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Development of Specifications for Engineered Cementitious Composites for Use in Bridge Deck Overlays

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Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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NEVADA DEPARTMENT OF TRANSPORTATION
Research Division
1263 S. Stewart St.
Carson City, NV 89712

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FINAL REPORT

UNIVERSITY
OF NEVADA, RENO

Pavements/Materials Program

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Environmental Engineering
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Final Report

for

NDOT Project 13-39

Submitted to
Nevada Department of Transportation

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EXECUTIVE SUMMARY

Engineered cementitious composite (ECC) material is a high strength, fiber-reinforced, ductile mortar mixture that can exhibit tensile strains of up to 5%. ECC has a dense matrix, giving the material exceptional durability characteristics. The durability and mechanical properties of ECC make it a desirable, though expensive, construction material. This study presents an extensive evaluation of modified engineered cementitious composite (MECC) using locally sourced raw materials for use as a bridge deck overlay material. MECC is a mixture of cement, fly ash, water, concrete sand, and poly-vinyl alcohol fibers. The concrete sand used in this study was used in lieu of the typically used silica sand to reduce the high material cost for ECC. Three different representative aggregates from throughout Nevada were selected to understand how the local aggregates would perform in MECC mixes. In total, eighteen different laboratory mixes of MECC were evaluated using multiple performance and mechanical tests. After the completion of the laboratory phase, two different field trials were conducted to determine the feasibility of batching large amounts of MECC at commercial concrete batch plants.

Based on the results of the laboratory evaluation, large-scale trial batches, and the analyses conducted in this study, the following conclusions and recommendations were made:

1. The laboratory test results show that MECC performed better than PCC in almost every test. Furthermore, MECC had comparable performance to the polymer concrete in most of the tests. The ductile behavior of MECC, combined with the material's superior durability and mechanical properties, make MECC a feasible material for bridge deck overlays in Nevada.

2. The large-scale trial batches showed that six cubic yard batches of MECC could be mixed in both a central-mix and dry-mix plant configurations. MECC batched on the large scale also had very similar properties to lab-mixed MECC, showing the material does not lose its hardened properties when batched on a large scale. These successful trial batches indicate that MECC can be transported in commonly available concrete trucks and can be delivered to the jobsite in a timely and uninterrupted manner during construction.

3. The aggregate source was the most influential variable in this study, signifying that selecting the appropriate aggregate for use in MECC mixes is critical. Additionally, the fiber type used also provided a great deal of influence on the MECC's performance. While the unoiled fibers cost less than the oiled fibers, the oiled fibers may be needed to produce an MECC mix meeting the required properties if a low-quality aggregate is used. The mix proportions for any MECC mixture need to be optimized for each aggregate. A certain mix proportion may work for one aggregate source, but not necessarily for another aggregate source. However, there is no substitute for choosing a sub-standard aggregate. k

4. The type of cement used can have a large influence on certain properties of the MECC. While a different cement may provide higher compressive strengths, the MECC mixture may have reduced tensile properties. When evaluating multiple cements, aggregates, or fiber types, there will be trade-offs. Multiple laboratory trial batches are needed to understand how different aggregates, cements, and mix proportions will affect the performance of an MECC mix.

CHAPTER 1: INTRODUCTION AND BACKGROUND INFORMATION

1.1 Problem Statement

A recent goal within highway design and construction has been durability and sustainability. The push to make longer-lasting highways and bridges using sustainable methods has never been greater. The Nevada Department of Transportation (NDOT) currently uses a polymer concrete for most of the non-structural overlays on bridge decks. This polymer concrete has proven to have superior performance compared to both asphalt and concrete bridge deck overlays. However, this polymer concrete is a proprietary material that has been only available from one supplier, resulting in high material cost. There is a relatively new material called engineered cementitious composites (ECC). ECC has been shown to have many desirable properties for a bridge-deck overlay, such as exceptional tensile properties, high corrosion resistance, and micro-cracking that can lead to self-healing and ductile behavior.

The purpose of this study was to determine if ECC would be suitable for use as a bridge deck overlay in Nevada. It is believed that the tensile properties and ductile behavior of ECC made with locally sourced materials could potentially replace the polymer concrete as the material for these overlays and save NDOT a significant amount of money. But because ECC is a relatively new material, there are several issues that need to be investigated. This include whether or not quality ECC can be made from the local aggregates, and if ECC can be consistently and reliably produced. In this study, commonly available and economically viable concrete sands conforming to ASTM C33 Specification for Concrete Aggregates were used as the only aggregate in the material. The use of locally available concrete sands would not only reduce the cost of ECC, but would allow for each contractor to develop their own ECC mix to pass the specification. The ECC made with the concrete sands in lieu of the silica sand is considered to be a modified ECC mixture (MECC).

1.2 Background Information

ECC is a fiber-reinforced mortar consisting of cement, fly ash, sand, water, and poly-vinyl alcohol (PVA) micro-fibers. Chemical admixtures can also be added, as needed, to modify the workability or set times of the ECC. The first ECC mixes were developed at the University of Michigan where an extensive amount of research has been conducted on ECC. These past studies showed that ECC has better performance than traditional Portland cement concrete (PCC) mixes. These studies have shown that ECC can reach tensile strain values of over 3.5%, which is vastly superior to traditional Portland cement concrete's (PCC) value of 0.01%. ECC also has the ability to form micro-cracks. These micro-cracks are very small (60 µm or 2.4 mils) and are held tight, allowing for the ECC to withstand large deflections without losing its ability to carry load (*1*).

While ECC has numerous benefits, there are a few negatives for the use of the material. First, almost all of the past work was performed on ECC material consisting of a very fine silica sand that is not commonly supplied by most aggregate pits. This silica sand consisted of more than 90% passing the No. 100 sieve size (*1*). A study by the Minnesota Department of Transportation (*2*) evaluated the use of coarse aggregates in ECC using a 3/8 inch maximum aggregate size gradation. The results showed that ECC made with coarse aggregates did not exhibit the desired tensile properties or ductile behavior that is unique to ECC. This specific silica sand is rare and only available from few suppliers within the United States, which would dramatically increase the cost to produce ECC. Additionally, the use of silica sand exclusively would impede on contractors' ability to develop innovative ECC mix designs. The use of locally available concrete sands becomes imperative in the implementation of ECC within Nevada.

1.3 Research Objectives

The laboratory experiment and field trials documented in this study had several objectives.

1. Develop multiple ECC mixes and define the expected performance of ECC using locally sourced materials. Determine how ECC mixes with different concrete sands, mix proportions, and fiber types will perform in a multitude of performance test. The MECC was compared to the polymer concrete currently used for non-structural bridge deck overlays in Nevada.

2. Determine if MECC could be mixed on a large scale at a concrete batch plant and delivered using commercially available concrete trucks. Additionally, determine if any adjustments need to be made to the standard of practice in order to batch MECC on a large scale, such as mixing sequences.

3. Determine the short-term and long-term performance of an ECC bridge deck overlay by constructing a trial overlay. Even if the MECC material has comparable performance to the polymer concrete, MCC may not perform the same in the field. A trial overlay will help determine how likely MECC overlays become implemented by NDOT.

4. Develop a specification for NDOT to allow for the use of ECC as a bridge deck overlay material throughout the state of Nevada. Using the findings from the first three objectives, a special provision will be drafted for MECC overlays. The specification will cover the minimum required MECC material properties, large-scale trial batches, and placement methods. The final version of the MECC special provision could be used by NDOT if MECC overlays are implemented in the state.

1.4 Summary of Literature Review

The first task of this research project was to conduct an extensive literature review of the most recent studies on ECC. The findings from the literature review would be used in a number of ways. First, it would help the research team become familiar with the material, to understand how it performs, and to determine the most appropriate way to evaluate the material. Second, it would show any potential problems with ECC, which would allow the research team to develop ways to improve the material. Third, the findings would be used to identify the raw materials and mix proportions that have been previously evaluated in ECC. Ultimately, the findings from the literature review would be used to shape the experimental program for this research project. The summary of the literature review is shown below. The full literature review is provided in its entirety in Appendix A.

1.4.1 Factors to Consider for ECC Mix Design

ECC mixes have a multitude of different mix proportions that can be varied and are summarized in Table 1. The critical variable was found to be the water-to-cementitious materials ratio (W/CM, CM = cement + fly ash). Various studies showed that the ideal W/CM ratio is 0.25±0.05. ECC mixes that have W/CM ratios outside of this range can still exhibit strain-hardening behavior, but will have reduced tensile strengths and tensile strains. W/CM ratios on the lower side of this range will exhibit reduced amounts of drying shrinkage cracks and higher tensile strengths and tensile strains.

Different cement types can be used depending on the intended application of the ECC. Normal Type I Portland cement is the most common cement used in ECC mixes. Type III cement and rapid-hardening cement may be used to achieve high early strength ECC where road closures need to be kept to a minimum.

To make ECC a viable construction material, fly ash should be used to minimize the unit cost. The ratio of fly ash to cement (FA/C) can vary between 0.11 and 2.8 but typical FA/C ratios were between 0.8 and 1.2. A higher FA/C ratio will reduce the amount of cement required for the ECC, but will reduce the materials resistance to scaling in the presence of a de-icing salt solution. Some ECC mixes with FA/C ratios of 2.2 and 2.8 can achieve high tensile strengths and tensile strains if the correct amounts of fly ash are used. Both fine ash, and bottom fly ash can be used in ECC mixes with high FA/C ratios whereas class F and class C fly ash are the most common types used in ECC.

The ratio of sand-to-cement (S/C) is another mix property that will reduce the unit cost of ECC. S/C ratios can range from 0.11 to 2.2, but ratios between 0.8 and 1.2 are most common. Ultimate tensile strengths were highest at a S/C ratio of 1.0. Tensile strain capacities were highest at S/C ratios between 0.8 and 1.0. ECC mixes with S/C ratios greater than 1.2 and smaller than 0.8 exhibited lower tensile strengths and tensile strains.

The amount of high-range water-reducer admixture to cementitious material ratio (HRWR, by weight) had a small effect on the tensile properties of ECC. Dosage rates can vary from 0 to 0.03, but ratios between 0.014 and 0.02 were the most common. HRWR was used primarily to increase the workability of the ECC mix. HRWR ratios above 0.02 resulted in ECC that was easier to mix in a gravity based drum mixer.

The amount of fibers used in ECC remained almost constant among the different studies. Fiber content of 2% by volume is seen in almost all of the ECC studies. Though, fiber contents of 1.7% and 2.5% were evaluated and test results showed that higher fiber contents will result in ECC that has higher tensile strengths and tensile strains. Higher fiber contents will also increase the unit cost of ECC.

The properties of fibers used in ECC varied from study to study, depending on the manufacturer. Most of the studies evaluated polyvinyl alcohol (PVA) fibers. The properties of the fibers are shown below in Table 2. The properties of the PVA fibers affect the fiber/matrix interface properties. Changing these properties affected the tensile properties of ECC. To counteract the change in interface properties, a hydrophobic oiling agent should be applied to the fiber prior to batching. Therefore, the oiling agent content (by weight of fibers) was found critical to the performance of ECC mixes because it prevents the PVA fibers from rupturing. It was critical that this oiling agent be applied to the fibers if high tensile strains are desired. Oiling agent contents from 0% to 1.2% have been evaluated. Test results showed that oiling agent contents between 0.8% and 1.2% produce the highest tensile strains and tensile strengths. Oiling agent contents less than 0.8% will only cause a slight increase in the ECC's tensile properties. The addition of oiling agent add to the cost of the fibers, and there are also concerns about the long-term durability of the oil on the fiber.

Table 3 shows the proposed ECC mix proportions for laboratory evaluation based on the findings of the literature review

Table 1: Overall Summary of ECC Mix Proportions (by Weight) and Mechanical Properties.

Ref. No. / Mix ID	**Cement**	**Sand**	**Fly Ash**	**Water**	**W/CM**	**HRWR**	**Fibers**	**Tensile strength (psi)**	**Tensile strain (%)**	**Comp. strength (ksi)**
(1)/10	1.0	1.0	None	0.45	0.450	0.03	43.8 lb/cy (26 kg/m^3)	650 (at 28 days)	3.70 (at 28 days)	Not Reported
(3) /1.2% oiling agent content	1.0 (Type I)	0.6	None	0.45	0.45	0.02	43.8 lb/cy (26 kg/m^3)	638 (at 14 days)	4.88 (at 14 days)	Not Reported
(4)/M-5	1.0 (Type I)	0.8	0.3 fly ash C 0.5 fly ash F	0.42	0.230	0.030	43.8 lb/cy (26 kg/m^3)	870	4.0	Not Reported
(6)/ECC	1.0 (Type I)	1.0	0.11 fly ash Type II	0.42	0.378	None	43.8 lb/cy (26 kg/m^3)	942 (after 26 weeks)	3.0 (after 26 weeks)	Not Reported
(11)/ECC-1	1.0 (Type I)	0.8	1.2 fly ash F	0.58	0.264	0.004	43.8 lb/cy (26 kg/m^3)	600 (after 50 cycles)	3.2 (after 50 cycles)	Not Reported
(12)/ECC G3	1.0 (Type I)	2.2	0.60 fine ash 0.79 bot. ash 0.79 fly ash F	0.91	0.286	0.019	43.8 lb/cy (26 kg/m^3)	685 (at 28 days)	4.3 (at 28 days)	Not Reported
(12)/ECC G2	1.0 (Type I)	2.2	2.2 fly ash F	0.91	0.284	0.019	43.8 lb/cy (26 kg/m^3)	696 (at 28 days)	3.9 (at 28 days)	Not Reported
(13)/Mix 7	1.0 (Composite)	0.8	None	0.55	0.550	0.010	43.8 lb/cy (26 kg/m^3)	623 (at 28 days)	2.6 (at 28 days)	Not Reported
(17)/M45	1.0 (Type I)	0.8	1.2 fly ash F	0.59	0.268	0.014	43.8 lb/cy (26 kg/m^3)	864 (at 28 days)	2.2 (at 28 days)	9 (at 28 days)
(17)/ECC #2	1.0 (Type I)	0.8	1.2 fly ash F	0.57	0.259	0.015	43.8 lb/cy (26 kg/m^3)	630 (at 28 days)	2.2 (at 28 days)	7.5 (at 28 days)
(18)/M45	1.0 (Type I)	0.8	1.2 fly ash F	0.56	0.255	0.012	43.8 lb/cy (26 kg/m^3)	860 (at 28 days)	2.2 (at 28 days)	9.3 (at 28 days)
(19)/Mix 7	1.0 (Type I)	1.4	1.4 fly ash C 1.4 fly ash F	0.81	0.213	0.003	43.8 lb/cy (26 kg/m^3)	932 (at 28 days)	2.7 (at 28 days)	8.4 (at 28 days)
(20)/ECC	1.0 (Type I)	0.8	1.2 fly ash F	0.59	0.268	0.015	43.8 lb/cy (26 kg/m^3)	640 (at 28 days)	2.2 (at 28 days)	7.5 (at 28 days)
(22)/ECC	1.0	0.8	1.2 fly ash	0.59	0.268	0.012	43.8 lb/cy (26 kg/m^3)	760 (at 28 days)	2.5 (at 28 days)	6.7 (at 28 days)

Table 2: Typical Properties of PVA Fibers Used in ECC.

Nominal Fiber Strength, σ_f^N	**Apparent Fiber Strength, σ_f^{APP}**	**Diameter D**	**Length L**	**Young's Modulus, E**	**Elongation (%)**	**Density,**
235 ksi 1,630 MPa	150 ksi 1,030 MPa	1.5 mil (39 μm)	0.5 inch (12 mm)	6,210 ksi (42.8 GPa)	6.0	2,190 lb/cy (1,300 kg/m^3)

Table 3: Proposed Mix Proportions for ECC Mixes (by Weight).

W/CM	**S/C**	**FA/C**	**Chemical Admixtures**	**Fiber**	**Oiling Agent (Weight of Fiber)**
0.24-0.26	0.8-1.0	1.2-1.6	TBD[1]	43.8 lb/cy (26 kg/m^3)	0.008-0.012

[1] To be determined

1.4.2 Expected Mechanical Properties and Durability of ECC

There are three main mechanical properties of ECC: (1) tensile strength, (2) tensile strain capacity, and (3) compressive strength. Table 1 shows a summary of the hardened mechanical properties of the highest performing ECC mixtures. Tensile strengths between 0.62 to 0.86 ksi (4.3 and 5.9 MPa) are expected after 28 days of curing. The tensile strain capacity of ECC can vary from 2 to 3% in the long-term. Test results showed that tensile strain capacity of ECC drops over time. An ECC that had a tensile strain of 5% at 10 days exhibited a tensile strain capacity of 3% after 180 days. It is expected that tensile strain capacity of 3% will remain constant over the life of the ECC mix. Compressive strengths of ECC ranged from 6.6 to 9.2 ksi (45 to 64 MPa) at 28 days. For high early strength ECC, compressive strengths of 3 ksi (20.7 MPa) were achieved in as little as 3 hours after placement.

ECC has been shown to exhibit high fatigue resistance when subjected to a monotonic bending load. It has a high flexural fatigue life compared with concrete. ECC has a high fatigue resistance when used as a bridge deck subjected to a vehicle wheel load. A bridge deck constructed out of ECC can function for over 100 years without showing any fatigue cracks. It is believed that ECC overlays would eliminate all reflective cracking from subsequent layers.

The durability of ECC is equally as important as the mechanical properties of ECC. Numerous studies have been conducted on ECC to evaluate the material's resistance to the environment. While conventional concrete samples did not survive the multiple freeze-thaw cycles, the ECC exhibited tensile strain capacities of 3%. Furthermore, ECC underwent self-healing when subjected to multiple wetting and drying cycles. ECC's ability to withstand multiple freeze-thaw cycles in the presence of de-icing salts has also been documented. ECC samples even maintained a tensile strength of 550 psi (3.8 MPa) and a tensile strain capacity of 3.4% after being subjected to 50 freeze-thaw cycles.

The long-term properties of ECC have also been evaluated. Accelerated aging studies have been carried out on ECC samples and the results showed ECC can easily retain its tensile strain capacity. ECC samples subjected to 26 weeks of accelerated aging (roughly 70 years) exhibited tensile strain capacities between 2.75% and 3.00%.

1.4.3 Production and Application of ECC

The production of ECC has been evaluated in a few different studies. The mixing sequence is just as important as the design of the ECC mix. ECC mixes can be mixed in concrete mixing trucks if they are kept in a semi-liquid state. Test results show that the gradation of the ECC sand can be an effective way of increasing the workability. The same study also evaluated seven different mixing sequences to determine which would produce the most desirable ECC mix. Field demonstrations of ECC also evaluated how to produce ECC that could be mixed in concrete trucks. When planning the Michigan ECC link slab, engineers met with the workers at the batch plant and made necessary revisions to the proposed batching sequence. The modified mixing sequence was found to produce consistent ECC that exhibited the desired mechanical properties.

The Michigan ECC link slab was constructed in the summer of 2005. The focus was to evaluate if ECC can be used as a construction material and determine if ECC used in the field will perform the same as laboratory produced ECC. The field demonstration validated the claim that ECC can be used as a construction material. The mechanical properties of the ECC were found to be sufficient and matched those of laboratory produced ECC *(6).*

ECC has also been tested extensively at the University of Nevada, Reno. Multiple studies evaluating ECC as a construction material for bridge columns have been carried out. Results showed that ECC columns outperformed the typical reinforced concrete columns when subjected to earthquake loadings. The studies showed that ECC can be successfully produced and applied in Nevada *(4, 5).*

CHAPTER 2: EXPERIMENTAL PROGRAM

2.1 Introduction

This chapter presents the experimental program for this research project. The findings from the literature review showed that a single source of fine silica sand was primarily used in ECC. In this study, multiple concrete sands from different aggregate sources were used in MECC mixes. The literature review also showed that ECC provide a number of desirable properties (such as good freeze-thaw durability). To evaluate the performance of the MECC mixes in this study, a multitude of tests were conducted on the material to evaluate its hardened mechanical and durability properties. From the literature review, multiple mix proportions for MECC mixtures were identified. From these, three mix proportions were selected and evaluated in this laboratory study. Previous studies on ECC showed that the mixing sequence would affect the quality of the material. Several mixing sequences were evaluated prior to the laboratory evaluation to determine which sequence would yield the most homogenous MECC material.

2.2 Material Information

The laboratory experiment consisted of the development and evaluation of different MECC mixes using locally available material. Mix proportions were selected based on the findings from previous research on ECC. NDOT assisted in the selection of three different and typical concrete sands sources in Nevada (Aggregates 1, 2, and 3). During the research project, the research team also obtained samples of three additional fine aggregate sources (Aggregates 4, 5, and 6). These additional fine aggregates were used to understand the influence of the different aggregate properties on the performance of MECC and were not fully evaluated like the original three fine aggregates sources. The six different concrete sands evaluated in this study were:

- Aggregate 1: Las Vegas Paving, Apex Pit, Concrete Sand
- Aggregate 2: Martin Marietta, Spanish Springs Pit, Blended Concrete Sand
- Aggregate 3: 3D Concrete, Battle Mountain Pit, Washed Concrete Sand
- Aggregate 4: 3D Concrete, Dayton Pit, Concrete Sand
- Aggregate 5: Western Nevada Materials, Tracy Clark Pit, Concrete Sand
- Aggregate 6: Cemex, Paiute Pit, Concrete Sand

Table 4 shows the properties of the three original fine aggregate sources evaluated. Table 5 shows the properties of the three additional fine aggregate sources evaluated. Figure 1 illustrates the gradations of all six fine aggregates evaluated along with the silica sand that is typically used in ECC; the original three fine aggregates (1, 2, and 3) are shown with solid lines while Aggregates 4, 5, and 6 are denoted with dashed lines. Two different fibers were evaluated in the MECC. One of the fiber types was coated in an oiling agent at a rate of 0.8% by weight of fiber, which was consistent with previous research on ECC (*3*). The second selected fiber was not coated in an oiling agent and was available for a lower cost compared to the oiled fiber. Table 6 shows the properties of the two different fibers. A locally produced Type II cement from Nevada Cement was used throughout the research project. Some MECC mixes using a second Type II cement from Lehigh Cement were also evaluated. A single source of Class F fly ash was used for all MECC mixes evaluated in this study. Table 7 shows the properties of these cementitious materials.

A polycarboxylate high-range water-reducer (HRWR) from BASF (MasterGlenium 7500) was used to adjust the workability of the MECC material to reach the target slump of 6 inches.

Table 4 Material Properties of the Original Aggregate Sources Evaluated.

	Concrete Sand Source		
Property	**Aggregate 1**	**Aggregate 2**	**Aggregate 3**
NDOT District	1	2	3
Fineness Modulus, ASTM C136/117	2.70	3.08	3.00
Bulk SDD Specific Gravity, Nev. T493	2.65	2.64	2.55
Absorption (%), Nev. T493	1.80	1.15	1.80
Sand Equivalent, Nev. T227	90	91	95
Uncompacted Voids (%), AASHTO T304	36	44	40

Table 5 Material Properties of the Additional Aggregate Sources Evaluated.

	Concrete Sand Source		
Property	**Aggregate 4**	**Aggregate 5**	**Aggregate 6**
NDOT District	2	2	2
Fineness Modulus, ASTM C136/117	2.85	2.81	3.03
Bulk SDD Specific Gravity, Nev. T493	2.59	2.60	2.58
Absorption (%), Nev. T493	2.4	3.9	2.9
Sand Equivalent, Nev. T227	82	85	88
Uncompacted Voids (%), AASHTO T304	38	38	38

Table 6 Material Properties of the PVA Fibers Evaluated.

