Sample	1	2	3	Mean	Mean
1	11.5	16.3	12.0	13.3	12.3
2	12.1	12.3	12.4	12.3	
3	11.2	13.8	11.9	12.3	
4	12.0	10.8	10.7	11.2	

Table 4-5 - Surface electrical resistivity of cores (KΩ.cm)

Sample	1	2	3	Mean	Mean
1	14.4	15.4	14.7	14.8	14.9
2	15.0	17.2	14.3	15.5	
3	15.0	13.0	15.9	14.6	
4	14.8	13.5	15.0	14.4	

4.5 Air-void system

Table 4-6 presents the air-void system parameters of the investigated CCP mixture. The average air void volume, chord length, paste to air ratio, and spacing factor of the mixtures were 4.33%, 0.005 in., 6.05, and 0.006 in., respectively. The CCP samples had very low spacing factor, which can be in part due to entrapped air voids in the hardened concrete as the mixture was non-air entrained.

Table 4-6 - Air void content and spacing factor of the two investigated mixtures

Property	Sample 1	Sample 2	Sample 3	Mean
Air Content (%)	4.35	4.49	4.15	4.33
Chord Length (in.)	0.005	0.006	0.005	0.005
Paste to Air Ratio	6.01	5.26	6.89	6.05
Spacing Factor (in)	0.006	0.007	0.006	0.006

4.6 Freeze-thaw resistance

Figure 4-2 shows the variation of dynamic modulus of elasticity of saw-cut samples with freeze and thaw cycles. Results showed that the increase of freeze-thaw cycles up to 150 cycles gradually decreased the relative dynamic modulus from 100% to 60%. Then, the dynamic modulus had a significant drop with the freeze-thaw cycles. For example, the increase in freeze-and-thaw cycles from 150 to 200 led to 50% decrease in relative dynamic modulus.

The average relative dynamic modulus of elasticity at 150 cycles was 60%, which translates into a durability coefficient of 30%. This indicates that the investigated concrete had poor capacity to resist the freeze and thaw. However, the results showed a significant improvement of CCP compared to RCC samples from the previous project (Khayat and Libre, 2014). Previous results of non-air entrained RCC showed that the samples failed before 60 cycles of freezing and thawing and cracks appeared in some samples after 30 cycles.

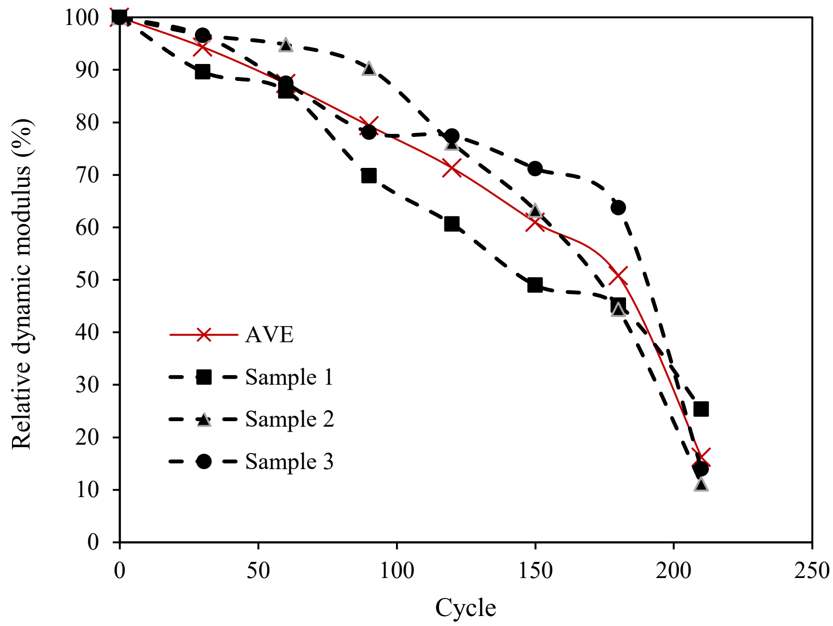


Figure 4-2 - Variations of relative dynamic modulus of elasticity

4.7 Drying shrinkage

Figure 4-3 shows the variation of drying shrinkage of the investigated mixture. The shrinkage testing was initiated at the age of 91 d to allow the concrete pavement to reach enough maturity before drying. In general, the drying shrinkage was limited to 60 με after 70 d of testing, indicating low drying shrinkage.

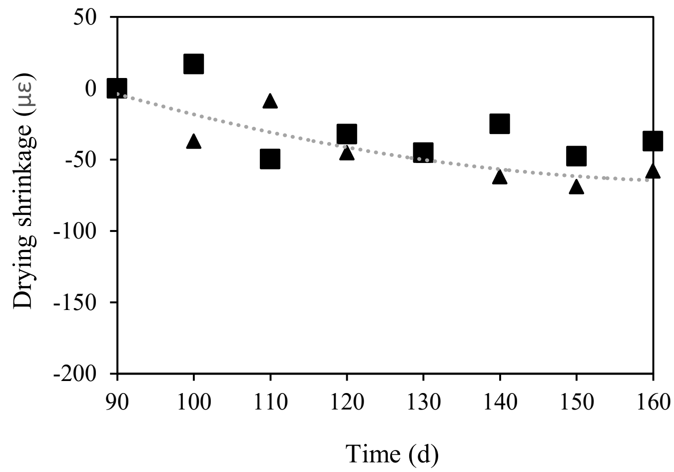


Figure 4-3 - Variation of drying shrinkage determined on saw-cut samples

4.8 Deicing salt-scaling resistance

The visual ratings of the concrete surface before testing and after 80 cycles of freeze-thaw are given in Table 4-7. No visible scaling was observed during 80 cycles indicating acceptable resistance of the mixture to salt scaling. Figure 4-4 shows the cumulative mass loss of scaled dry materials of the mixtures during the salt scaling test after 80 freeze-thaw cycles. The cumulative mass loss increased with the increase of freeze-thaw cycles. In general, the average value of cumulative mass was 200 g/m^2, which is under the upper limit of 1000 g/m^2 to date. This indicated that the specimens had a good capacity to resist the chloride penetration.