Fiber Name	**RECS15**	**REC15**
Manufacturer	Nycon	Kuraray
Specific Gravity	1.3	1.3
Length	1/3 inch	1/3 inch
Diameter	0.038 inch	0.038 inch
Tensile Strength	240 ksi	240 ksi
Oiling Agent	None	0.8% (by weight of fiber)

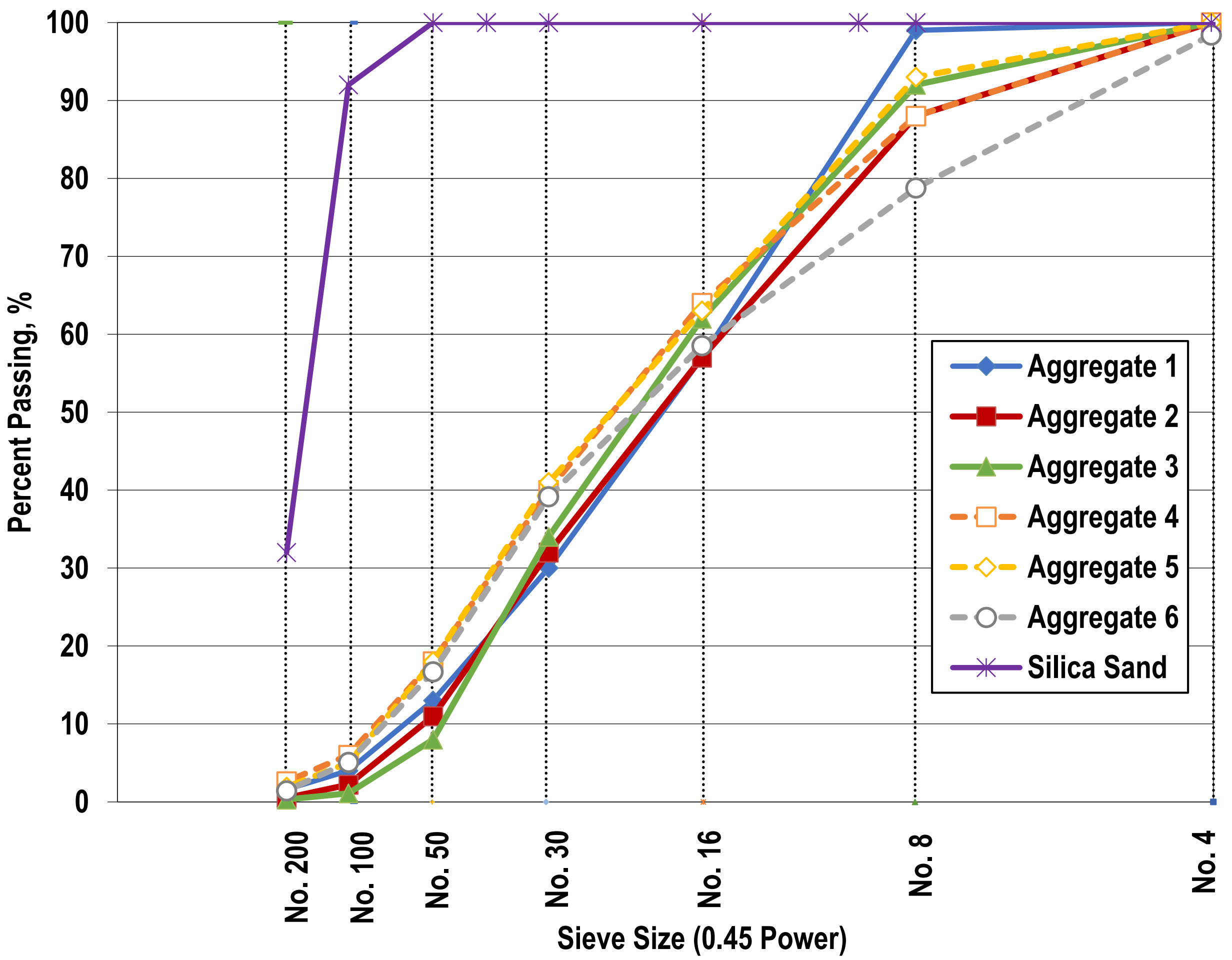

Figure 1 Gradations for Evaluated Fine Aggregate Sources (Concrete Sands) and Typically Used Silica Sand.

Table 7 Material Properties of the Cementitious Materials Evaluated.

Material	Type II Cement	Type II Cement	Class F Fly Ash
Producer	Nevada Cement	Lehigh Cement	Headwaters
Specific Gravity	3.15	3.15	2.38
Silicon Dioxide (%)	21.3	19.8	62.19
Aluminum Oxide (%)	3.8	5	18.85
Ferric (Iron) Oxide (%)	2.0	3.3	4.65
Sum of Constituents (%)	N/A	N/A	85.69
Tricalcium Silicate (%)	59	55	N/A
Dicalcium Silicate (%)	16	15	N/A
Tricalcium Aluminate (%)	7	8	N/A
Blaine Fineness (m^2/kg)	362	451	N/A
3 Day Compressive Strength (psi)	3,733	4,089	N/A
7 Day Compressive Strength (psi)	4,643	4,974	N/A

2.3 Testing Plan

To determine the applicability of using MECC as a bridge deck overlay, the material was subjected to several tests to determine the fresh and hardened properties of the MECC as shown in Table 8. Samples of a typical PCC mix and the polymer concrete were cast and tested to compare with the results of the MECC. While most of the tests in the experimental plan (Table 8) are standard test procedures, three of the tests were modified for this study: uniaxial tensile test, ductility test, and L.I.S.S.T test.

The uniaxial tensile test consisted of a dog-bone shaped specimen measuring 0.5 inches thick, 2.25 inches wide, and 11 inches long with a necked test section measuring 1 inch wide and 3.5 inches long. The specimens were stored in a chamber at 100% relative humidity (R.H.) until time of testing and were demolded 24 hours after casting. Samples were subjected to a tensile load applied by constant displacement of 0.1 mil per second. The applied load and displacement of the necked region were measured to calculate the tensile strength and tensile strain properties.

The ductility test is a modified flexural strength test in which test specimens consisted of 3-inch thick, 6-inch wide, and 21-inch long beams. The specimens were made thinner (i.e., 3 inches thick instead of 6 inches) so that the test would better represent how the material would perform in the field as a thin overlay. These thinner specimens would have less rigidity than full beams, allowing for easy observation of the ductile behavior of MECC. All specimens were stored in a chamber at 100% R.H. until time of testing. Specimens were tested in accordance with the NDOT test method T442G. The peak load applied to each test specimen was measured to calculate the flexural strength of the various MECC mixes.

The L.I.S.S.T (Louisiana Inter-layer Shear Strength Tester) was originally developed to characterize the effectiveness of tack coats between two lifts of asphalt layers. The samples are 6-inch diameter cylinders consisting of a top and bottom part, with a tack coat at the interface. The sample is laid on the side, with the bottom part fastened to resist movement. A shear load is applied to the top part of the specimen only. The peak load was recorded to calculate the bond strength.

Appendix B further discusses all of the tests performed on the hardened MECC, including pictures of test setup and test procedures.

Table 8 Summary of Tests Performed in Laboratory Evaluation.

State of Concrete	Property	Method
Fresh	Workability	Slump of fresh concrete (Nev. T438C)
	Air Content	Volume Method (Nev. T431D)
	Density	Unit Weight (Nev. T435F)
Hardened (Mechanical)	Compressive Strength	Mortar Cubes (ASTM C109)
	Tensile Strength	Uniaxial Tensile Test
	Tensile Strain	
	Ductility (Flexural Strength)	Third-point Thin Beam (Nev. T442G)
	Bond Strength	Pull-off Tester (ASTM C1583)
		Slant Shear (ASTM C882)
		Louisiana Interlayer Shear Strength Tester, L.I.S.S.T. (NCHRP 9-40)
Hardened (Durability)	Shrinkage	Length Change (ASTM C157)
	Abrasion Resistance	Rotating-Cutter (ASTM C944)
	Freeze-Thaw Durability	Rapid Repeated Cycles (ASTM C666)
	Resistance to Chloride Ion Penetration	Electrical Indication (ASTM C1202)

2.4 Mix Proportions

From the literature review summary, three different mix proportions were identified and selected for evaluation with locally sourced concrete sands and materials. The weights were adjusted to account for different specific gravities of the three sands. Table 9 shows the nomenclature used in this study to identify the different MECC mixes evaluated. As an example: M1-A1-O mix refers to the MECC mix with 0.24 W/CM, 0.8 S/C, 1.2 FA/C, Aggregate 1, and Oiled Fibers. A total of eighteen different MECC mixes (Aggregates 1, 2, and 3) were developed and evaluated in this study. Table 10 shows the detailed mix proportion for the eighteen different MECC mixes. In addition, fifteen MECC mixes were partially evaluated to better understand the influence of different cements and different aggregates on the material properties.

The PCC mix was obtained from 3D Concrete and was being produced for use in a local airport runway. The research team was able to obtain a small amount (1 cubic yard) of this PCC to cast samples. This mix consisted of water, cement, fly ash, coarse and fine aggregates, and a mid-range water reducer for increased workability. There were no other admixtures, fibers, or any additional materials added to this mix. Samples of the PPC 1121 polymer concrete were obtained from Kwik Bond Polymers. The components of the polymer concrete (resin and aggregate) were shipped to the university where these raw materials were mixed together in the lab to produce the polymer concrete samples. The mix proportions for the polymer concrete were taken from previous NDOT contracts which showed that a ratio of 14% resin to aggregates was the primary mix for the polymer concrete overlays. The amount of DDM 9 initiator and Z-Cure accelerator were based on recommendations from the supplier. Table 10 shows the mix proportions for both the PCC and polymer concrete mixes.

Table 9 Mix Nomenclature Used to Identify MECC Mixes Evaluated.

Mix Nomenclature: XX-YY-Z			
Mix Proportions (XX) (By Weight)	**Water-to-Cementitious Material (W/CM)**	**Sand (Dry) to Cement (S/C)**	**Fly Ash to Cement (FA/C)**
M1	0.24	0.8	1.2
M2	0.24	1.0	1.2
M3	0.24	1.0	1.4
Fine Aggregate (YY)		**Fiber Type (Z)**	
A1	Aggregate 1	O	Oiled
A2	Aggregate 2	U	Unoiled
A3	Aggregate 3		
A4	Aggregate 4		
A5	Aggregate 5		
A6	Aggregate 6		

Table 10 Mix Proportions for the MECC, PCC, and Polymer Mixes.

MECC Mix Proportions (lbs per cubic yard)					
Mix ID	**Cement**	**Fly Ash**	**Water**	**Sand (Dry)**	**Fibers**
M1-A1	976	1171	515	781	44
M1-A2	979	1175	517	772	44
M1-A3	972	1167	513	764	44
M2-A1	933	1119	492	933	44
M2-A2	936	1124	494	923	44
M2-A3	929	1114	490	913	44
M3-A1	867	1214	499	867	44
M3-A2	870	1218	501	857	44
M3-A3	863	1208	497	848	44
Portland Cement Concrete (PCC) Mix Proportions (lbs per cubic yard)					
Cement	**Fly Ash**	**Water**	**Coarse Aggregate**	**Fine Aggregate**	Eucon X15 (fl oz)
639	160	242	1730	966	71.9
Polymer Concrete Mix Proportions (per 100 lbs aggregate)					
Resin (fl oz)	**DDM 9 (fl oz)**	**Z-Cure (fl oz)**	**Aggregate (Dry, lbs)**		
171	3.33	0.55	100		

Note: MECC mix proportions were the same regardless of fiber type. For example, M1-A1-O and M1-A1-U have the same amount of cement, fly ash, ect.

2.5 Mixing Procedure

Previous literature on ECC showed the material was mixed using a high-speed shear-action mixer (*1*). However, these mixers would not be representative of the large gravity-based drum mixers commonly found at concrete batch plants. Discussions with local concrete experts led to the use of a mortar-mixer to mix the MECC in the laboratory. This research also showed that the mixing sequence used could drastically affect the properties of the MECC. For instance, certain mixing sequences would not adequately mix the MECC, resulting in a material that had large clumps of cement or small-sized clumps of fibers. Prior to the evaluation of the MECC, several test batches were used to evaluate four different mixing sequences. The mixing sequences were judged based on how well the MECC material was mixed and whether or not there were any clumps of cement or fibers present. None of the four mixing sequences evaluated caused cement or fiber clumping in the MECC. But because mixing sequence No. 4 produced the most homogeneous and consistent MECC material, it was the mixing sequence used throughout the experimental plan. Table 11 shows the various mixing sequences that were evaluated in this study.

Table 11 Mixing Sequences Evaluated Prior to Laboratory Testing.

Mixing Sequence No.	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
1	100% Water	100% Sand	100% Fly Ash	100% Cement	100% Fibers	
	0.5 Min	0.5 Min	2 Min	3 Min	5 Min	
2	75% Water	100% Sand	100% Fly Ash	100% Cement + 25% Water	100% Fibers	
	0.5 Min	0.5 Min	2 Min	4 Min	3 Min	
3	75% Water	100% Sand	100% Fly Ash + 50% HRWR	100% Cement + 25% Water	100% Fibers	50% HRWR
	0.5 Min	0.5 Min	2 Min 30 Sec	4 Min	5 Min	30 Sec
4*	75% Water	100% Sand	100% Fly Ash + 100% HRWR	100% Cement + 25% Water	100% Fibers	
	0.5 Min	0.5 Min	2 Min 30 Sec	4 Min	5 Min	

Note: *Mixing Sequence 4 was used throughout study.

CHAPTER 3: TEST RESULTS AND DISCUSSIONS

3.1 Introduction

This chapter presents the laboratory test results of this study. The results for each test are grouped by the Aggregate, Mix Proportions, and Fiber Type. This helps to show how the MECC's properties changed when using different aggregates, mix proportions, and fiber types. In addition to graphs, the average values for each mix are shown in tables to show the test results for each mix. While the test results may suggest certain mixes performed better than others, these differences may not be statistically significant when taking into account the variability of the test results. Chapter 5 discusses the statistical analysis performed on these test results and whether or not the differences between certain mixes were statistically significant.

3.2 Fresh Properties

The target slump of all laboratory MECC mixes was 6 inches. This was achieved by adjusting the amount of HRWR that was added to the mix. About 0.7 gallons of HRWR per cubic yard was needed to achieve this level of workability for all eighteen MECC mixes. There was no air-entrainment admixture within the MECC, so the air content readings were a measurement of the entrapped air. On average, all MECC mixes had between 1% and 2% air content. The unit weight of the MECC is critical because an overlay represents a dead load on the bridges, and should be kept to a minimum. Test results show that all eighteen MECC mixes had a unit weight of between 125-130 pounds per cubic foot. Table 12 breaks down the fresh properties for each of the MECC mixes.

Table 12 Fresh Properties of MECC Mixes.

Mix ID	Slump (in.)	Air Content (%)	Unit Weight (pcf)
M1-A1-O	6.25	1.2	129
M1-A1-U	6.00	1.2	128
M2-A1-O	6.00	1.3	128
M2-A1-U	6.25	1.4	126
M3-A1-O	5.75	1.2	127
M3-A1-U	6.00	1.1	130
M1-A2-O	6.00	1.3	129
M1-A2-U	5.75	1.4	127
M2-A2-O	6.00	1.3	126
M2-A2-U	5.75	1.5	127
M3-A2-O	5.75	1.9	125
M3-A2-U	6.00	1.5	126
M1-A3-O	6.25	1.4	127
M1-A3-U	6.25	1.8	125
M2-A3-O	6.25	1.6	126
M2-A3-U	6.00	1.3	130
M3-A3-O	6.50	1.8	125
M3-A3-U	6.25	1.5	128

3.3 Compressive Strength

The compressive strengths for the MECC mixes and polymer concrete were measured at 0.5, 1, 1.5, 3, 7, and 28 days after mixing. Because of the size of coarse aggregate in the PCC, it was not possible to ca`st cube samples for this material (2 in by 2 in by 2 in.). Table 13 show the compressive strength test results for the MECC mixes and the polymer concrete mix. Overall, the MECC mixes had average compressive strengths of 2,000 psi at 0.5 days, 3,400 psi at 1 day, 4,500 psi at 1.5 days, 5,100 psi at 3 days, 6,100 psi at 7 days, and 8,000 psi at 28 days. When compared to the polymer concrete, the MECC had lower early-age compressive strengths. It wasn't until 7 days that the compressive strengths for MECC and the polymer concrete were the same value. However, after 7 days, all the evaluated MECC mixes had higher compressive strengths at 28 days when compared to the polymer concrete material. The polymer concrete had about 1,000 psi higher compressive strengths than the MECC mixes during the first 3 days. At 28 days, the MECC mixes had about 2,000 psi higher compressive strengths than the polymer concrete.

Figures 2 to 5 show the compressive strength results when grouped based on the aggregate used in the MECC mixes. These graphs show that there is a small difference between the oiled and unoiled fibers. During the first 3 days, there is only a small difference between mixes with different fibers. However, this difference becomes apparent at 7 days, where the oiled fiber mixes are on average about 400 psi lower than the unoiled fiber mixes. What also was apparent is that the mix proportions appear to have only a small influence on the compressive strengths of the MECC mixes. This is most apparent in Figure 5. Mixes with Aggregates 2 and 3 had approximately the same compressive strengths at all ages. However, mixes with Aggregate 1 had lower compressive strengths. These differences existed at very early ages (0.5 days, a difference of 1,000 psi) and after 3 days (where the differences are all about 1,000 psi). This suggests that the aggregate used in the MECC mixes is the most important variable to achieve high compressive strengths.

Figures 6 to 9 show the compressive strength results when grouped based on the mix proportions used in the MECC mixes. These figures show that there is a large difference between mixes with different aggregates, regardless of the mix proportions. For each of the three mix proportions evaluated, mixes with Aggregate 2 had the highest compressive strengths while mixes with Aggregate 1 had the lowest compressive strengths. Figure 9 shows that on average, there is no difference between mixes with mix proportions 1, 2, and 3. This suggests that the mix proportions have no influence on the compressive strengths, confirming that the aggregate used in the MECC mixes is the most influential variable for compressive strengths.

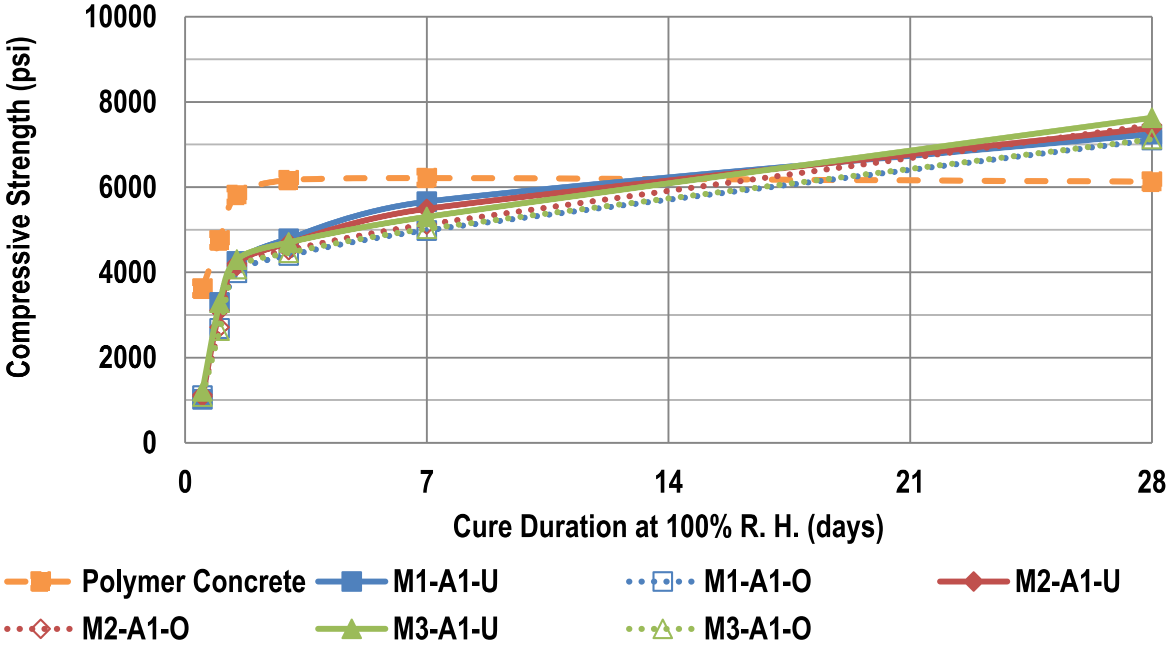

Figure 2 Compressive Strengths for Mixes with Aggregate 1.

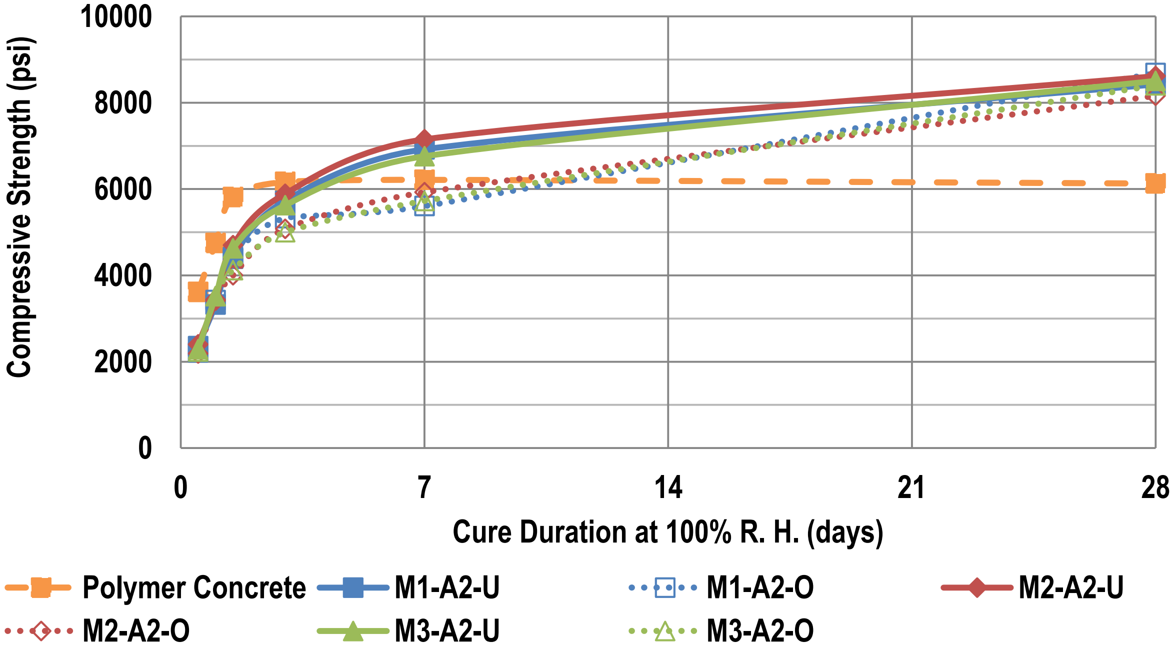

Figure 3 Compressive Strengths for Mixes with Aggregate 2.

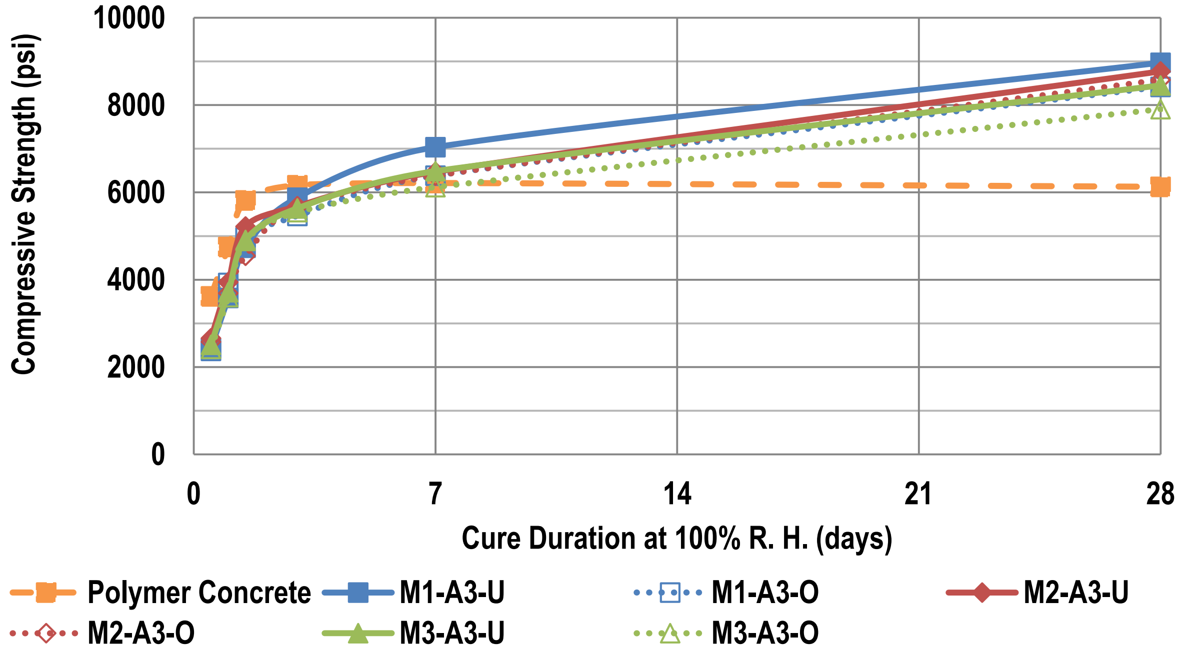

Figure 4 Compressive Strengths for Mixes with Aggregate 3.

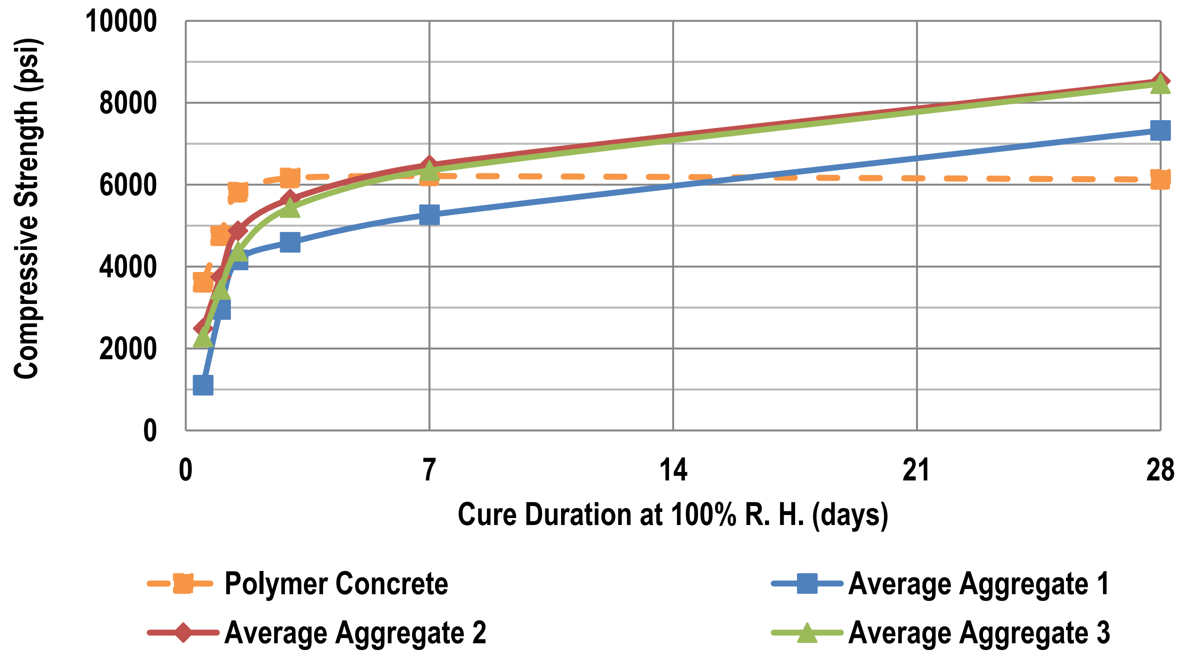

Figure 5 Average Compressive Strengths for Mixes with Aggregates 1, 2, and 3.

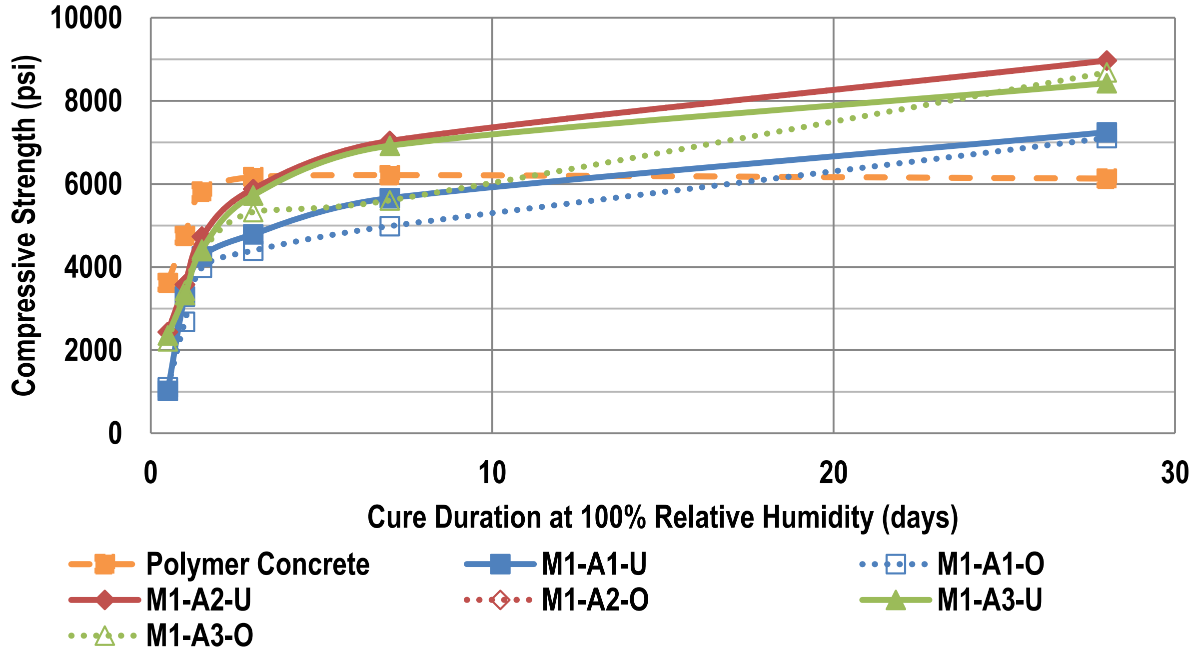

Figure 6 Compressive Strengths for Mixes with Mix Proportion 1.

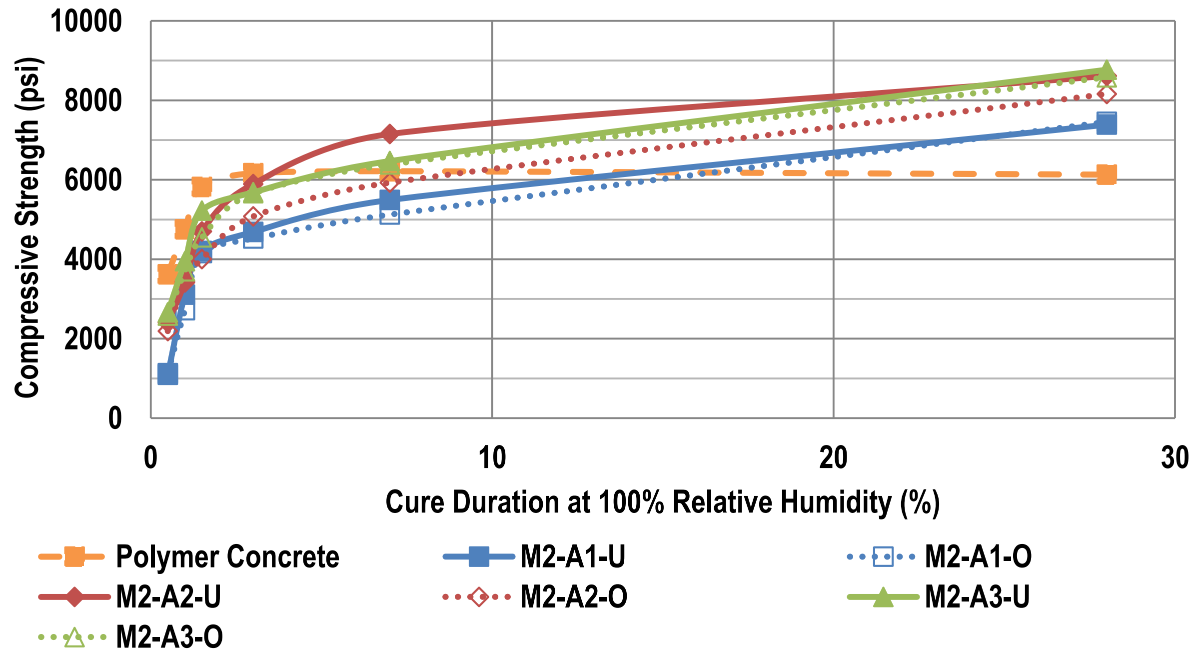

Figure 7 Compressive Strengths for Mixes with Mix Proportion 2.

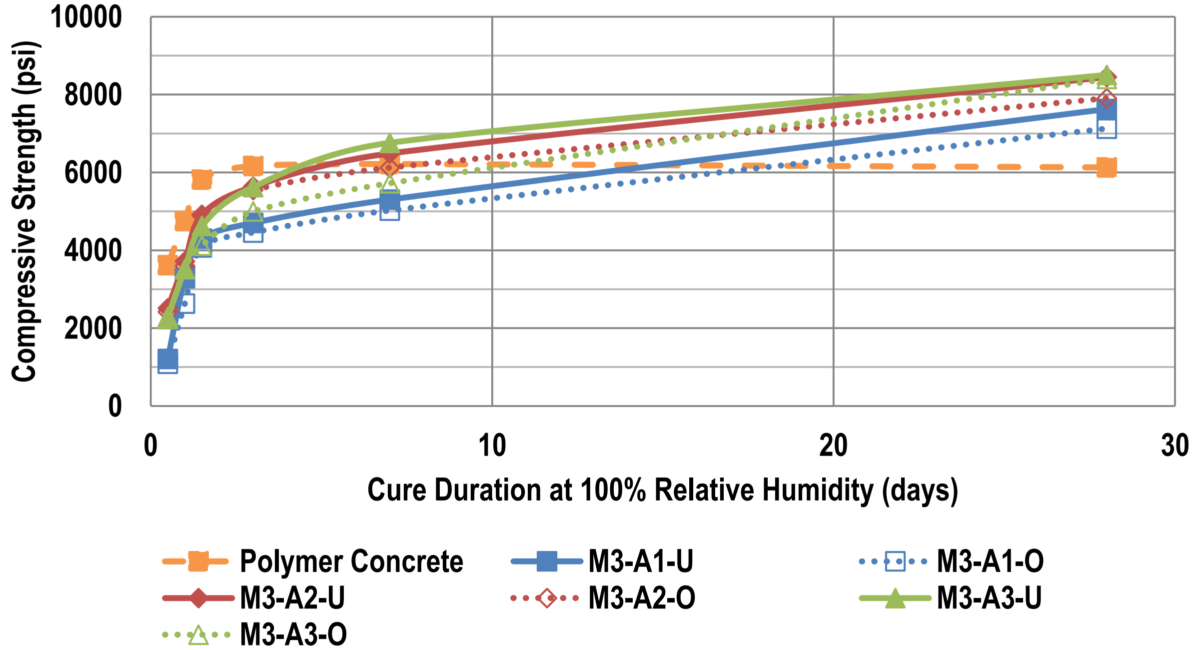

Figure 8 Compressive Strengths for Mixes with Mix Proportion 3.

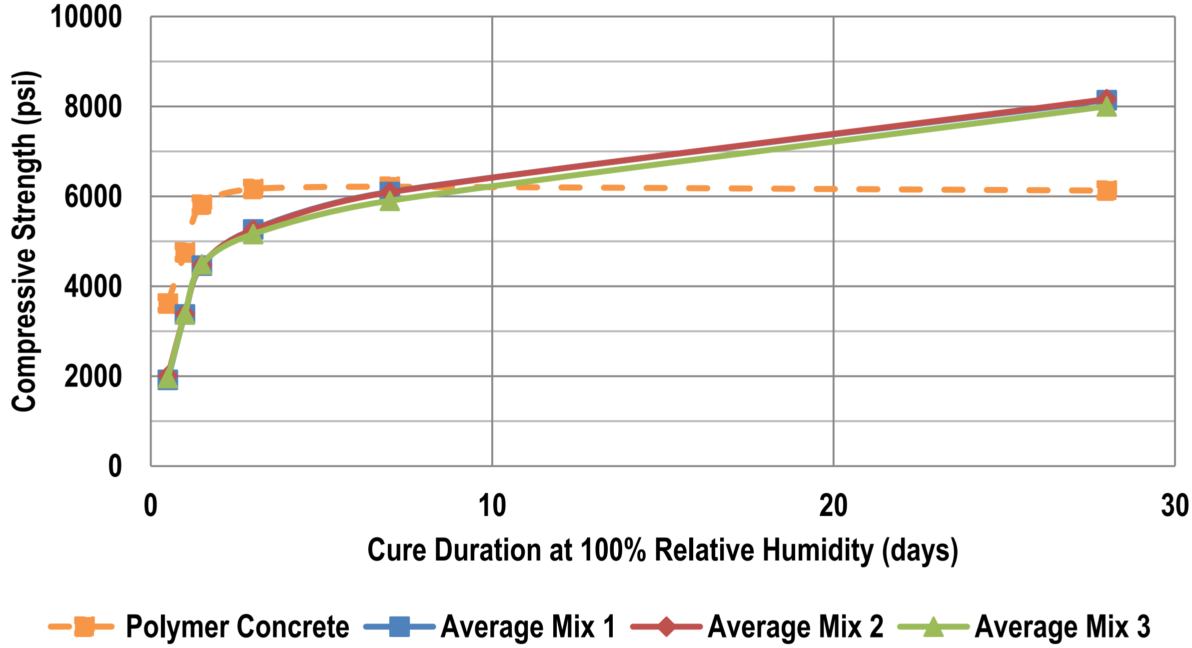

Figure 9 Average Compressive Strengths for Mixes with Mix Proportion 1, 2, and 3.

Table 13 Summary of Compressive Strength Results (in psi).

Mix ID	0.5 Day	1 Day	1.5 Days	3 Days	7 Days	28 Days
M1-A1-O	1,116	2,706	3,984	4,396	4,995	7,104
M1-A1-U	1,028	3,302	4,270	4,804	5,658	7,230
M2-A1-O	887	2,718	4,156	4,556	5,110	7,465
M2-A1-U	1,096	2,864	4,207	4,652	5,515	7,369
M3-A1-O	1,090	2,630	4,084	4,438	5,004	7,115
M3-A1-U	1,212	3,286	4,301	4,723	5,298	7,605
M1-A2-O	2,381	3,899	4,978	5,437	6,389	8,407
M1-A2-U	2,439	3,341	4,727	5,886	7,027	8,953
M2-A2-O	2,587	3,717	4,561	5,644	6,377	8,561
M2-A2-U	2,660	3,960	5,216	5,977	6,482	8,763
M3-A2-O	2,410	3,614	4,910	5,537	6,114	7,894
M3-A2-U	2,514	3,719	4,920	5,627	6,440	8,431
M1-A3-O	2,214	3,442	4,385	5,317	5,580	8,716
M1-A3-U	2,347	3,324	4,441	5,715	6,905	8,400
M2-A3-O	2,183	3,453	4,027	5,059	5,898	8,163
M2-A3-U	2,416	3,422	4,712	5,888	7,138	8,591
M3-A3-O	2,213	3,518	4,124	4,997	5,696	8,403
M3-A3-U	2,306	3,525	4,600	5,595	6,780	8,504
Polymer	3,618	4,752	5,816	6,165	6,214	6,128

3.4 Tensile Properties

The tensile properties of the MECC and polymer concrete mixes were evaluated at 3 and 28 days after mixing. It was not possible to determine the tensile properties of the PCC using the proposed procedure because of the size of the coarse aggregates in PCC. Table 14 summarizes the results of the tensile test. On average, the MECC had 3 and 28-day tensile strength of 580 psi and 700 psi, respectively. The polymer concrete mix had a 3-day and 28-day tensile strength of 643 psi and 744 psi, respectively. The MECC also had an average 3-day and 28-day tensile strain of 0.78% and 0.89%, respectively. However, the polymer concrete had a brittle behavior with tensile strains of 0.22% at 3 days and only 0.057% at 28 days. While some MECC mixes had comparable tensile strengths with the polymer concrete, all MECC mixes had higher tensile strains at both 3 and 28 days.

Figures 10 and 11 show the 3-day tensile properties of the MECC mixes as grouped based on the fine aggregates used. The results show that on average, the oiled fiber mixes had higher 3-day tensile strengths (50 psi) and tensile strains (0.16%) compared to the mixes with unoiled fibers. These graphs show that the tensile strengths may be slightly influenced by the fine aggregates source used in the mixes, as mixes with Aggregate 3 on average had the lowest 3-day tensile strengths (519 psi) and tensile strains (0.559). Mixes with Aggregate 1 had average tensile strengths of 615 psi and tensile strains of 1.04% while mixes with Aggregate 2 had average strengths of 629 psi and 0.76%.

Figures 12 and 13 show the 28-day tensile properties when grouped by mix proportions used. The results show that on average, the oiled fiber mixes had higher 28-day tensile strengths (100 psi) and tensile strains (0.12%) compared to the mixes with unoiled fibers. These figures show that there is little difference between the tensile strength values between groups, indicating that the aggregate may not have a big influence on the tensile strengths. Mixes with Aggregate 1 had 28-day tensile strengths of 700 psi, which was lower than mixes with Aggregate 2 (732 psi), and roughly the same as mixes with Aggregate 3 (694 psi). However, the 28-day tensile strains do appear to be influenced by the aggregate used. Mixes with Aggregate 3 had the lowest tensile strains of 0.61%, while mixes with Aggregate 1 and 2 were on average equal with values of 1.04% and 1.01%, respectively. This suggests that the tensile strain of the MECC material may be influenced by the fine aggregate source used.

Figures 14 and 15 show the 3-day tensile properties of the MECC mixes as grouped by the mix proportions used. When looking at the tensile strengths, there are differences within the groups, suggesting again, that the aggregate may have a small influence on the early age tensile strengths. The average values for mixes with Mix Proportions 1, 2, and 3 were 585 psi, 570 psi, and 607 psi, respectively. When taking into account the test variability, these small differences may not be statistically significant, indicating that the mix proportions have little or no effect on the 28-day tensile strengths. The same is true for the tensile strains, as the difference between mixes with different aggregates is apparent. The average values for mixes with Mix Proportions 1, 2, and 3 were 0.89%, 0.72%, and 0.75% respectively.

Figures 16 and 17 show the 28-day tensile properties of the MECC mixes grouped by mix proportions. These figures show that there is not a big difference between the mixes with different mix proportions. The average values for mixes with Mix Proportions 1, 2, and 3 were 704 psi, 712 psi, and 709 psi, respectively. These differences are very small and suggest the mix proportions have no effect on the 28-day tensile strengths of MECC. However, there are some differences within the groups, suggesting that the fine aggregates may have a small influence on the tensile strengths. The tensile strain values showed similar trends. The average values for mixes with Mix Proportions 1, 2, and 3 were 1 %, 0.63%, and 1.02% respectively. While the fine aggregates had a large influence on the 28-day tensile strains, it would also appear that the mix proportions also can affect the MECC materials performance. However, Chapter 7 discusses the statistical analyses of the test results and identifies which variables significantly influence the tensile properties of the MECC material.

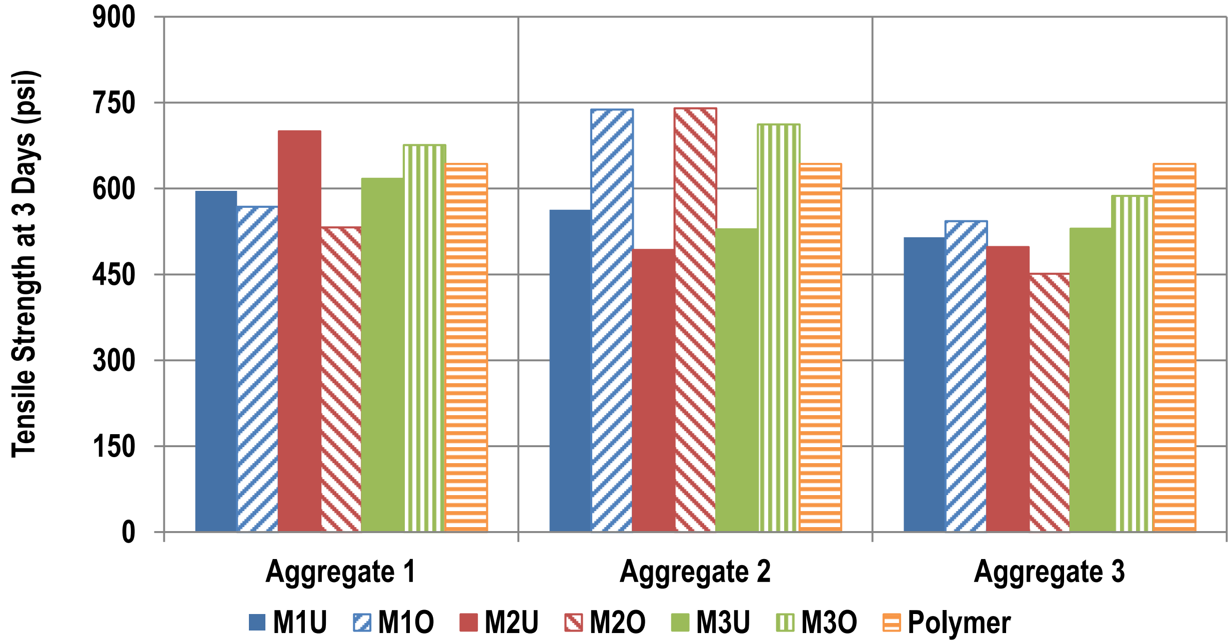

Figure 10 Tensile Strength Values at 3 Days by Aggregate.

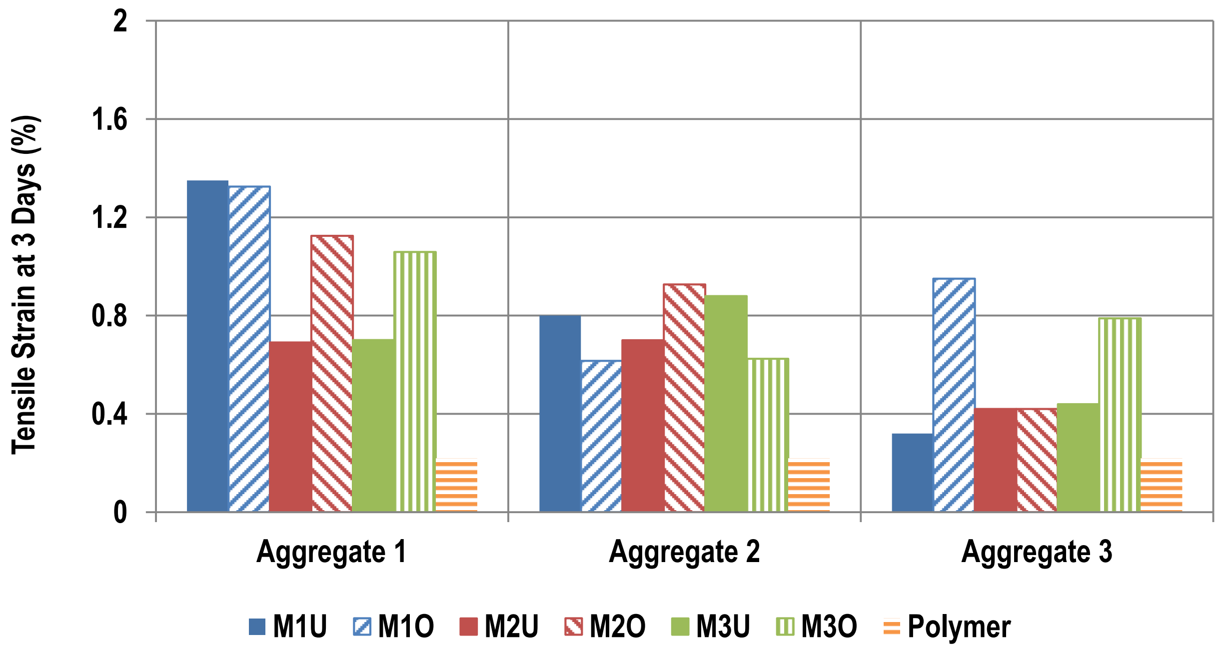

Figure 11 Tensile Strain Values at 3 Days by Aggregate.

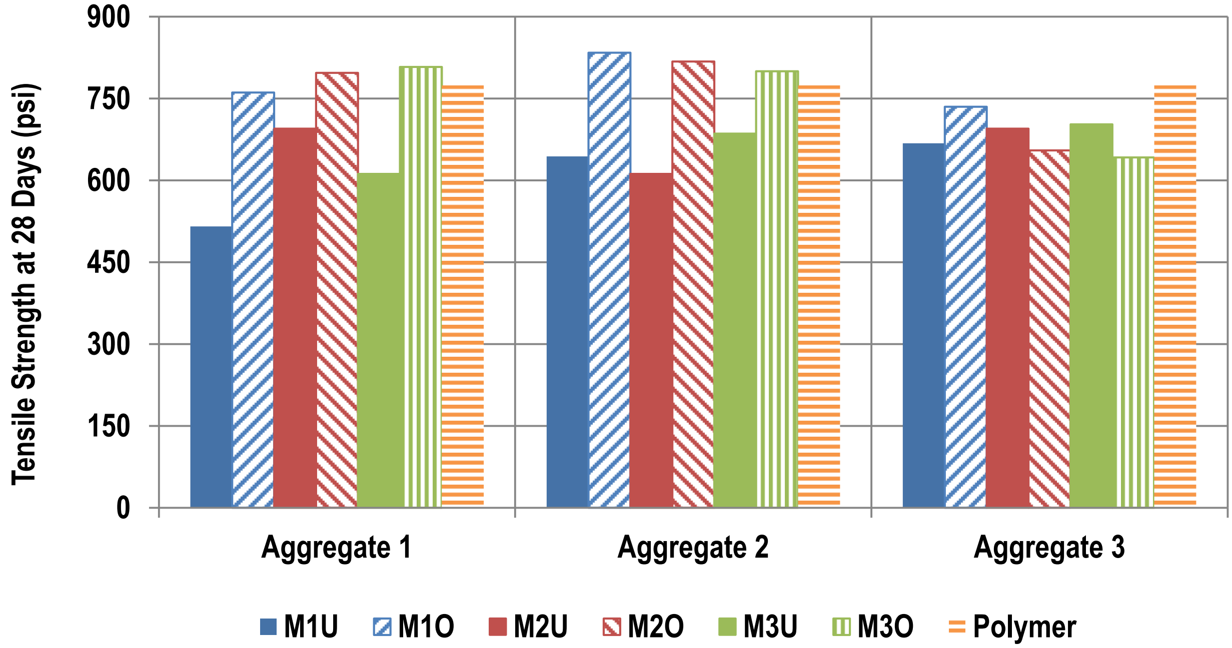

Figure 12 Tensile Strength Values at 28 Days by Aggregate.