Table 4-7 - Saw-cut slabs before and after exposure (80 cycles)

	Sample 1	Sample 2		Sample 1	Sample 2
Initial			5 cycles		
10 cycles			15 cycles		
20 cycles			25 cycles		
30 cycles			35 cycles		
40 cycles			45 cycles		
50 cycles			55 cycles		

60 cycles			65 cycles		
70 cycles			75 cycles		
80 cycles					

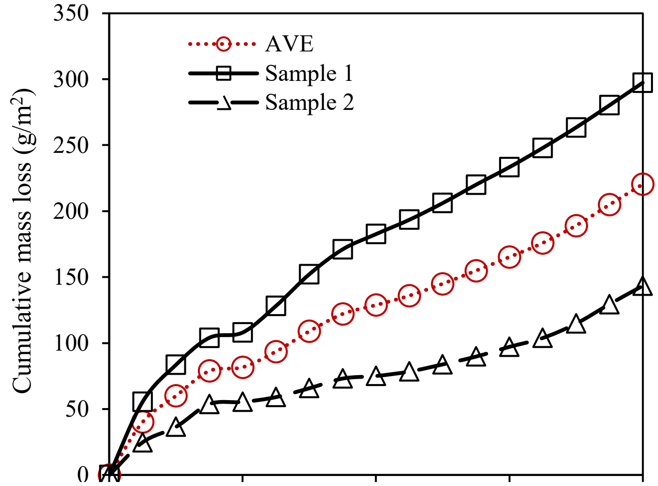


Figure 4-4 - Mass loss of saw-cut slabs after different de-icing salt scaling cycles

5. SUMMARY AND CONCLUSIONS

This research project presented in this report was undertaken to evaluate a new class of RCC that was placed using the CCP paving technology. Several key material properties were investigated, including consistency, mechanical strength, drying shrinkage, and durability. Based on the test results from research presented in this investigation, the general performance of CCP is superior to that of RCC for pavement construction from the previous project. The following are the conclusions of this research project:

5.1 Drying shrinkage

The drying shrinkage after 70 d was limited to 60 με, indicating low shrinkage. The drying shrinkage testing determined at temperature of 70 ± 3 °F and relative humidity of 50% ± 4% was initiated at 91 d of age.

5.2 Mechanical properties

- The compressive and flexural strengths and elastic modulus were approximately 4500 psi, 450 psi, and 3800 ksi, respectively. This proves the reliability of mechanical properties for the investigated new class of RCC that was placed using the CCP paving technology.
- The increase of curing time from 91 to 120 d led to 5% increase in the compressive and 2% increase in flexural strength of saw-cut samples, respectively. This indicates that the effect of curing time from 91 to 120 d was limited for strength development.
- The compressive strengths of cast-in-field samples and saw-cut samples at 120 d were 4970 and 4470 psi, respectively, while flexural strength of cast-in-field samples and saw-cut samples at 120 d were 405 and 450 psi. Such similar results proved the sufficient consolidation was applied during the casting.

5.3 Durability

- The volume of air voids, chord length, paste to air ratio, and spacing factor of the mixture were 4.33%, 0.005 in., 6.05, and 0.006 in., respectively, indicating an adequate air-void system.
- The values of bulk and surface electrical resistivity were 11.9 and 14.9 KΩ.cm, respectively. This indicated that the chloride ion permeability of the material is moderate.
- The durability factor was 30%, indicating that the investigated concrete had poor capacity to resist freeze and thaw exposure.
- No visible scaling was observed during 80 cycles, indicating acceptable resistance of the mixture to salt scaling.

REFERENCES

AASHTO T358. "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration." Washington, DC (2011).

ACI Committee 325. "Report on Roller-Compacted Concrete Pavements." ACI committee report (1995).

ASTM C39. "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." West Conshohocken, PA (2010).

ASTM C157. "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete." West Conshohocken, PA (2004).

ASTM C457. "Standard Test Method for Microscopical Determination of Parameters of The Air-Void System in Hardened Concrete." West Conshohocken, PA (1998).

ASTM C469. "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." West Conshohocken, PA (2002).

ASTM C617. "Standard Practice for Capping Cylindrical Concrete Specimens." West Conshohocken, PA (1998).

ASTM C666. "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." West Conshohocken, PA (2008).

ASTM C672. "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals." West Conshohocken, PA (2008).

ASTM C1170. "Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table." West Conshohocken, PA (2010).

ASTM C1202. "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." West Conshohocken, PA (2010).

ASTM C1345. "Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer." West Conshohocken, PA (2008).

ASTM C1609. "Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (using Beam with Third-Point Loading)." West Conshohocken, PA (2010).

Mehdipour, Iman. "Characterization and Performance of Eco and Crack-Free High-Performance Concrete for Sustainable Infrastructure." Missouri University of Science and Technology (2017).

Khayat, Kamal H., and Nicolas Ali Libre. "Roller Compacted Concrete: Field Evaluation and Mixture Optimization." Missouri University of Science and Technology. Center for

Transportation Infrastructure and Safety (2014).

Iffat, Shohana. "Relation Between Density and Compressive Strength of Hardened Concrete." Concrete Research Letters 6, No. 4 (2015): 182-189.