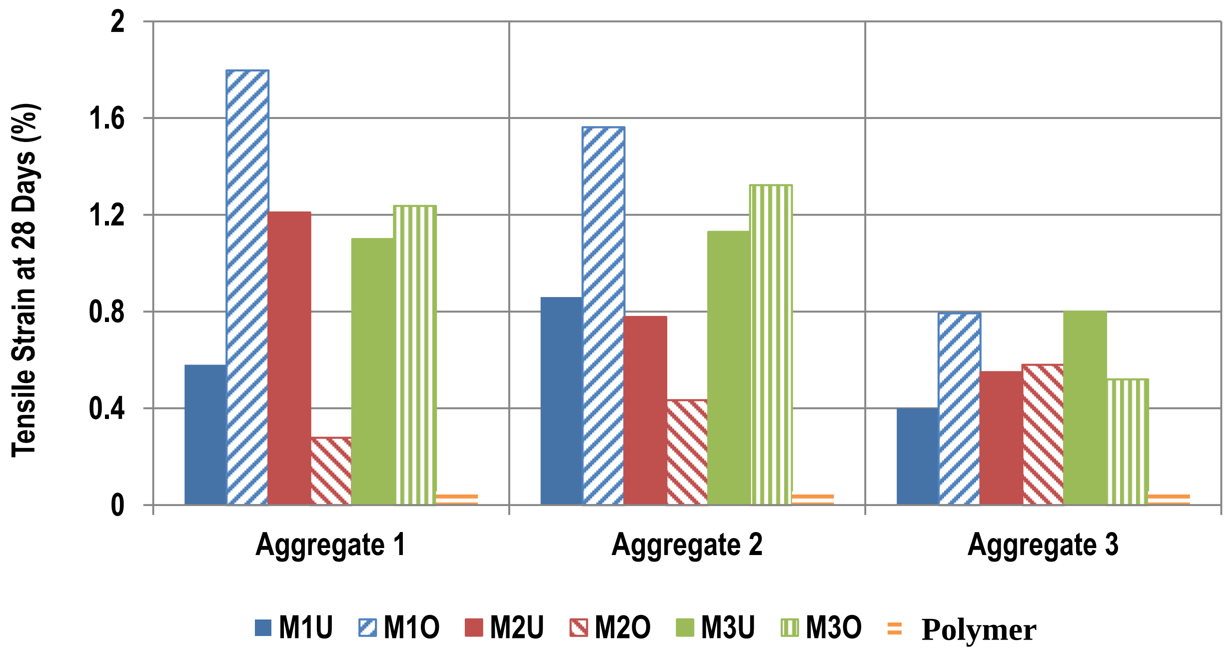

Figure 13 Tensile Strain Values at 28 Days by Aggregate.

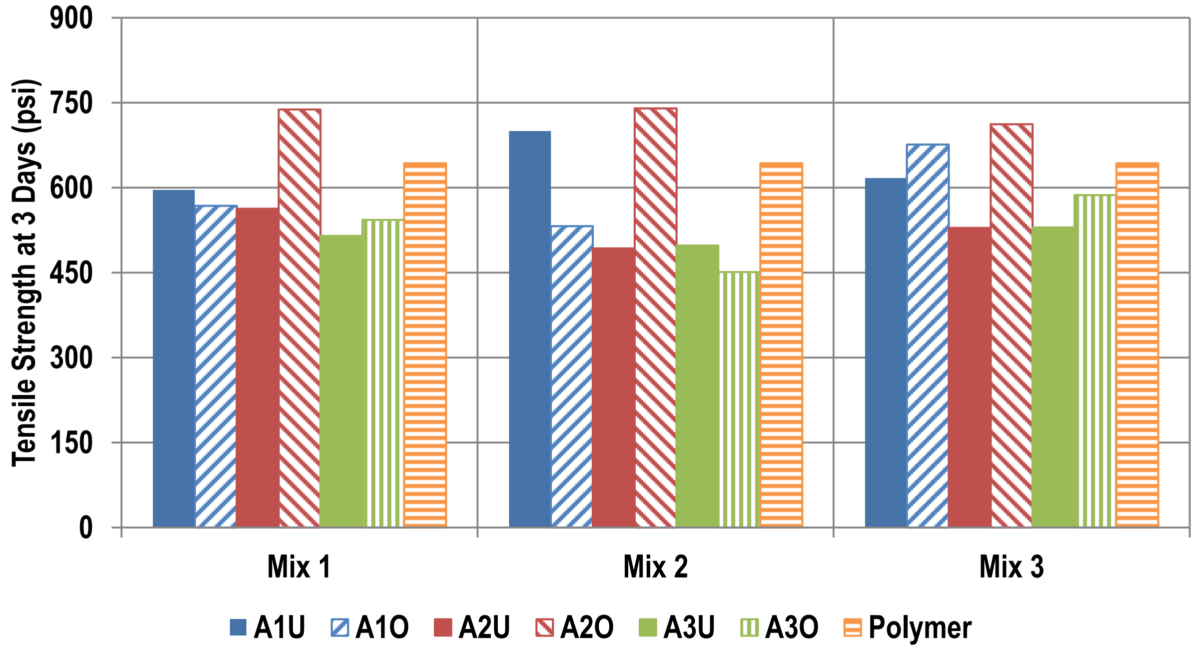

Figure 14 Tensile Strength Values at 3 Days by Mix Proportions.

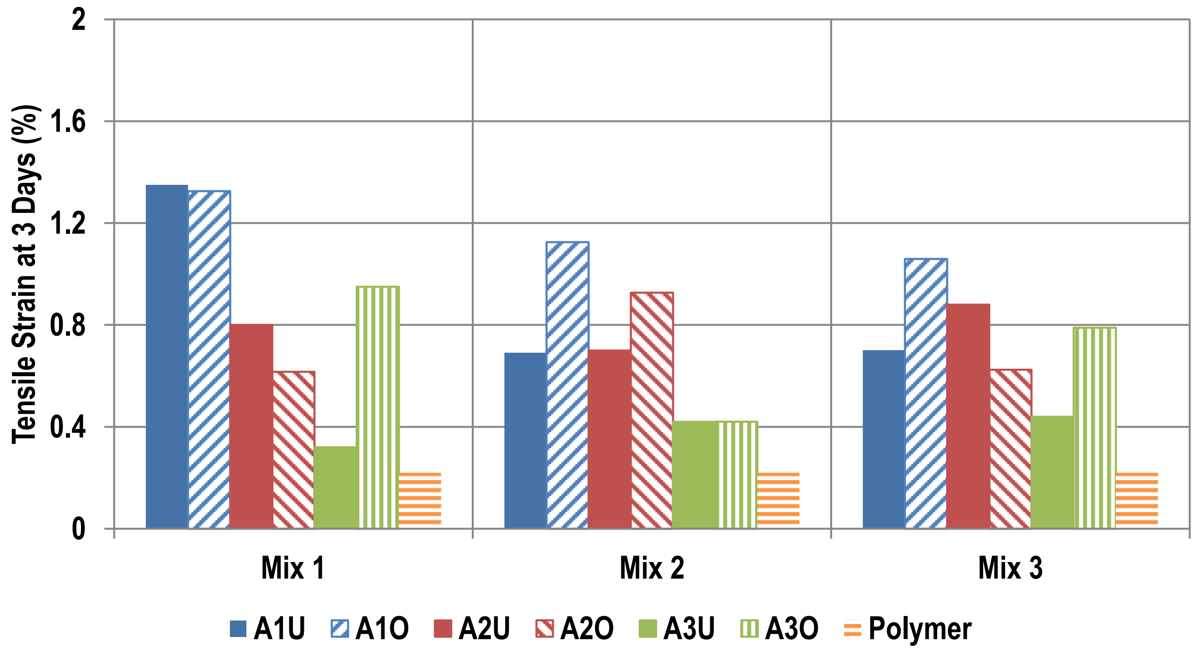

Figure 15 Tensile Strain Values at 3 Days by Mix Proportions.

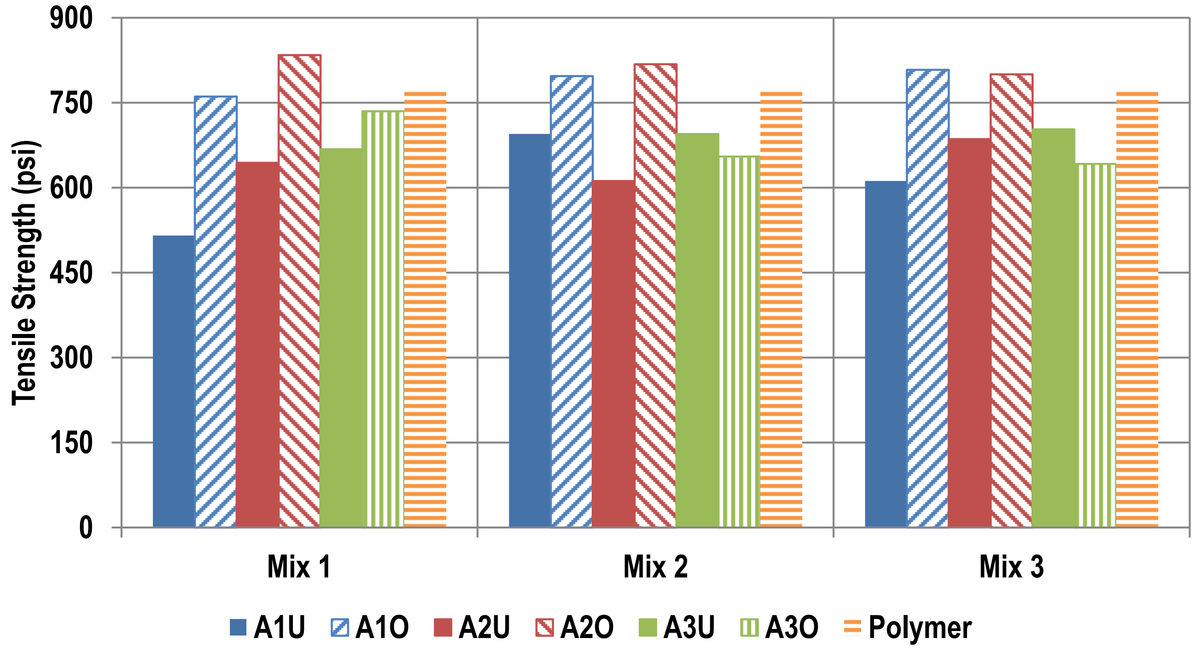

Figure 16 Tensile Strength Values at 28 Days by Mix Proportions.

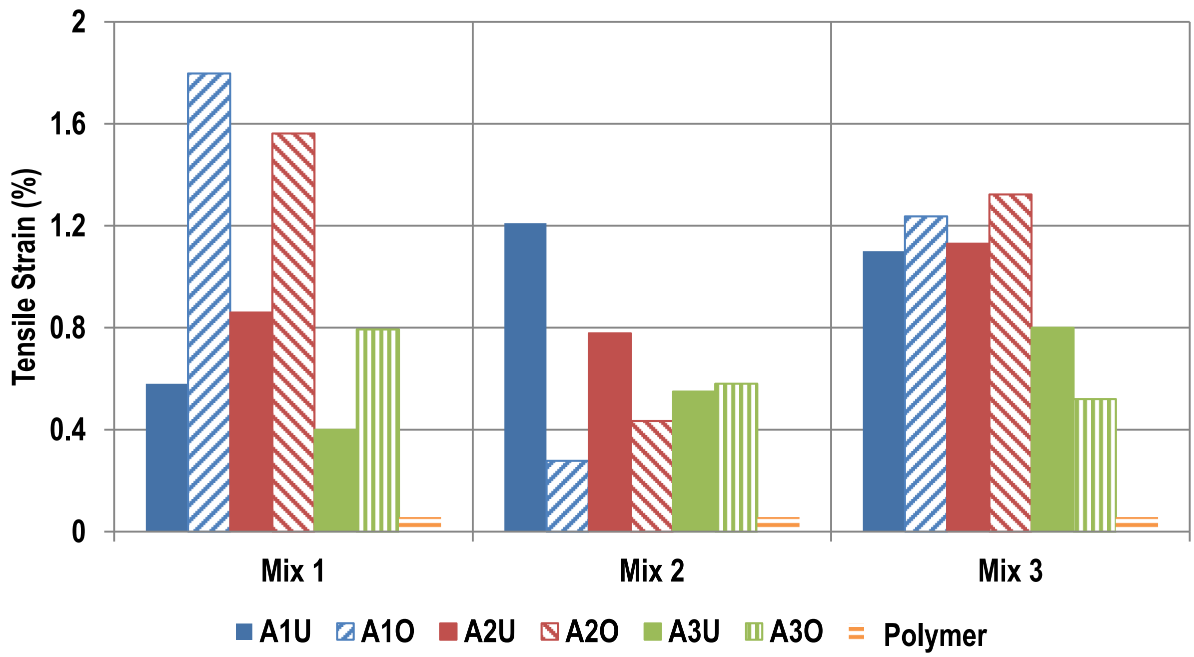

Figure 17 Tensile Strain Values at 28 Days by Mix Proportions.

Table 14 Summary of Tensile Test Results.

Mix ID	Three Days		Twenty-Eight Days	
	Tensile Strength (psi)	Tensile Strain (%)	Tensile Strength (psi)	Tensile Strain (%)
M1-A1-O	566	1.31	759	1.80
M1-A1-U	595	1.34	516	0.58
M2-A1-O	532	1.15	802	0.27
M2-A1-U	707	0.69	692	1.22
M3-A1-O	676	1.05	809	1.23
M3-A1-U	611	0.70	615	1.11
M1-A2-O	739	0.60	832	1.54
M1-A2-U	563	0.81	647	0.86
M2-A2-O	738	0.92	817	0.42
M2-A2-U	492	0.70	614	0.77
M3-A2-O	712	0.63	797	1.35
M3-A2-U	528	0.88	686	1.13
M1-A3-O	535	0.95	737	0.80
M1-A3-U	516	0.32	732	0.42
M2-A3-O	449	0.42	647	0.57
M2-A3-U	498	0.43	697	0.55
M3-A3-O	589	0.79	647	0.52
M3-A3-U	530	0.44	702	0.80
Polymer	643	0.22	744	0.06

3.5 Ductility

The ductility test was conducted after 3 and 28 days of curing. Because of shortage of oiled fibers, no samples with the oiled fibers were cast or tested. In addition to the flexural strength, the center-point deflection of each beam samples was recorded. The deflection values reported were the deflection of the beam at the time of when the peak flexural strength occurred. Table 15 summarizes the results of the ductility test for the MECC mixes, polymer concrete, and PCC.

Figures 18 to 21 show the 3-day test results of the ductility test. MECC mixes had 3-day strengths between 725 and 1,000 psi. These values were lower than the polymer concrete strength of 1,250 psi. On average, mixes with Aggregate 1, 2, and 3 had flexural strengths of 915 psi, 792 psi, and 772 psi, respectively. The MECC mixes had 3-day deflections between 0.097 in. and 0.165 in. The polymer concrete had a deflection of only 0.053 in. On average, mixes with Aggregate 1, 2, and 3 had deflections of 0.131 in., 0.136 in., and 0.121 in., respectively. On average, mixes with Mix Proportions 1, 2, and 3 had flexural strengths of 791 psi, 823 psi, and 865 psi, respectively. Additionally, mixes with Mix Proportions 1, 2, and 3 had deflections of 0.138 in., 0.123 in., and 0.128 in., respectively.

Figures 22 to 25 show the 28-day test results of the ductility test. MECC mixes had 28-day strengths between 750 and 1,100 psi. These values were lower than the polymer concrete strength of 1,700 psi. However, the MECC mixes had vastly higher flexural strengths when compared to the PCC mix which had a strength of only 400 psi. On average, mixes with Aggregate 1, 2, and 3 had flexural strengths of 962 psi, 960 psi, and 1,005 psi, respectively. The MECC mixes had 28-day deflections between 0.021 in. and 0.063 in. The polymer concrete had a deflection of only 0.051 in, and the PCC had a deflection of only 0.012 in. On average, mixes with Aggregate 1, 2, and 3 had deflections of 0.033 in., 0.057 in., and 0.049 in., respectively. On average, mixes with Mix Proportions 1, 2, and 3 had flexural strengths of 1,058 psi, 937 psi, and 932 psi, respectively. Additionally, mixes with Mix Proportions 1, 2, and 3 had deflections of 0.052 in., 0.033 in., and 0.049 in., respectively. The purpose of looking at the deflections was to determine the feasibility of using the ductility test for QA/QC instead of the direct tensile test, for simplicity. However, the test results showed that there is almost no difference between the 28-day deflections. This is possibly due to the stiffness of the beams resisting the movement, regardless of the properties of the material within the beam samples.

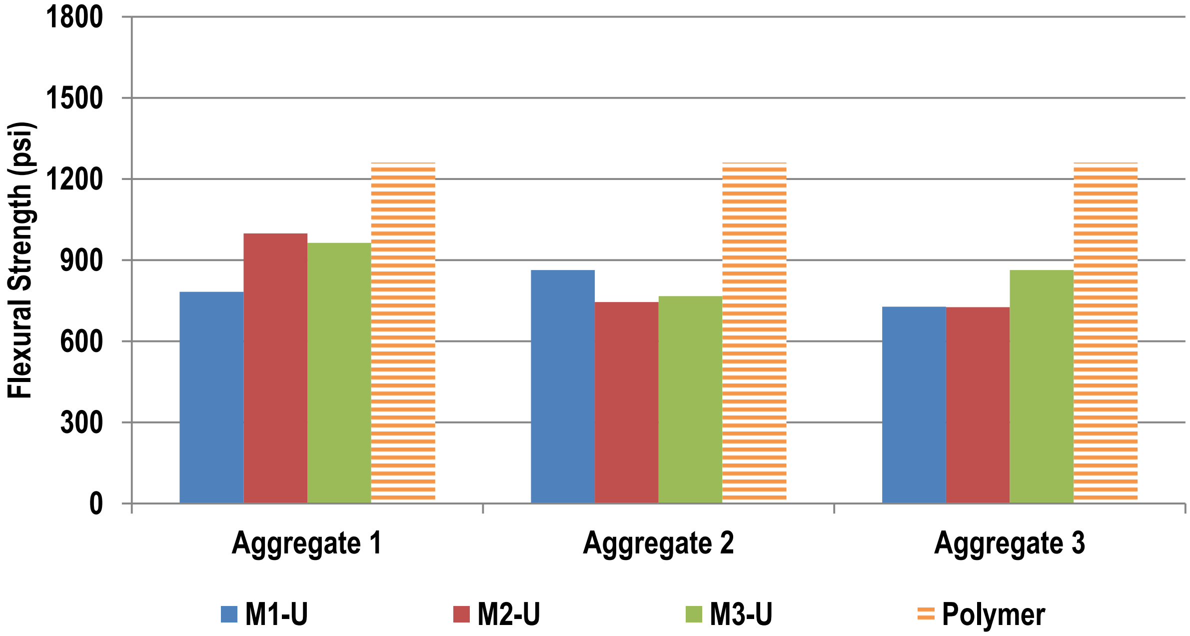

Figure 18 Three-Day Flexural Strength Results when Grouped by Aggregate Used.

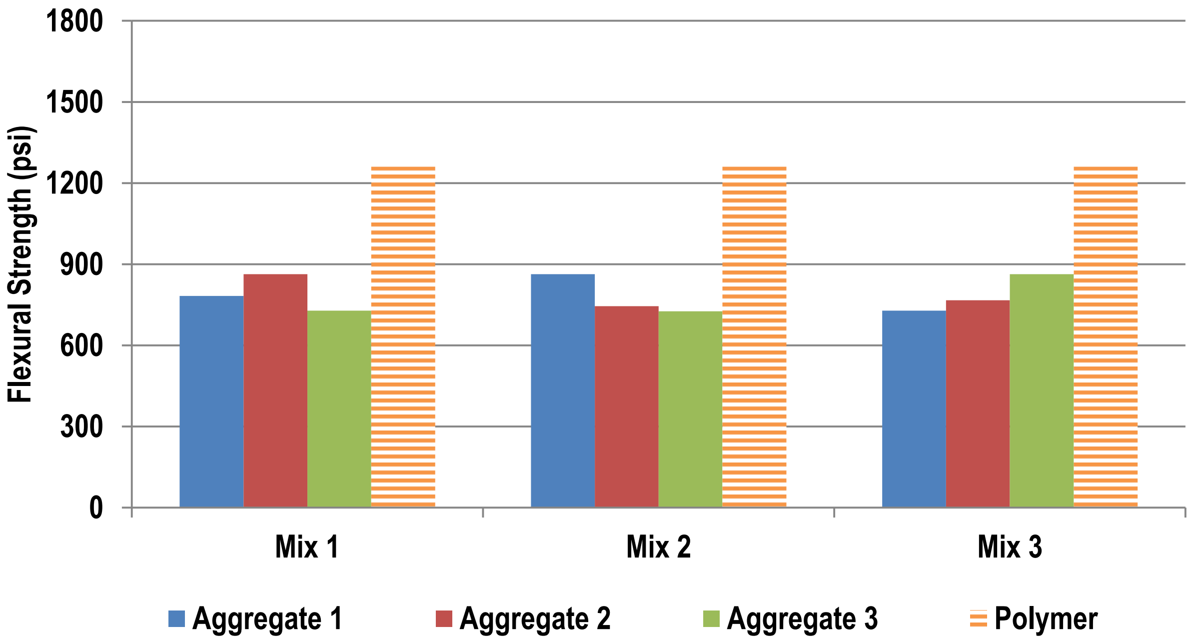

Figure 19 Three-Day Flexural Strength Results when Grouped by Mix Proportions Used.

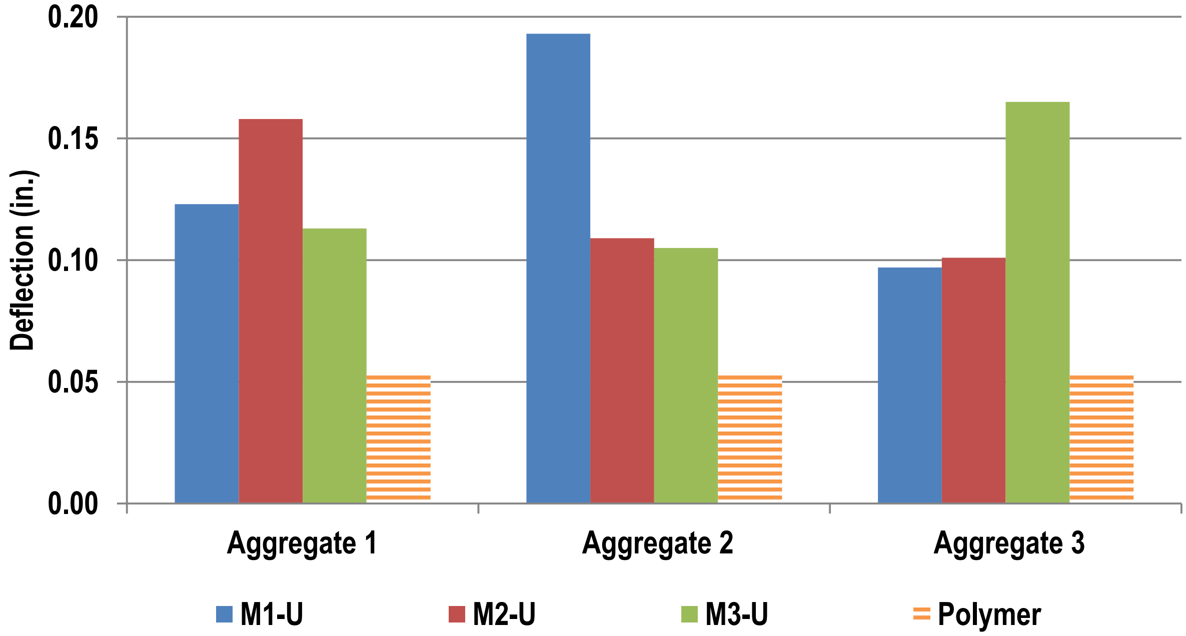

Figure 20 Three-Day Beam Deflections when Grouped by Aggregate Used.

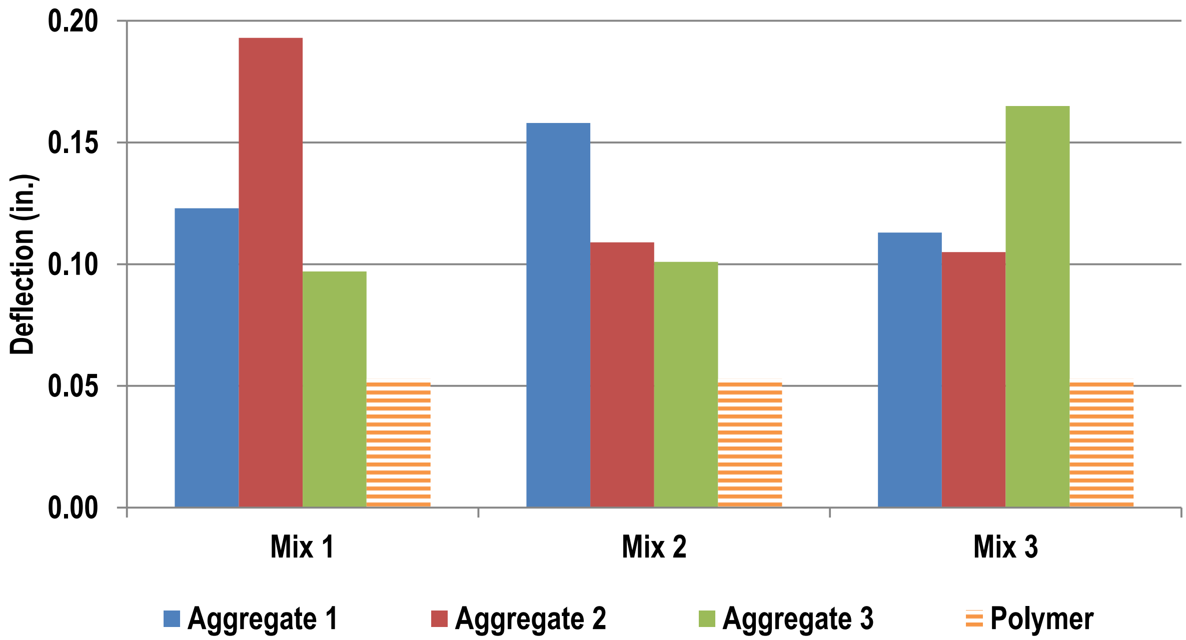

Figure 21 Three-Day Beam Deflections when Grouped by Mix Proportions Used.

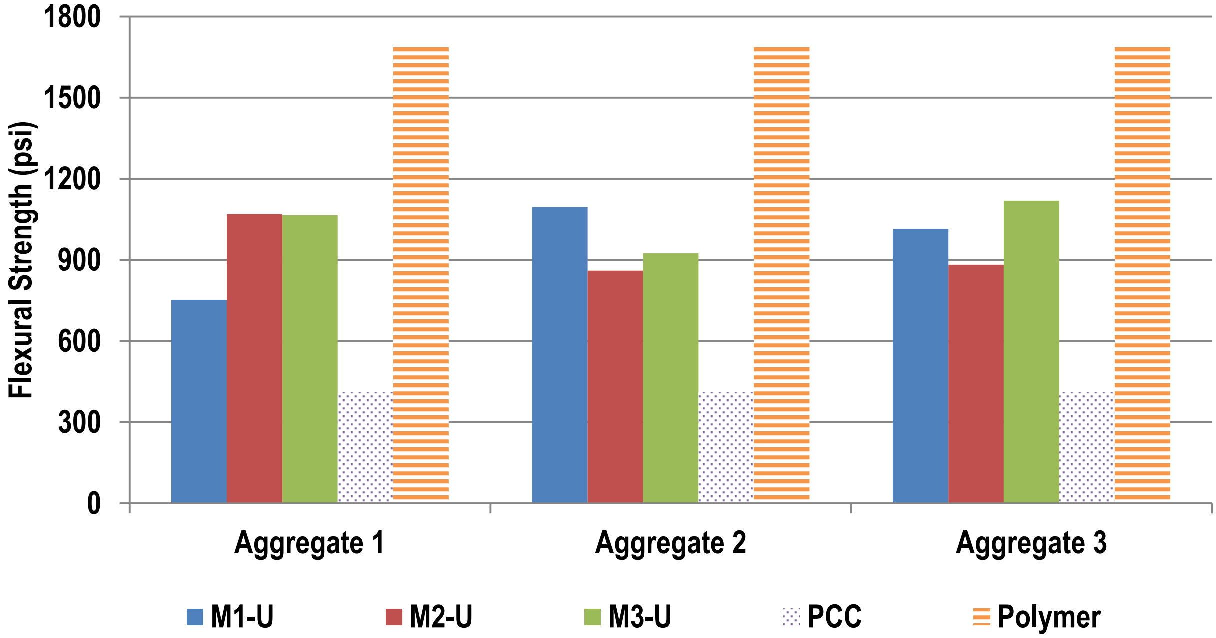

Figure 22 Twenty-Eight Day Flexural Strength Results when Grouped by Aggregate Used.

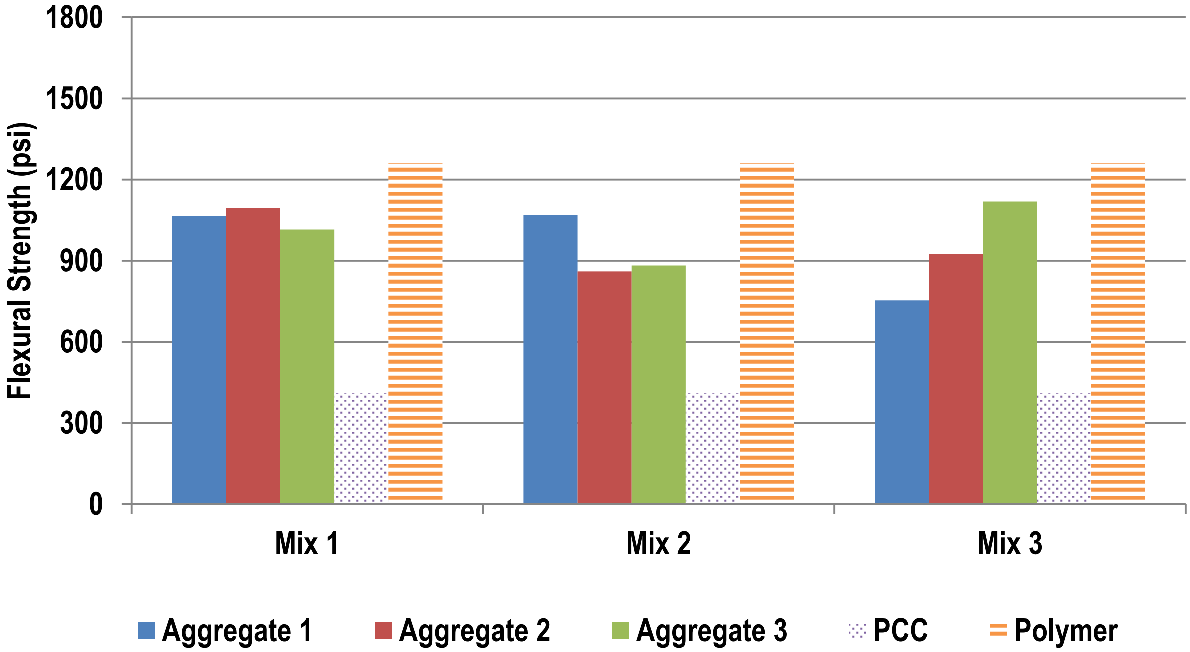

Figure 23 Twenty-Eight Day Flexural Strength Results when Grouped by Mix Proportions Used.

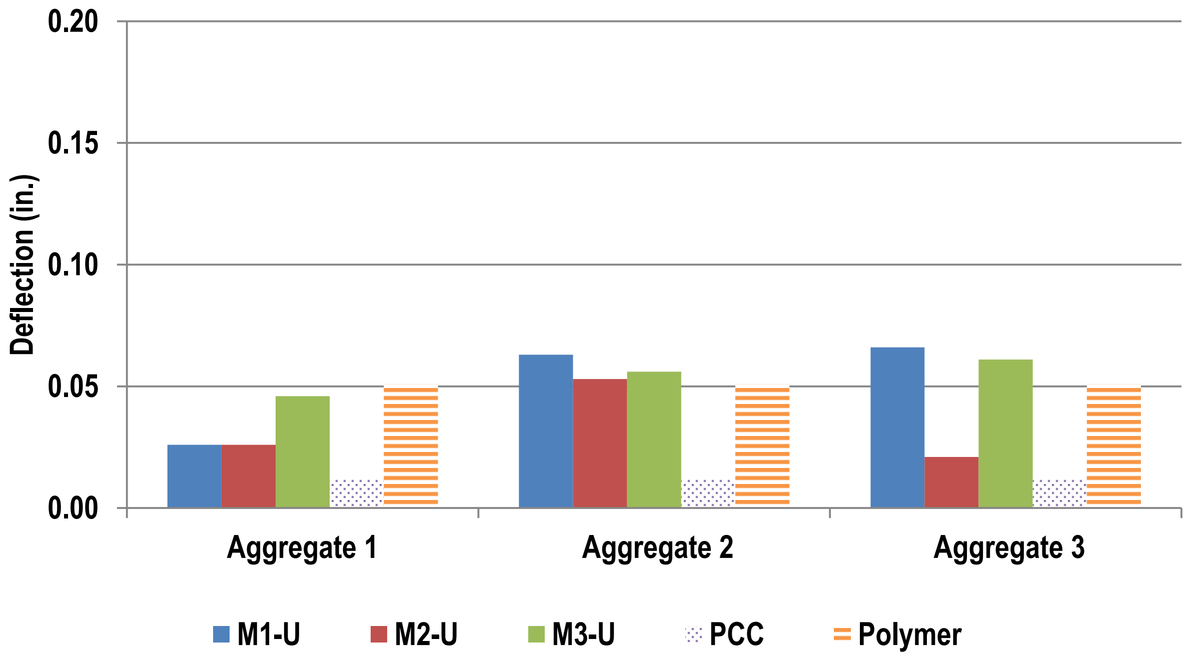

Figure 24 Twenty-Eight Day Deflections when Grouped by Aggregate Used.

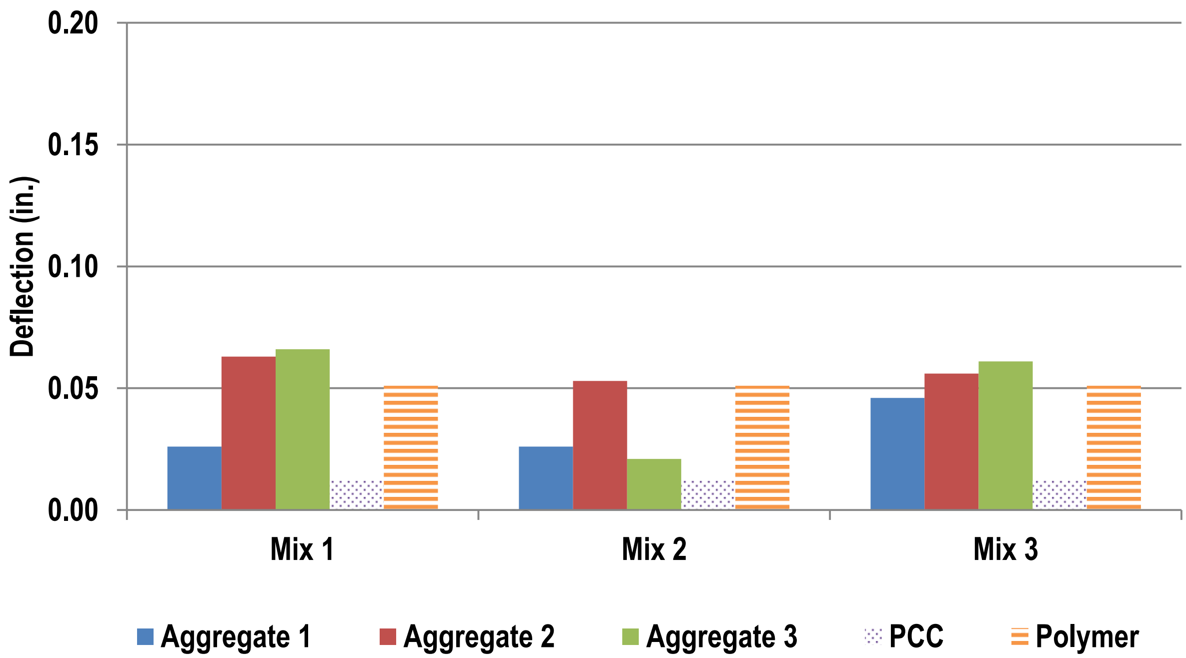

Figure 25 Twenty-Eight Day Deflections when Grouped by Mix Proportions Used.

Table 15 Summary of Ductility Test Results.

Mix ID	Three Days		Twenty-Eight Days	
	Flexural Strength (psi)	Deflection (in.)	Flexural Strength (psi)	Deflection (in.)
M1-A1-U	783	0.123	1,065	0.026
M2-A1-U	999	0.158	1,069	0.026
M3-A1-U	964	0.113	753	0.046
M1-A2-U	863	0.193	1,095	0.063
M2-A2-U	745	0.109	860	0.053
M3-A2-U	767	0.105	925	0.056
M1-A3-U	728	0.097	1,015	0.066
M2-A3-U	726	0.101	882	0.021
M3-A3-U	863	0.165	1,119	0.061
Polymer	1,261	0.053	1,695	0.051
PCC	---	---	411	0.012

3.6 Bond Strength

To evaluate the bond strength between an MECC overlay and the existing concrete bridge deck, three different bond strength tests were performed. Two different types of surface preparation for the existing PCC were evaluated: shot-blasting with aluminum pellets, and water-blasting with a 4,000 psi pressure washer. The surface preparation for the polymer concrete was shot-blasting followed by the application of a methacrylate sealer in accordance with the NDOT standard of practice. The test specimens consisted of a three-inch thick, six-inch diameter piece of 28-day PCC with the surface prepared. Three inches of MECC or polymer concrete was placed on top of the surface-treated PCC and the MECC samples were stored in a chamber at 100% R.H (polymer concrete samples were left in the laboratory) until time of testing. Slant-shear testing was not conducted for the polymer concrete mix because casting these samples proved too difficult and any results would not be representative of the bond strength. The M2-A2-U was the MECC mix used primarily because the M2-U mixes had the lowest 3-day tensile strength. There were three different types of samples evaluated in the bond strength tests:

1. Water-blasting with a 4,000 psi pressure washer for MECC (blue line).
2. Shot-blasting with aluminum beads for MECC (green line).
3. Shot-blasting with aluminum beads and application of methacrylate sealer for the polymer concrete (red line).

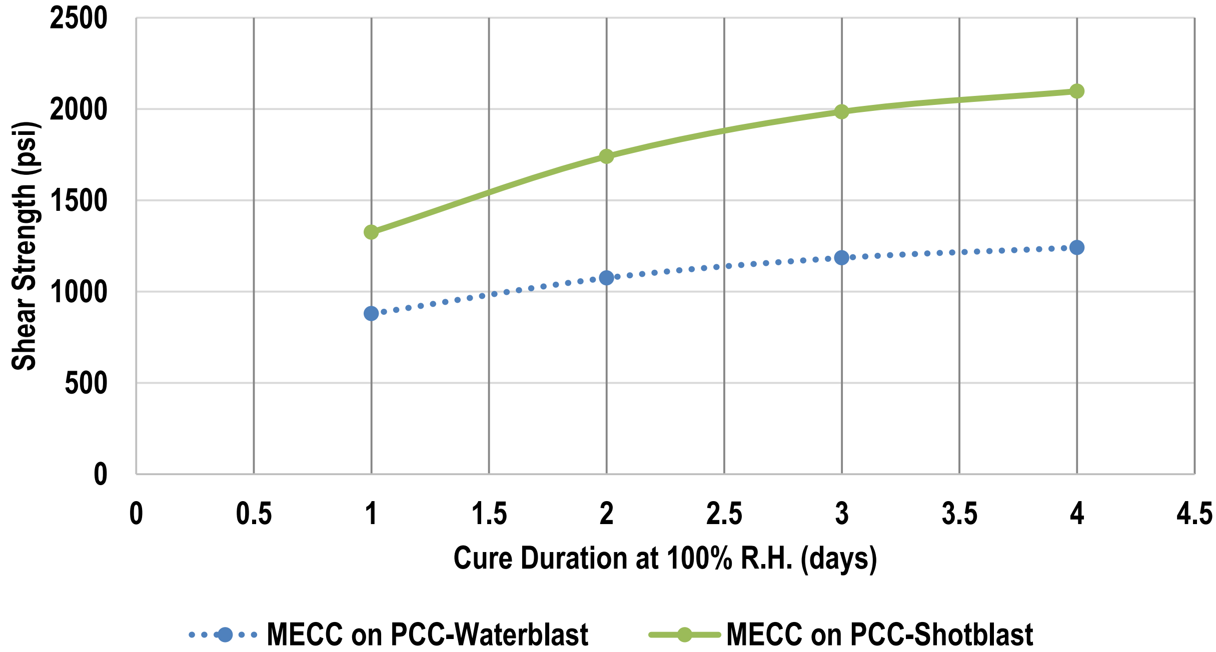

Figure 26 Slant-Shear Bond Strength Test Results.

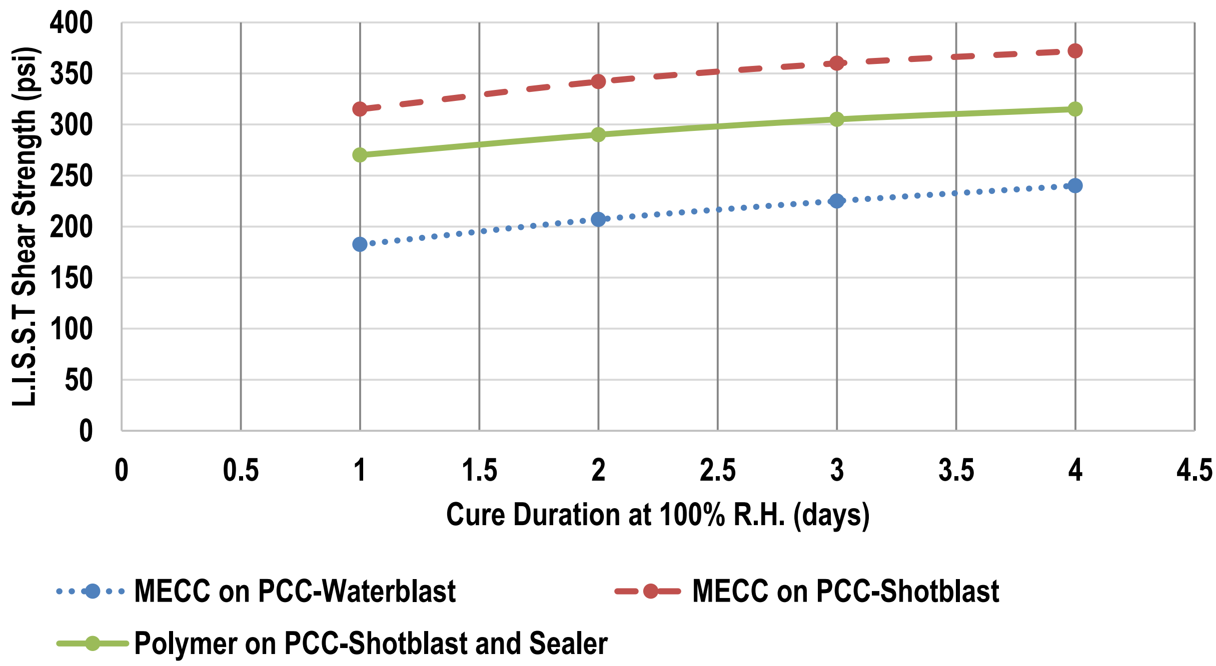

Figure 27 L.I.S.S.T Bond Strength Test Results.

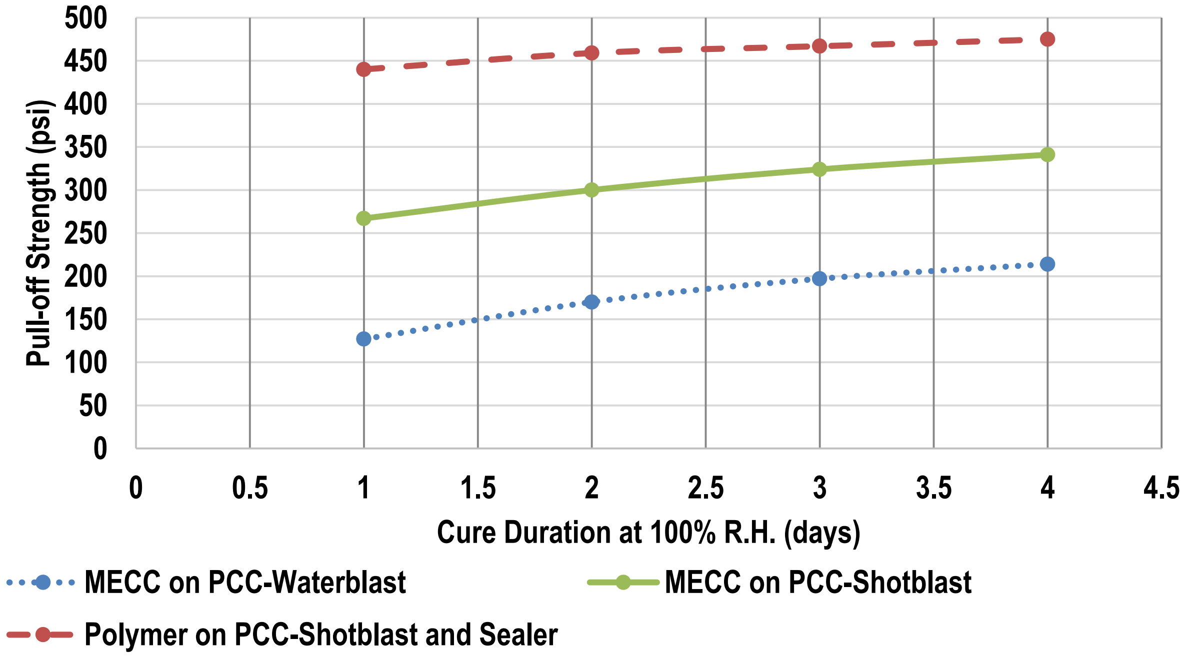

Figure 28 Pull-off Bond Strength Test Results.

Figures 26 to 28 shows the results for the three bond tests performed. The data show that the polymer concrete mix had the highest bond strength in all three tests, most likely because of the application of the methacrylate sealer. For the MECC, the shot-blasting surface preparation consistently produced much higher bond strengths than the water-blasting. Visual inspection of the PCC after the surface preparation showed that the pressure washer was only able to slightly texture the concrete and was not able to expose the coarse aggregates whereas the shot-blasting treatment was able to expose the coarse aggregate to a depth of approximately ¼ of an inch. NDOT specification 496.03.04 for overlay bond strength requires 250 psi tensile strength, determined by the pull-off test. This value applies if the failure occurs at the bond interface between the PCC and the MECC/Polymer concrete. During the pull-off test, all MECC and polymer concrete samples experienced failure at the bond interface. These results showed that water-blasting did not produce a bond that would meet this specification within four days (214 psi after 4 days), whereas both the shot-blast MECC samples and polymer concrete samples were able to meet this specification after one day (with bond strengths of 267 psi and 440 psi, respectively). Tables 16 to 18 summarizes the test results for the slant-shear, L.I.S.S.T, and pull-off test, respectively.

Table 16 Results of the Slant-Shear Bond Strength Test.

Sample	1 Day	2 Days	3 Days	4 Days
MECC-WB	880	1,075	1,185	1,241
MECC-SB	1,325	1,74	1,985	2,098
Polymer	---	---	---	---

Table 17 Results of the L.I.S.S.T. Bond Strength Test.

Sample	1 Day	2 Days	3 Days	4 Days
MECC-WB	183	207	225	240
MECC-SB	268	290	305	318
Polymer	315	342	360	372

Table 18 Results of the Pull-off Bond Test.

Sample	1 Day	2 Days	3 Days	4 Days
MECC-WB	127	170	197	214
MECC-SB	267	300	324	341
Polymer	440	459	467	475

3.7 Drying Shrinkage

Beam samples were cast and stored in a humidity chamber at 100% R.H. for 24 hours. The samples were removed from the molds and stored in a lime-saturated water bath for 27 days, and then placed in a different humidity chamber at 50% R.H. Shrinkage measurements were taken 4, 7, 14, 21, and 28 days after samples were placed in the 50% R.H. environment. Table 19 summarizes the shrinkage values for each of the MECC mixes.

Figures 29 to 32 show the shrinkage values for the MECC mixes as grouped based on the fine aggregates used. These figures show that the mixes with oiled fibers and mixes with unoiled fibers have approximately the same shrinkage values. The differences between mixes with oiled fibers and mixes with unoiled fibers were small, with the differences being less than 0.002%. This would suggest that the influence of fiber type on the shrinkage values would be very low. Mixes with Aggregate 1 and Aggregate 3 had the highest shrinkage values at all test times, values of 0.008 at 4 days, 0.016 at 7 days, 0.0324 at 14 days, 0.0381 at 21 days, and 0.0425 at 28 days. Mixes with Aggregate 2 had shrinkage values of 0.007, 0.012, 0.0275, 0.0343, and 0.0392 at 4, 7, 14, 21, and 28 days. When compared to the PCC, mixes with Aggregate 1 and Aggregate 3 had the same shrinkage values. However, the mixes with Aggregate 2 had lower shrinkage values compared to the PCC. On average, mixes with Aggregate 2 had shrinkage values that were 0.004% lower.

Figures 33 to 36 show the shrinkage values from the MECC mixes as grouped based on the mix proportions used. Again, these figures show that there is only a small difference between mixes with oiled fibers and mixes with unoiled fibers. This shows that the influence of the fiber type on the shrinkage values for the MECC material may be minimal. These figures show that the mixes with Mix Proportions 3 had the lowest shrinkage values, whereas mixes with Mix Proportions 1 and 2 had approximately equal shrinkage values. Overall, the average shrinkage values for each group of mix proportions were lower than the PCC.

Figure 37 shows the average values for mixes with unoiled fibers and oiled fibers. When looking at this graph, there is a very small difference between these two groups. The differences between these two groups are all less than 0.002 for each test times. This would suggest that the fiber type most likely does not have any effect on the shrinkage values for MECC mixes.

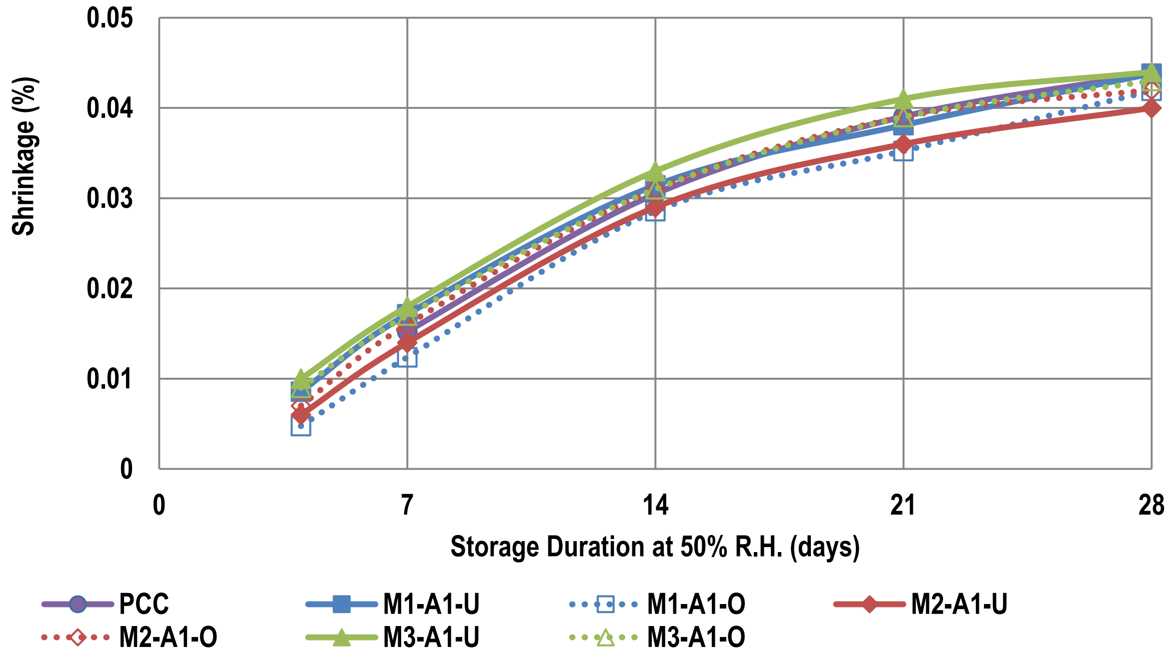

Figure 29 Shrinkage Values for Mixes with Aggregate 1.

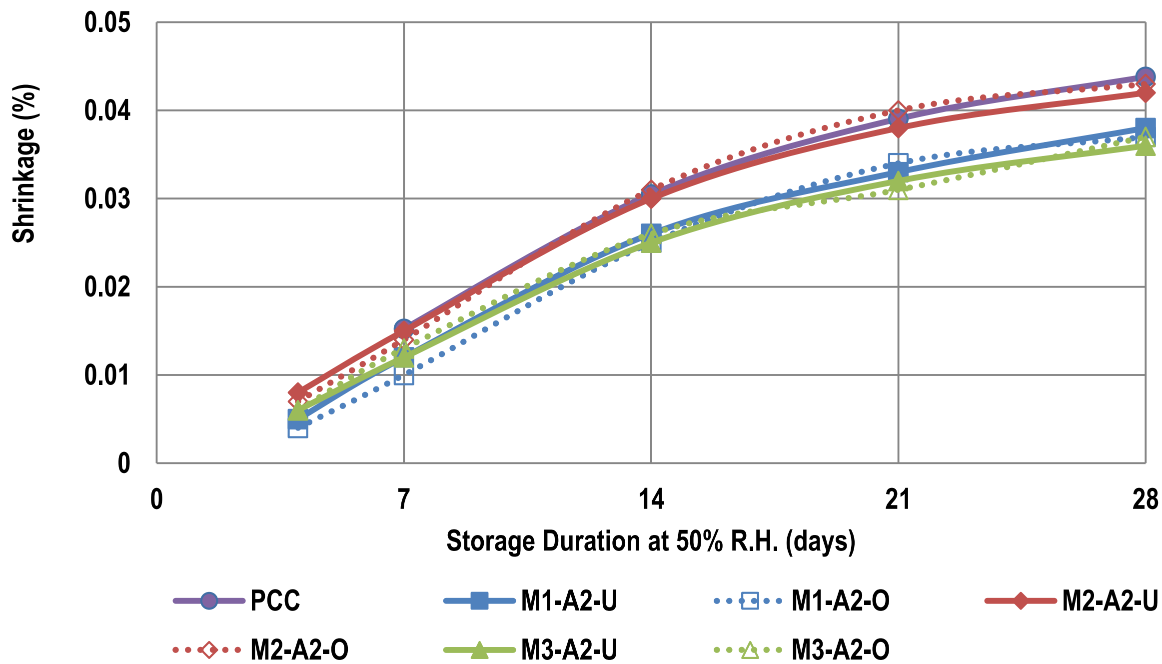

Figure 30 Shrinkage Values for Mixes with Aggregate 2.

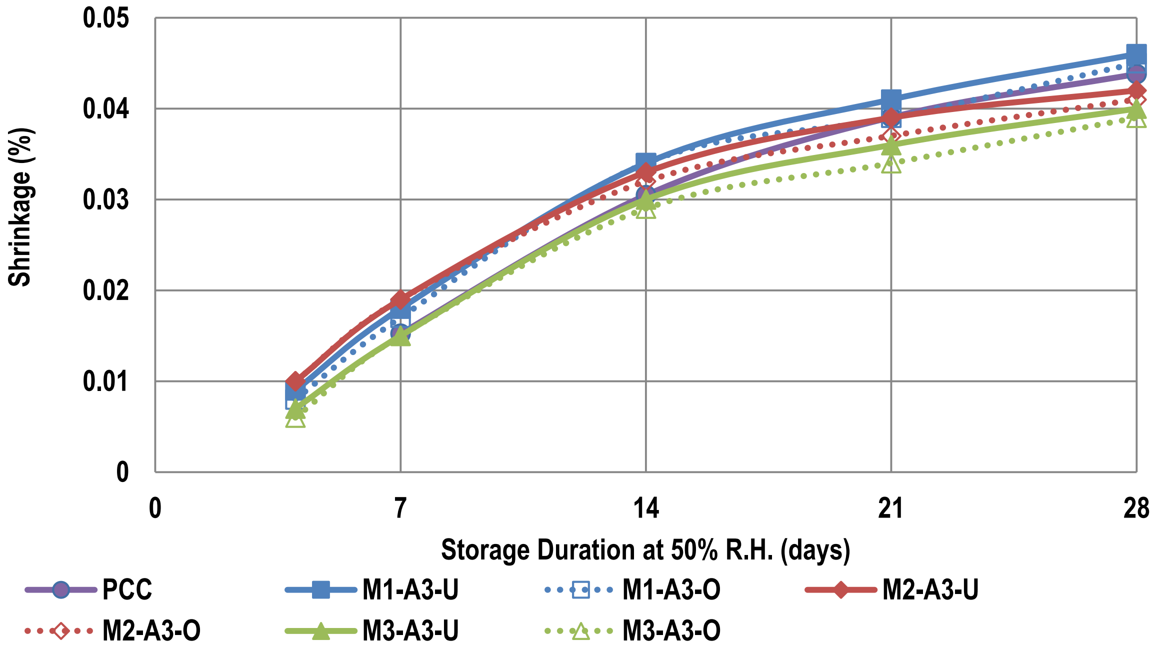

Figure 31 Shrinkage Values for Mixes with Aggregate 3.

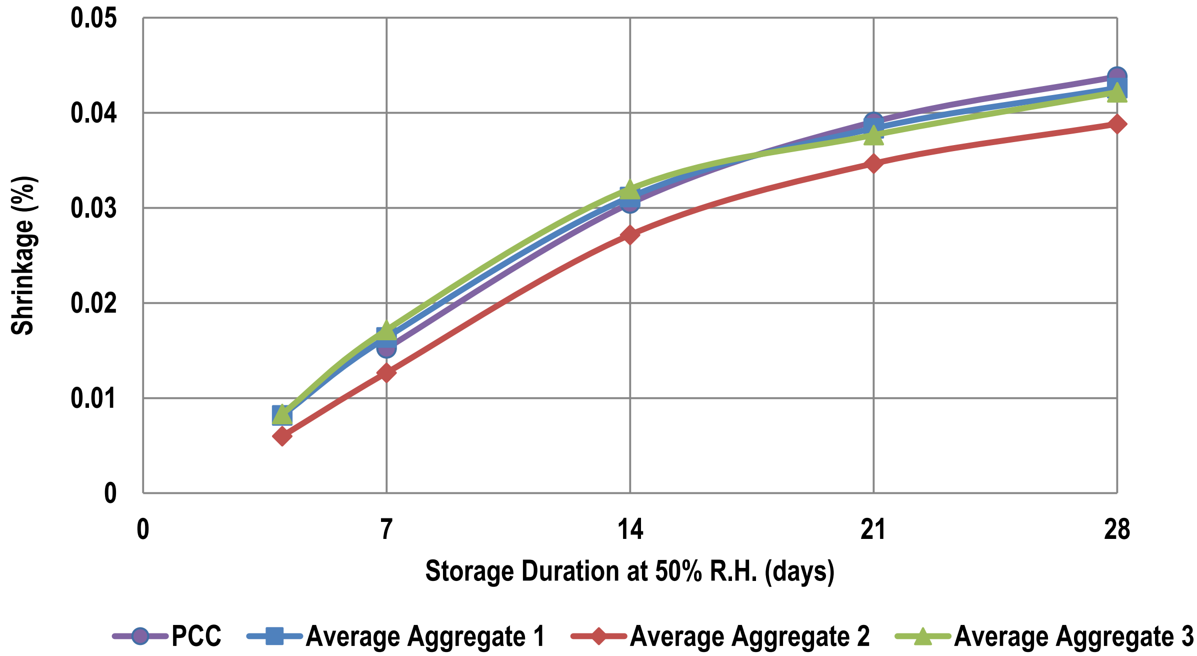

Figure 32 Average Shrinkage Values for Mixes with Aggregate 1, 2, and 3.

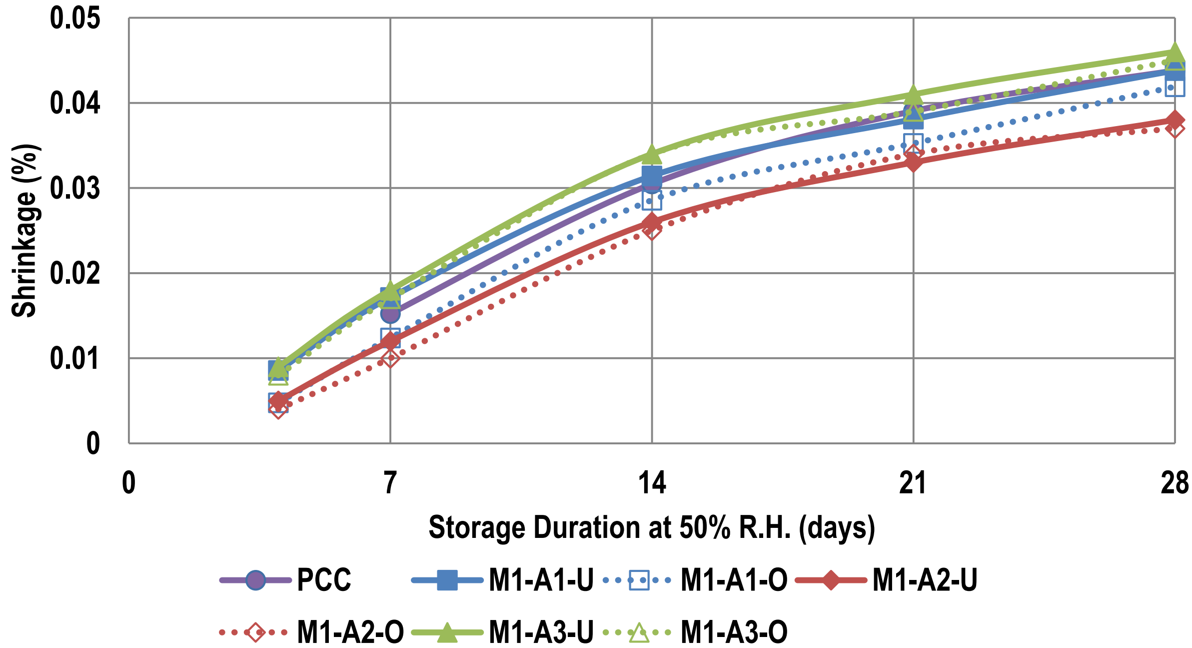

Figure 33 Shrinkage Values for Mixes with Mix Proportions 1.

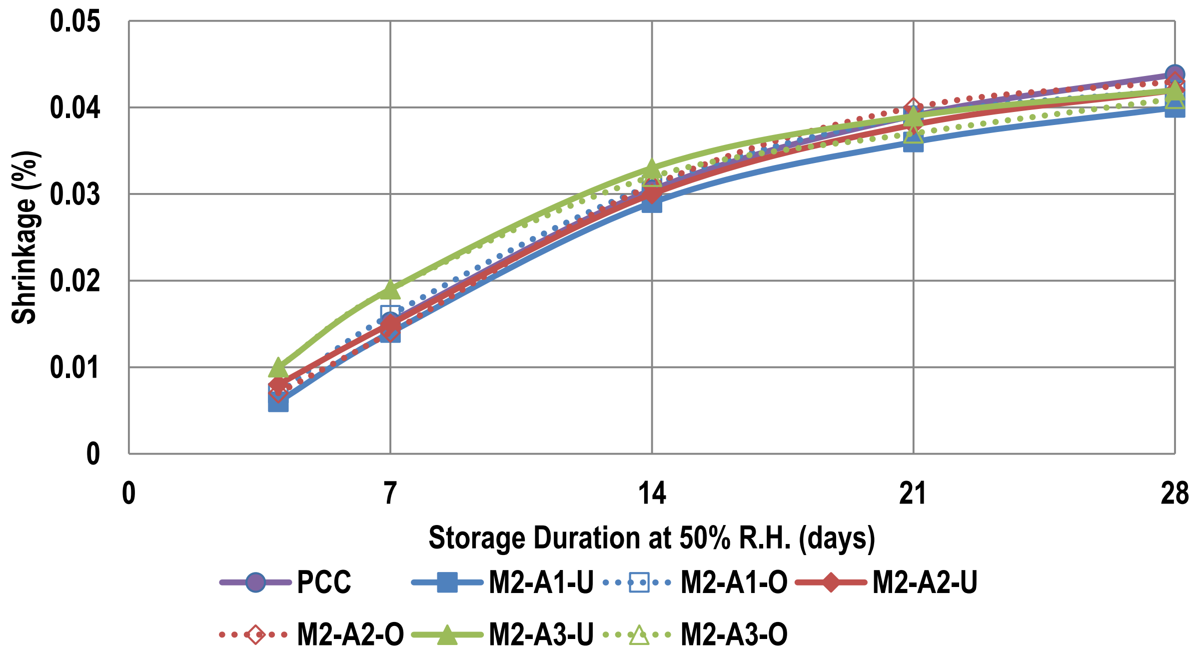

Figure 34 Shrinkage Values for Mixes with Mix Proportions 2.

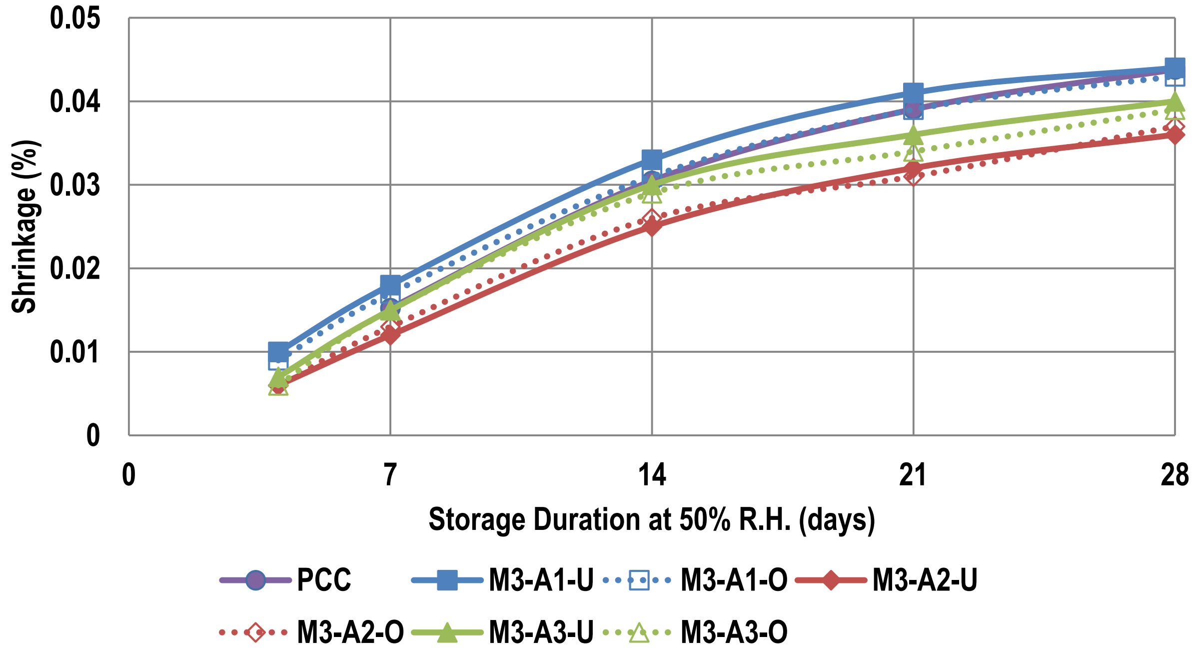

Figure 35 Shrinkage Values for Mixes with Mix Proportions 3.

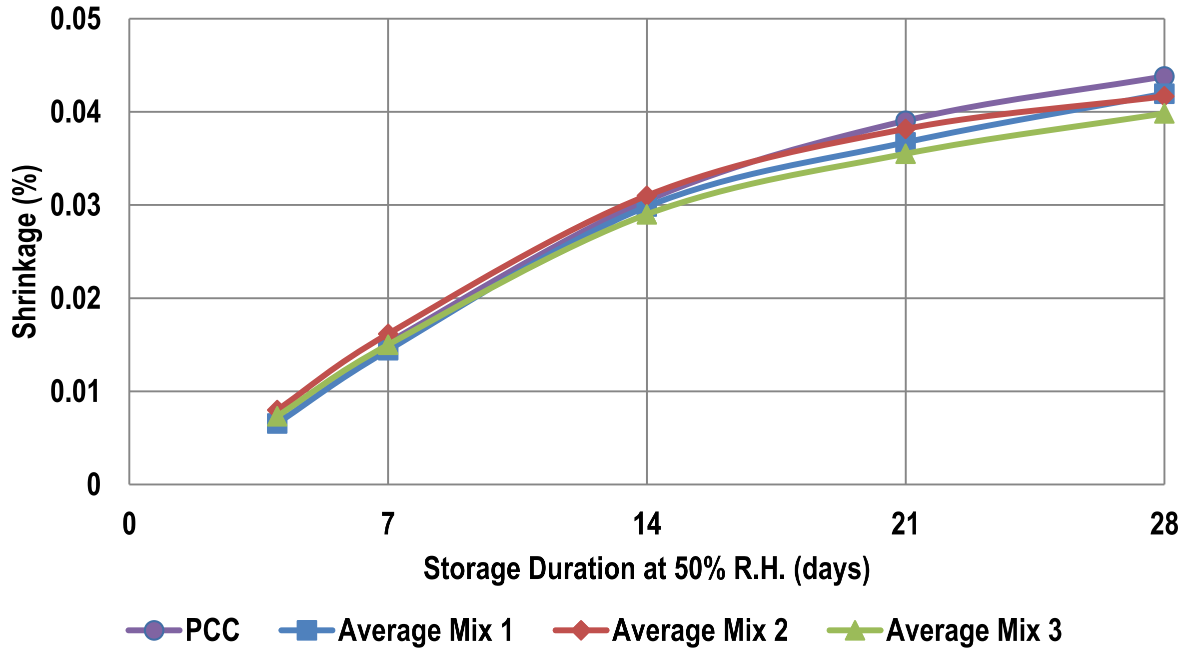

Figure 36 Average Shrinkage Values for Mixes with Mix Proportions 1, 2, and 3.

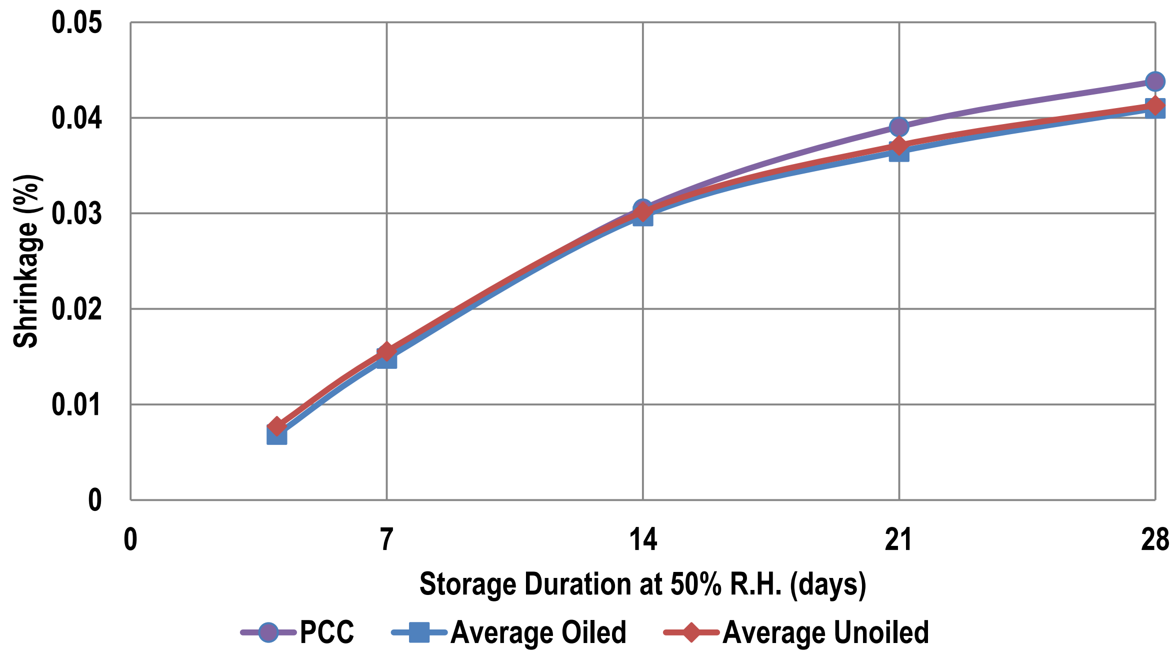

Figure 37 Average Shrinkage Values for Mixes with Oiled and Unoiled Fibers.

Table 19 Summary of Shrinkage Results (in %).

Mix ID	Storage Duration at 50% Relative Humidity				
	4 Days	7 Days	14 Days	21 Days	28 Days
M1-A1-O	0.0048	0.0124	0.0286	0.0353	0.0420
M1-A1-U	0.0086	0.0171	0.0314	0.0382	0.0438
M2-A1-O	0.0070	0.0162	0.0309	0.0389	0.0430
M2-A1-U	0.0061	0.0142	0.0392	0.0360	0.0400
M3-A1-O	0.0090	0.0170	0.0311	0.0391	0.0430
M3-A1-U	0.0101	0.0181	0.0334	0.0412	0.0441
M1-A2-O	0.0049	0.0114	0.0250	0.0342	0.0373
M1-A2-U	0.0050	0.0123	0.0260	0.0333	0.0381
M2-A2-O	0.0073	0.0142	0.0311	0.0400	0.0431
M2-A2-U	0.0082	0.0153	0.0311	0.0381	0.0426
M3-A2-O	0.0080	0.0134	0.0266	0.0311	0.0371
M3-A2-U	0.0069	0.0168	0.0254	0.0328	0.0367
M1-A3-O	0.0086	0.0174	0.0348	0.0392	0.0452
M1-A3-U	0.0096	0.0183	0.0343	0.0415	0.0457
M2-A3-O	0.0101	0.0196	0.0324	0.0375	0.0415
M2-A3-U	0.0114	0.0199	0.0333	0.0389	0.0426
M3-A3-O	0.0066	0.0153	0.0294	0.0344	0.0393
M3-A3-U	0.0073	0.0157	0.0312	0.0365	0.0399
PCC	---	0.0152	0.0305	0.0390	0.0438

3.8 Abrasion Resistance

Six-inch diameter cylinders were cast and the top 0.5-inch was cut off and used for the evaluation of abrasion resistance. Samples were stored in a chamber at 100% R.H. for 28 days and were air-dried in the laboratory for three hours prior to testing. The samples are weighted prior to and after each two minute abrasion cycle, and the mass lost during each cycle is recorded. Table 20 summarizes the mass lost during testing for the MECC, polymer concrete, and PCC mixes.

Figures 38 thru 41 show the abrasion resistance values for the MECC mixes as grouped based on the aggregate used. The test results show that all MECC mixes had higher mass loss compared to the polymer concrete after all five cycles (2.1 grams mass loss). However, all MECC mixes had lower mass loss values compared to the PCC after all five cycles (8.3 grams mass loss). These figures show that on average, mixes with the same aggregate have approximately the same mass loss after two cycles (1.7 grams mass loss). However, with subsequent abrasion cycles, the mass loss values begin to separate. This would suggest that the mix proportions have a low influence on the early-age abrasion resistance of the material, but become more influential as the number of cycles increases. When looking at the average values for the mixes with Aggregate 1, 2, and 3 it is apparent that there is only a small difference between these groups after two cycles. However, afterwards mixes with Aggregate 2 have the lowest mass loss (3.7 grams after five cycles), mixes with Aggregate 1 have the highest mass loss values (4.6 grams after five cycles), and mixes with Aggregate 2 have intermediate values (4 grams after 5 cycles).

Figures 42 to 45 show the abrasion resistance values for the MECC mixes as grouped based on the mix proportions used. These figures show that on average, mixes with the same mix proportions have approximately the same amount of mass loss after two cycles. However, after additional abrasion cycles, these values begin to spread out, allowing for better understanding of how each MECC mix performs. When looking at the average values for the mixes with Mix Proportions 1, 2, and 3 it is apparent that there is only a small difference between these groups throughout the test. Mixes with Mix Proportions 2 and 3 had the lowest mass loss (3.8 grams after five cycles) while mixes with Mix Proportions 1 had the highest mass loss values (4.6 grams after five cycles).

Figure 46 shows the abrasion resistance values for the MECC mixes as grouped based on the fiber type used. Previous figures illustrating the abrasion resistance test results showed that there was a small difference between mixes with oiled fibers and unoiled fibers. On average, when looking at mixes with oiled fibers and mixes with unoiled fibers, the differences between these two groups was less than 0.1 grams. This suggests that the influence of the fiber type on the abrasion resistance of MECC mixes is very small, if negligible.

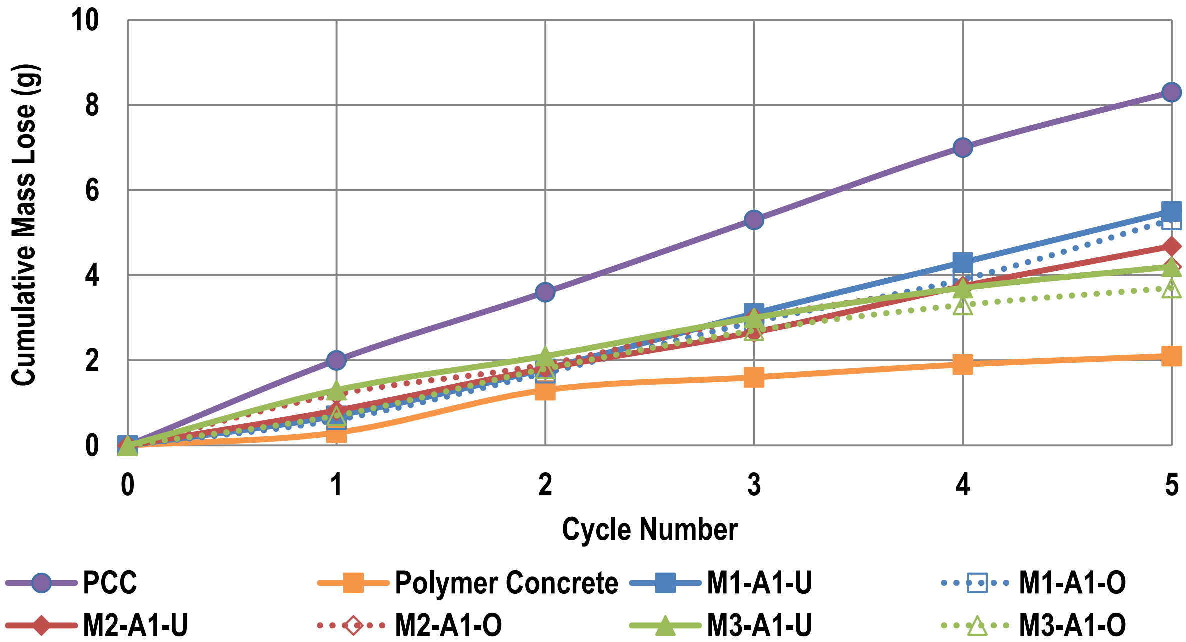

Figure 38 Abrasion Resistance for Mixes with Aggregate 1.

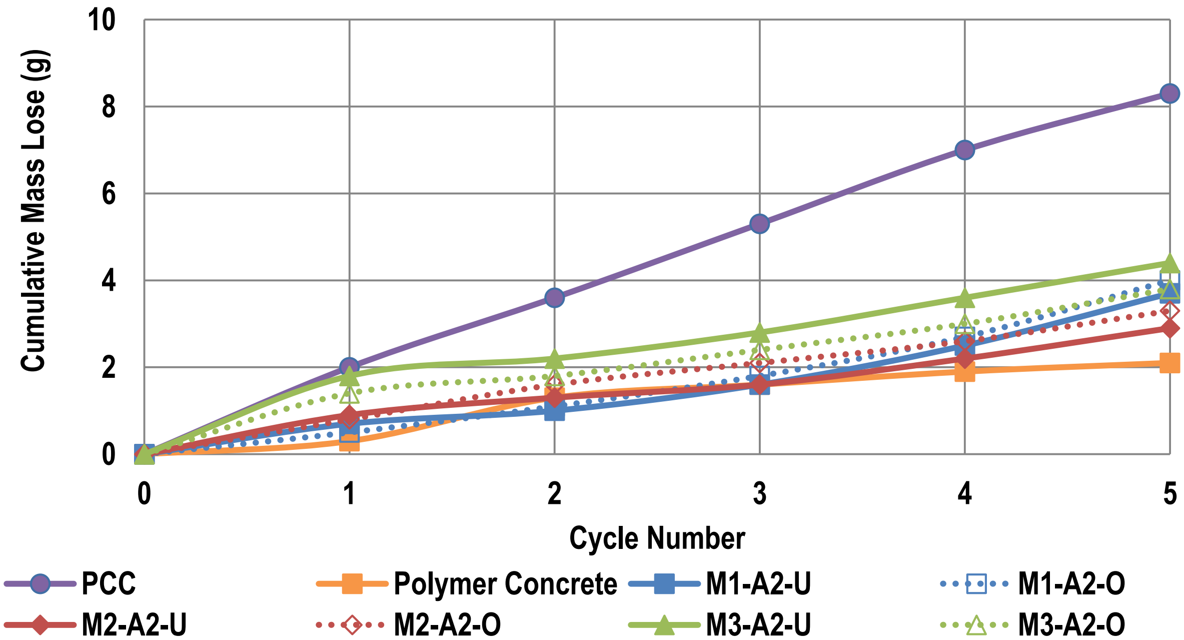

Figure 39 Abrasion Resistance for Mixes with Aggregate 2.

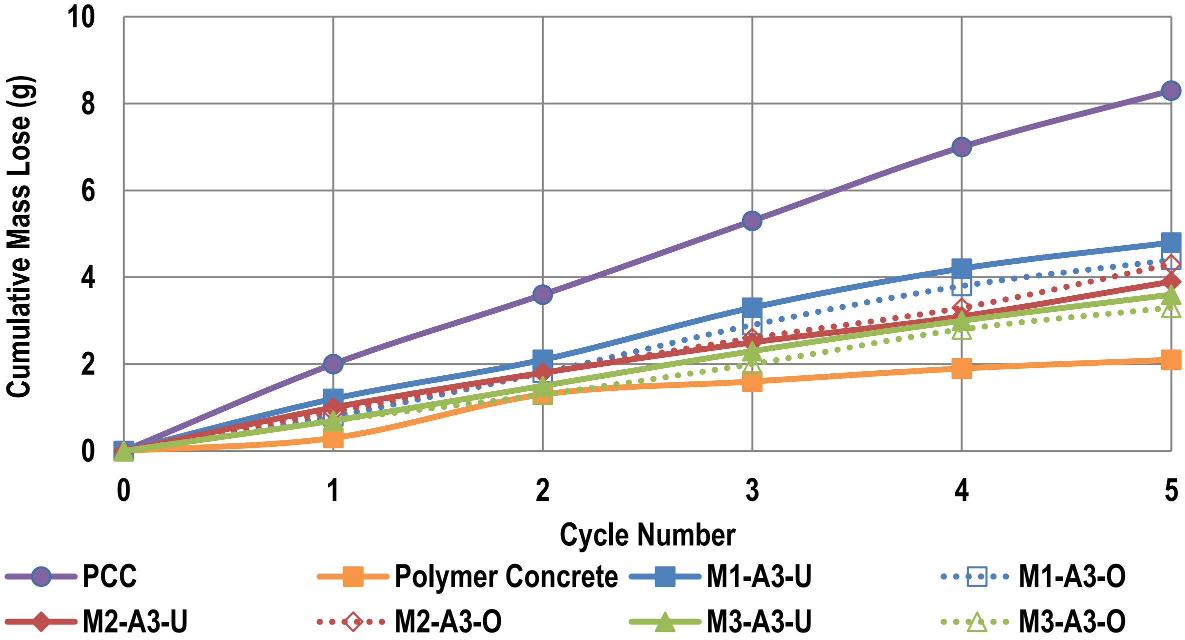

Figure 40 Abrasion Resistance for Mixes with Aggregate 3.

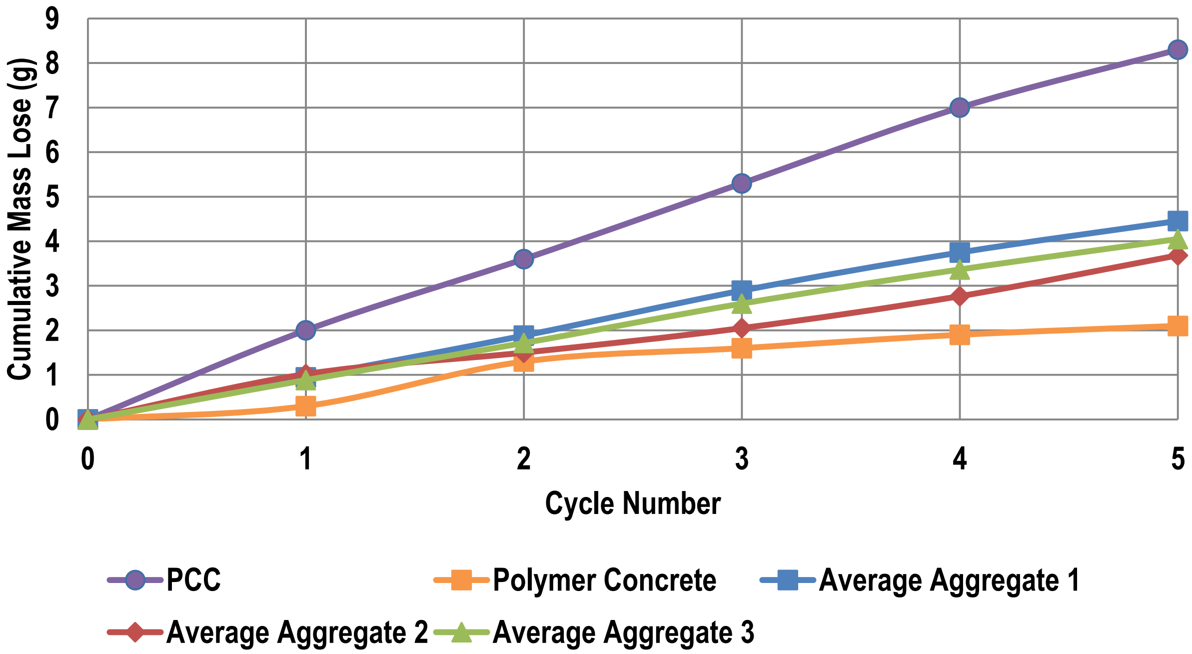

Figure 41 Average Abrasion Resistance for Mixes with Aggregate 1, 2, and 3.

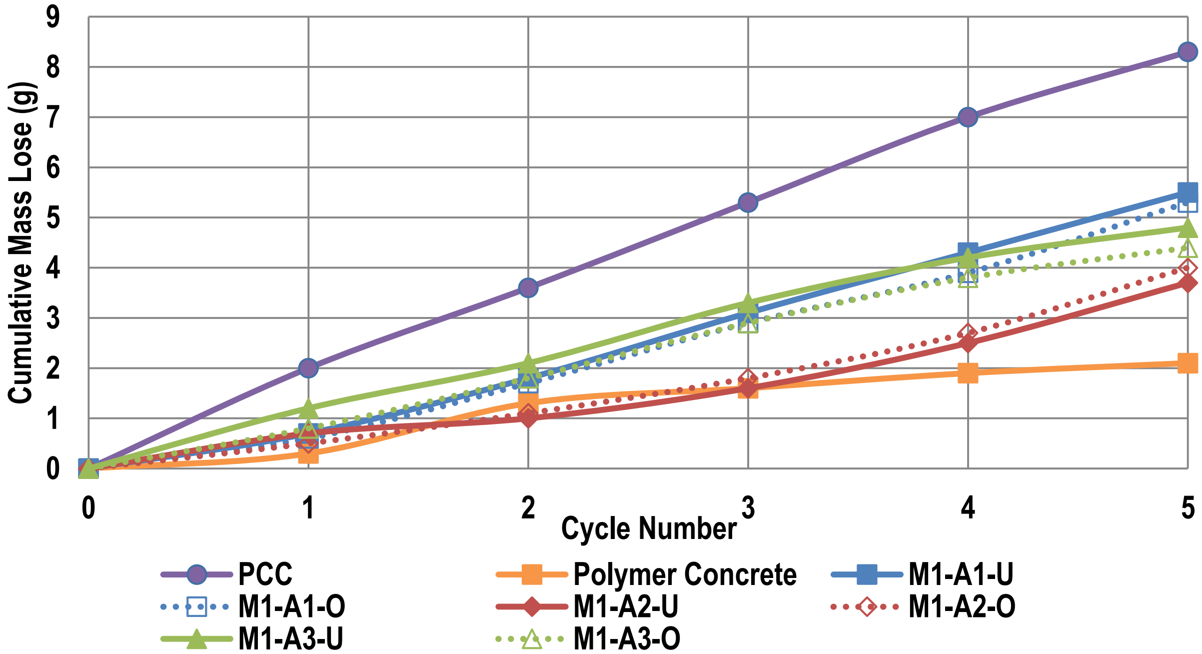

Figure 42 Abrasion Resistance for Mixes with Mix Proportions 1.

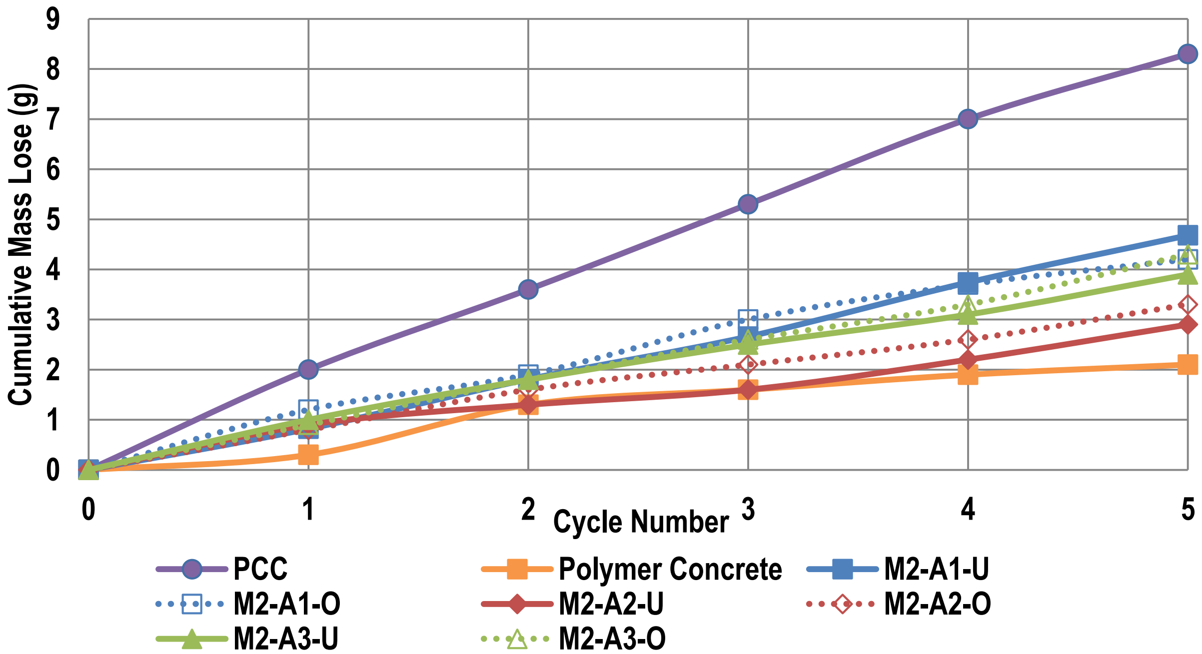

Figure 43 Abrasion Resistance for Mixes with Mix Proportions 2.

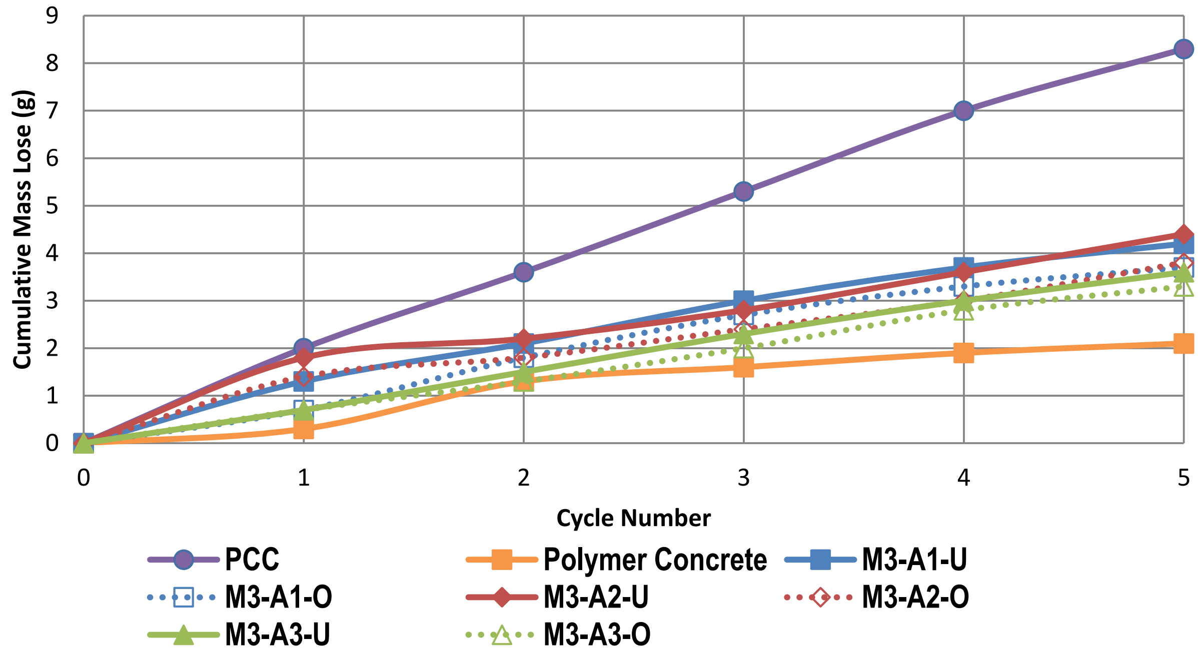

Figure 44 Abrasion Resistance for Mixes with Mix Proportions 3.

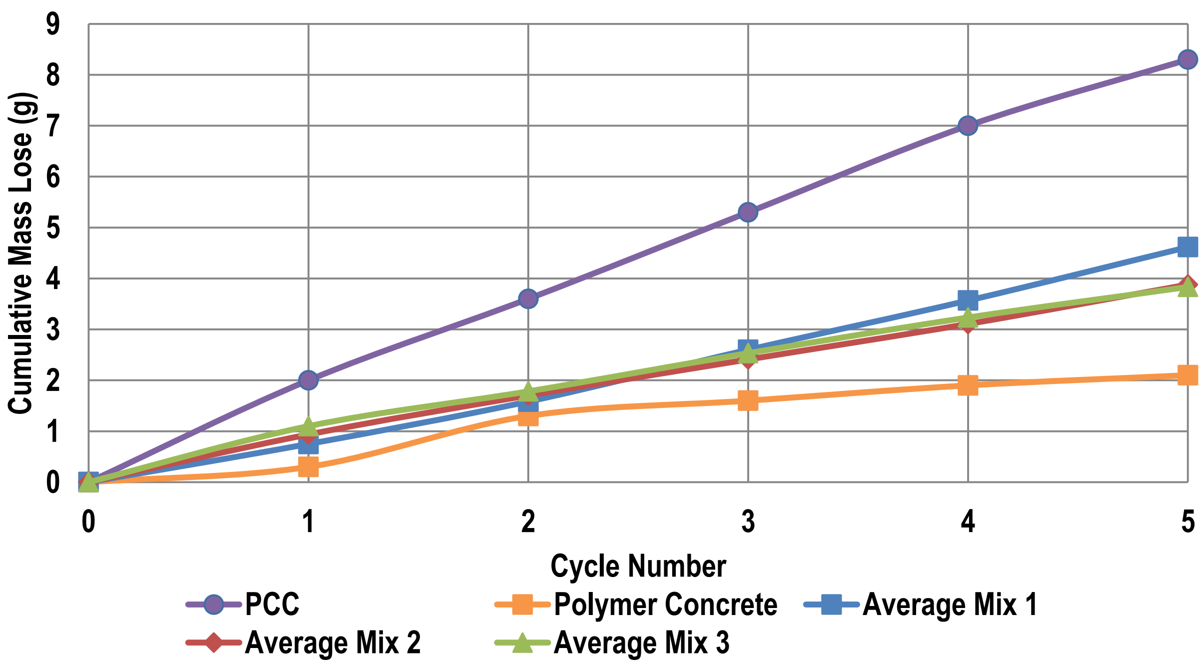

Figure 45 Average Abrasion Resistance for Mixes with Mix Proportions 1, 2, and 3.

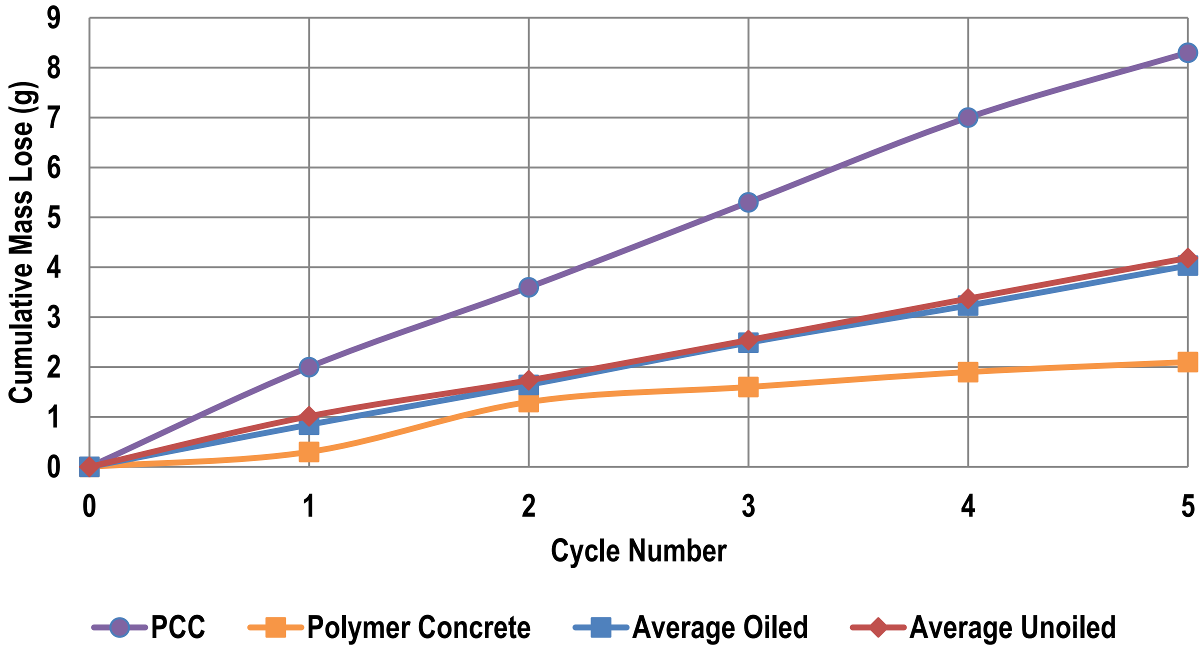

Figure 46 Average Abrasion Resistance for Mixes with Oiled and Unoiled Fibers.

Table 20 Summary of Abrasion Resistance Test Results.

Mix ID	Cumulative Amount of Mass Loss After Each Cycle (g).				
	Cycle1	Cycle2	Cycle3	Cycle4	Cycle5
M1-A1-O	0.6	1.7	2.9	3.9	5.3
M1-A1-U	0.7	1.8	3.1	4.3	5.5
M2-A1-O	1.2	1.9	3.0	3.7	4.3
M2-A1-U	0.8	1.8	2.7	3.8	4.7
M3-A1-O	0.7	1.8	2.7	3.3	3.7
M3-A1-U	1.3	2.1	3.0	3.7	4.2
M1-A2-O	0.5	1.1	1.8	2.7	4.0
M1-A2-U	0.7	1.0	1.6	2.5	3.7
M2-A2-O	0.8	1.6	2.2	2.7	3.3
M2-A2-U	0.9	1.3	1.6	2.2	2.9
M3-A2-O	1.4	1.8	2.4	3.0	3.8
M3-A2-U	1.8	2.2	2.8	3.6	4.4
M1-A3-O	0.8	1.8	2.9	3.9	4.4
M1-A3-U	1.2	2.1	3.3	4.2	4.8
M2-A3-O	0.9	1.8	2.6	3.3	4.4
M2-A3-U	1.0	1.8	2.5	3.1	3.9
M3-A3-O	0.7	1.3	2.1	2.8	3.3
M3-A3-U	0.7	1.5	2.3	3.1	3.6
Polymer	0.3	1.3	1.6	1.9	2.1
PCC	2.0	3.6	5.3	7.0	8.3

3.9 Freeze-thaw Durability

Northern Nevada is a dry-freeze environment where MECC would be exposed to freeze-thaw cycles in accordance with ASTM C666. Samples for M3-A2-U and M3-A3-U were cast in the laboratory and were shipped frozen to CTL Thompson, a third-party consultant laboratory, for testing where samples were subjected to 300 freeze-thaw cycles. The results showed that the durability factor for all four samples tested after the 300 freeze-thaw cycles was 100%, indicating exceptional freeze-thaw performance. These results confirmed previous literature on ECC which showed an air-entrainment admixture is not needed for freeze-thaw resistance (8). Appendix C shows the report from CTL Thompson showing the test results for the MECC samples sent for freeze-thaw durability testing.

3.10 Resistance to Chloride Ion Penetration

Bridges in the northern part of Nevada are subjected to deicing salts during the winter months. The polymer concrete mix has excellent resistance to chloride ion penetration, which is one of the primary reasons it is used as an overlay material. In this test, the lower amount of coulombs passed indicates a higher resistance to chloride ion penetration. Table 21 summarizes the results of the chloride ion penetration test. On average, the charge passed by the MECC mixes was 1,764 coulombs indicating a low chloride ion penetrability according to ASTM C1202 (between 1,000 and 2,000 coulombs).

Figure 47 shows the test results when mixes are grouped by the aggregate used. All MECC mixes had lower coulombs passed than the PCC did (1,975 coulombs passed). However, the MECC mixes did not perform as well as the polymer concrete (287 coulombs passed). On average mixes with Aggregate 1 had the most coulombs passed (1,799), mixes with Aggregate 2 had the lowest (1,726), and mixes with Aggregate 3 had intermediate values of 1,768 coulombs passed. This figure also shows that there is a very small difference between mixes with oiled fibers and mixes with unoiled fibers. The average difference between mixes with oiled fibers and mixes with unoiled fibers was only 8 coulombs. This would suggest that the fiber type has no influence on the material’s resistance to chloride ion penetration.

Figure 48 shows the test results when mixes are grouped based on the mix proportions used. This graph shows that there appears to be smaller differences with these groups and larger differences between groups when compared to the previous figure. This suggests that the mix proportions used may have a higher influence on the resistance to chloride ion penetration of the MECC material. On average mixes with Mix Proportions 3 had the most coulombs passed (1,837), mixes with Mix Proportions 2 had the lowest (1,697), and mixes with Mix Proportions 1 had intermediate values of 1,759 coulombs passed.

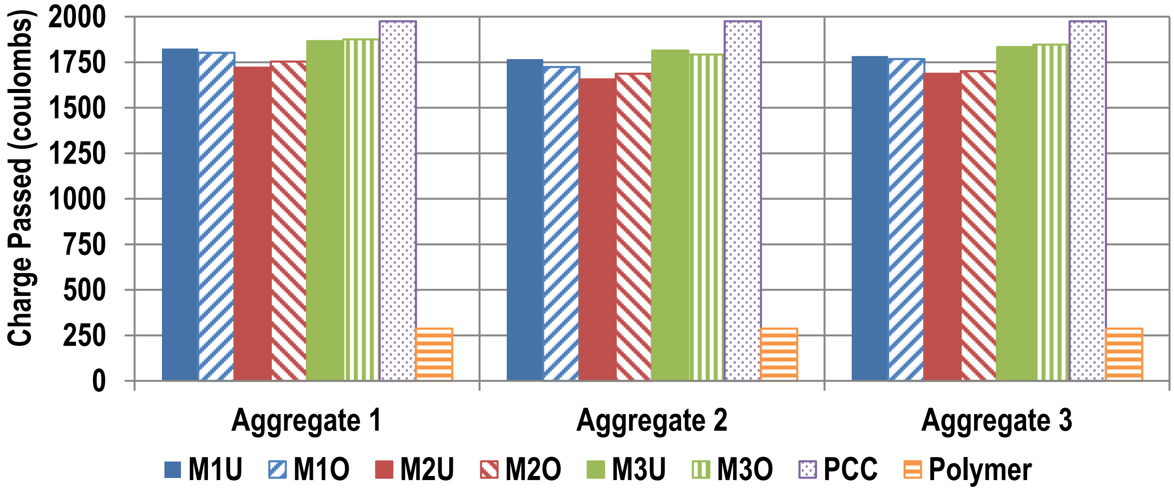

Figure 47 Chloride Ion Penetration by Aggregate.

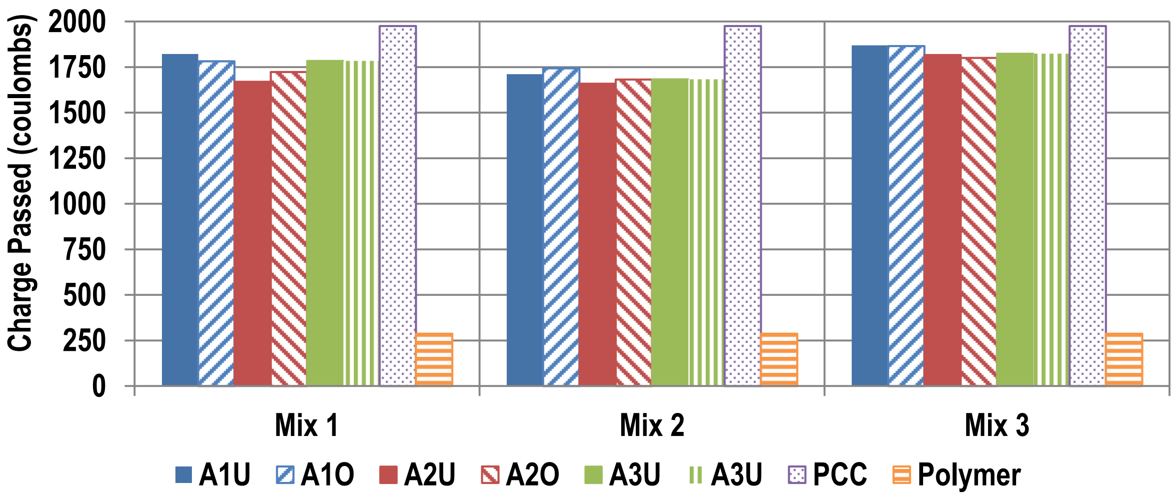

Figure 48 Chloride Ion Penetration by Mix Proportion.

Table 21 Summary of Chloride Ion Penetration Test Results.

Mix ID	**Coulombs passed (ohms)**
M1-A1-O	1,782
M1-A1-U	1,822
M2-A1-O	1,744
M2-A1-U	1,711
M3-A1-O	1,866
M3-A1-U	1,869
M1-A2-O	1,723
M1-A2-U	1,670
M2-A2-O	1,682
M2-A2-U	1,660
M3-A2-O	1,801
M3-A2-U	1,817
M1-A3-O	1,771
M1-A3-U	1,784
M2-A3-O	1,699
M2-A3-U	1,684
M3-A3-O	1,845
M3-A3-U	1,824
Polymer	287
PCC	1,975

CHAPTER 4: EVALUATION OF ADDITIONAL MECC MIXES

4.1 Introduction

This chapter presents the test results for the additional MECC mixes that were partially evaluated in the laboratory study. Because these mixes fall outside the original scope for this study, they were not subjected to all of the performance tests like the original eighteen MECC mixes. Some of these mixes were used to compare the laboratory test results with the large-scale trial batch test results (both trial batches performed for this study did not use one of the three original fine aggregates). Other mixes presented in this section were used to study the influence of cement on the MECC's properties. These results were used to better characterize the influence of the aggregate properties on the MECC's performance. Lastly, at the conclusion of the research study, NDOT personnel requested the research team perform two additional laboratory experiments to evaluate the bond strength using a bonding agent and how changing the curing regiment would affect the MECC's mechanical properties and bond strength.

4.2 Additional Mixes

In total, there were fifteen additional mixes that were partially evaluated. Table 22 summarizes these mixes. Because the oiled fibers were in short supply, only unoiled fibers were evaluated in these additional mixes. Additionally, the test results showed that there was only a moderate increase in performance of the MECC mixes with oiled fibers compared to the unoiled fibers, with this small increase in performance came at a high cost. The research team decided to move forward and focus on evaluating only the unoiled fibers in these additional MECC mixes. It should be noted that mixes using the Lehigh Cement are designated with the letter "L" at the end of the Mix ID while the mixes with the Nevada Cement do not have any special designation. The difference between the two cements was that the Lehigh Cement was finer than the Nevada Cement. This means the Lehigh Cement would hydrate faster, and MECC mixes with Lehigh Cement could gain strength at a faster rate than mixes with Nevada Cement. Table 7 summarizes the material properties for both the Lehigh and Nevada cements.

Table 22 Additional MECC Mixes.

Mix ID	Cement Used
M1-A4-U	Nevada Type II
M2-A4-U	Nevada Type II
M3-A4-U	Nevada Type II
M1-A5-U	Nevada Type II
M2-A5-U	Nevada Type II
M3-A5-U	Nevada Type II
M1-A6-U	Nevada Type II
M2-A6-U	Nevada Type II
M3-A6-U	Nevada Type II
M1-A3-U-L	Lehigh Type II
M2-A3-U-L	Lehigh Type II
M3-A3-U-L	Lehigh Type II
M1-A5-U-L	Lehigh Type II
M2-A5-U-L	Lehigh Type II
M3-A5-U-L	Lehigh Type II

4.3 Compressive Strengths

The compressive strengths for the additional mixes were measured at the same intervals as the original MECC mixes: 0.5, 1, 1.5, 3, 7, and 28 days. Table 23 summarizes the compressive strengths for the additional MECC mixes.

Figures 49 to 52 show the compressive strengths for the additional MECC mixes. The test results show that for the mixes with the Nevada Cement, there was only a small difference between the mixes with Aggregate 4, 5, and 6, respectively, within the first 1.5 days. At 3 days, mixes with Aggregate 5 and 6 had higher compressive strengths than the mixes with Aggregate 4 (4,950 psi vs. 4,350 psi). At 7 days, the mixes with Aggregate 5 had the highest compressive strengths and mixes with Aggregate 4 and 6 had roughly the same strengths (6,250 psi vs. 5,900 psi). At 28 days, mixes with Aggregate 5 had the highest compressive strengths with 9,000 psi, followed by mixes with Aggregate 6 at 8,600 psi, and mixes with Aggregate 4 having strengths of 8,100 psi.

When looking at the Lehigh Cement compared to the Nevada Cement, the Lehigh cement had higher compressive strengths at all ages (about 250 psi greater). For mixes with Aggregate 3, the Lehigh Cement led to about 300 psi higher compressive strengths compared to the mixes with Aggregate 3 using Nevada Cement. For mixes with Aggregate 5, the Lehigh Cement added about 200 psi higher compressive strengths compared to mixes with Aggregate 5 using Nevada Cement.

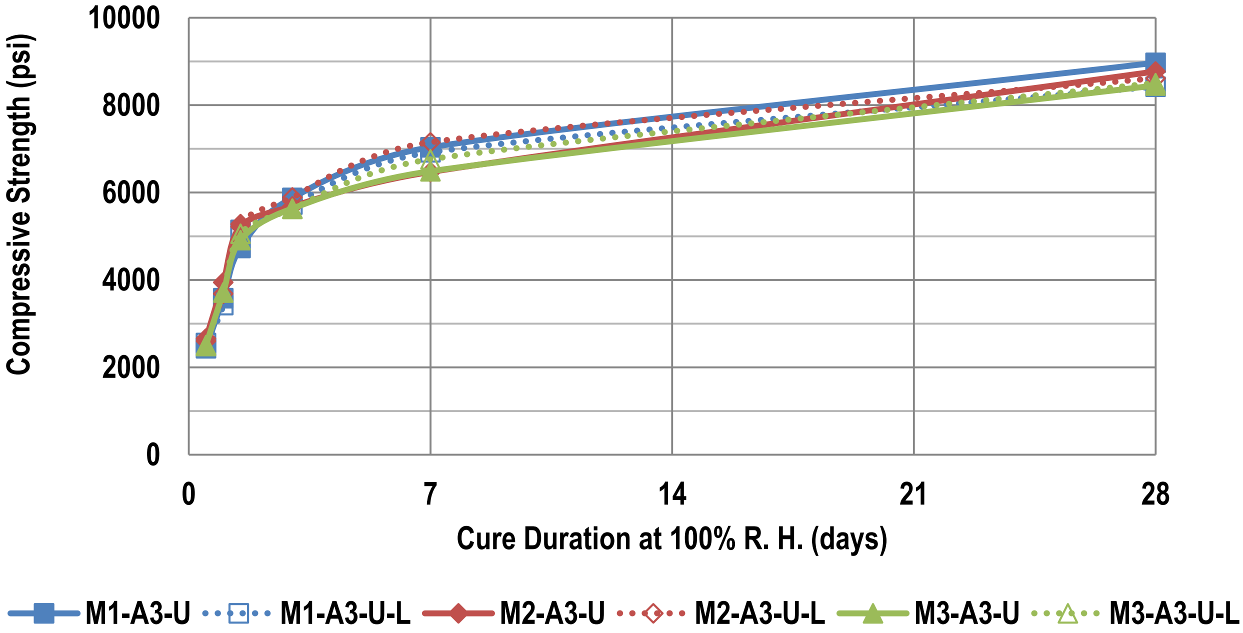

Figure 49 Compressive Strength Results for Mixes with Aggregate 3 (Both Cement Types).

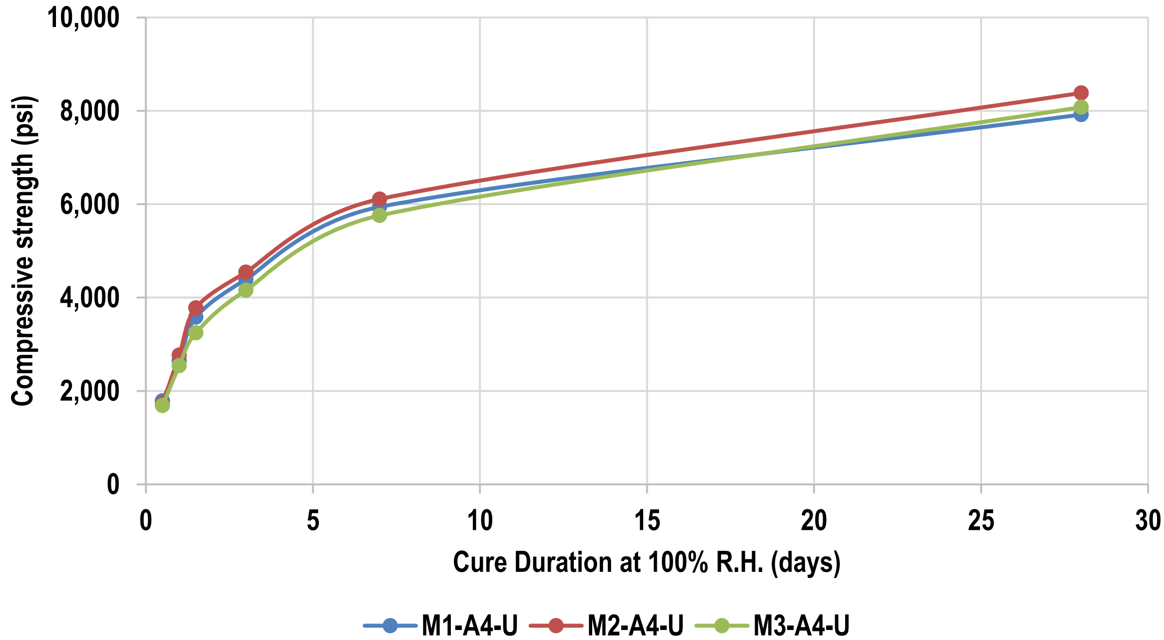

Figure 50 Compressive Strength Results for Mixes with Aggregate 4.

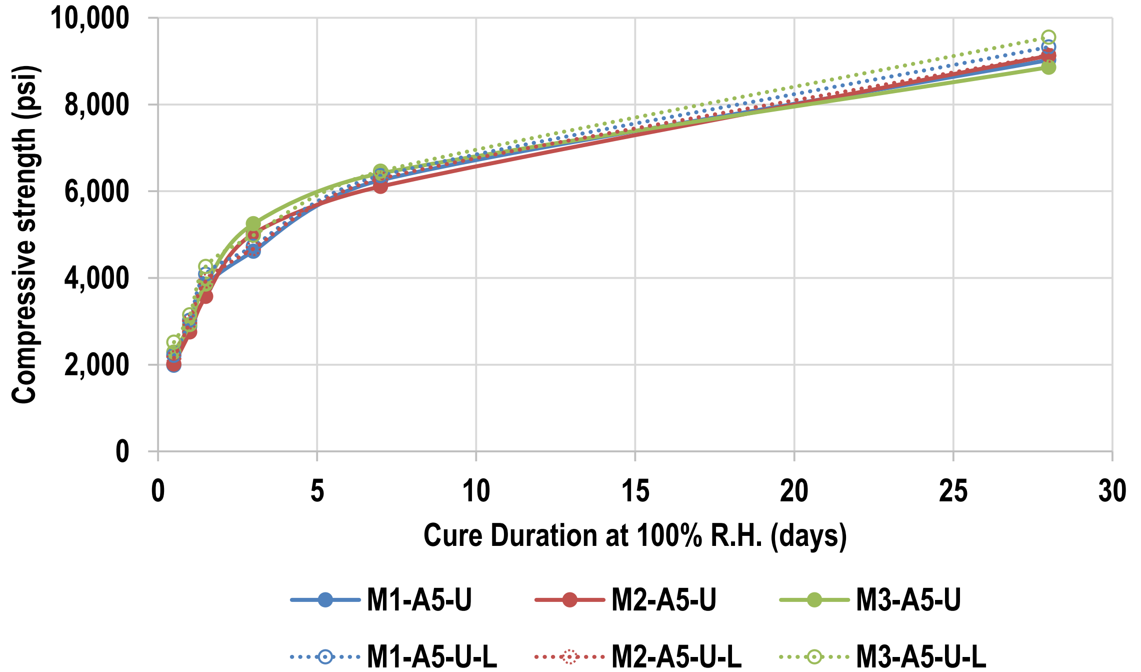

Figure 51 Compressive Strength Results for Mixes with Aggregate 5 (Includes both Cement Types).

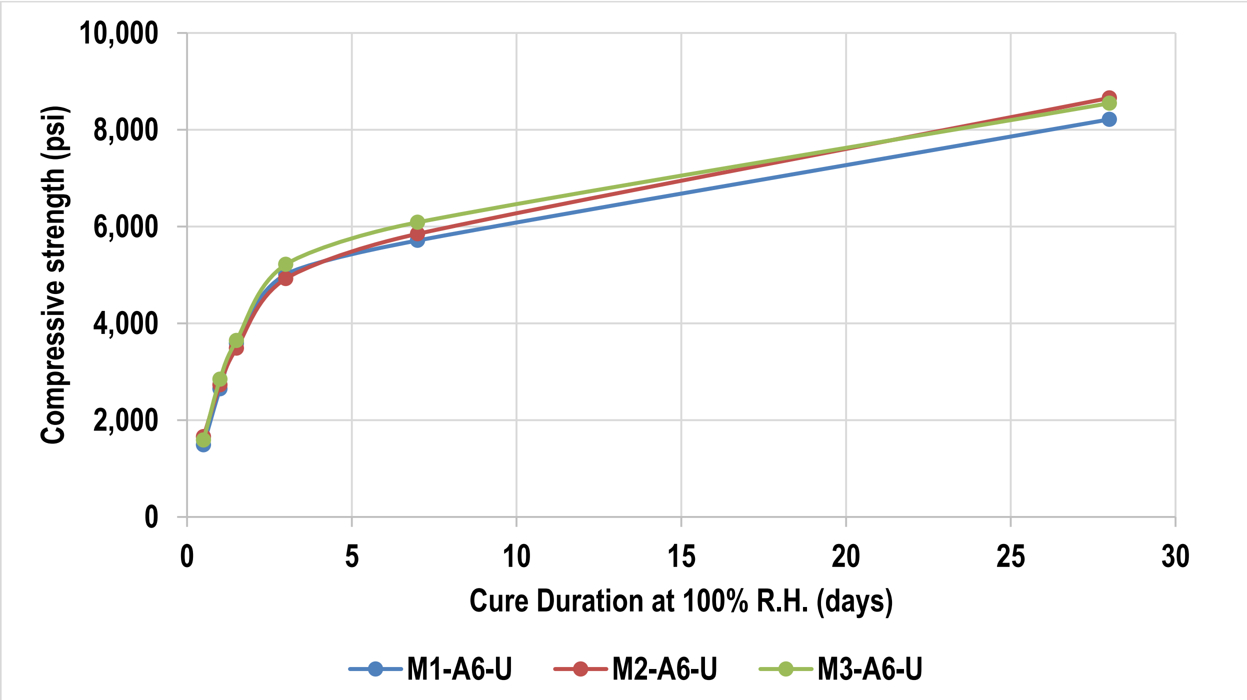

Figure 52 Compressive Strength Results for Mixes with Aggregate 6.

Table 23 Compressive Strengths for Additional MECC Mixes (in psi).

Mix ID	0.5 Day	1 Day	1.5 Days	3 Days	7 Days	28 Days
M1-A4-U	1,787	2,649	3,580	4,389	5,942	7,918
M2-A4-U	1,723	2,768	3,781	4,543	6,109	8,383
M3-A4-U	1,687	2,541	3,245	4,158	5,758	8,076
M1-A5-U	1,985	2,880	3,821	4,615	6,254	9,025
M2-A5-U	2,014	2,754	3,572	4,468	6,109	9,125
M3-A5-U	2,287	2,924	3,857	4,811	6,412	8,858
M1-A6-U	1,487	2,647	3,587	5,012	5,712	8,214
M2-A6-U	1,657	2,728	3,484	4,925	5,849	8,657
M3-A6-U	1,587	2,845	3,645	5,218	6,087	8,547
M1-A3-U-L	2,358	3,325	4,425	5,726	6,921	8,425
M2-A3-U-L	2,401	3,412	4,698	5,889	7,151	8,615
M3-A3-U-L	2,289	3,514	4,626	5,625	6,761	8,505
M1-A5-U-L	2,215	3,024	4,087	4,728	6,357	9,325
M2-A5-U-L	2,157	2,983	3,928	4,676	6,289	9,137
M3-A5-U-L	2,516	3,147	4,264	4,984	6,459	9,550

4.4 Tensile Properties

The tensile properties for the additional MECC mixes were evaluated at 3 and 28 days, just like the original MECC mixes. Table 24 summarizes the results of the tensile test for the additional MECC mixes.

Figures 53 and 54 show the 3-day tensile properties of the additional MECC mixes. The results show that the Lehigh Cement increased the tensile strengths of mixes with Aggregate 3 by about 75 psi and increased the strengths of mixes with Aggregate 5 by about 60 psi compared to mixes with Nevada Cement. For the tensile strains, the Lehigh Cement did not cause an overall significant change when compared to the Nevada Cement mixes. However, individual mixes did experience changes when using Lehigh Cement compared to Nevada Cement. When looking at mixes with Nevada Cement, mixes with Aggregate 4, 5, and 6, had average strengths of about 535 psi. The mixes with Aggregate 4 had tensile strains of 0.92%, while mixes with Aggregate 5 had strains of about 0.83%. Mixes with Aggregate 6 had average strain values of 1.03%.

Figures 55 and 56 show the 28-day tensile properties of the additional MECC mixes. The results show that the Lehigh Cement decreased the tensile strengths of mixes with Aggregate 3 by about 15 psi and decreased the strengths of mixes with Aggregate 5 by about 30 psi compared to mixes with Nevada Cement. For the tensile strains, the Lehigh Cement did not cause an overall significant change when compared to the Nevada Cement mixes. However, individual mixes did experience changes when using Lehigh Cement compared to Nevada Cement. When looking at mixes with Nevada Cement, mixes with Aggregate 4 had average strengths of 640 psi, mixes with Aggregate 5 had strengths of 670 psi and mixes with Aggregate 6 had strengths of 635 psi. The mixes with Aggregate 4 had tensile strains of 0.79%, mixes with Aggregate 5 had strains of about 0.72%, and mixes with Aggregate 6 had strain values of 0.84%.

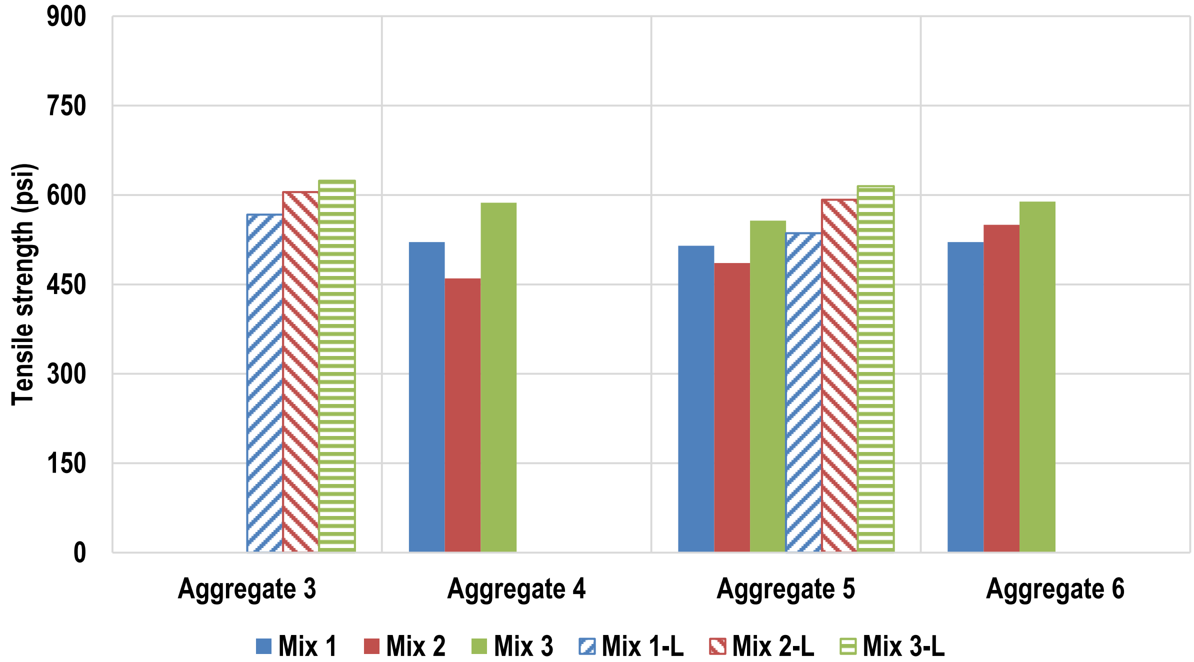

Figure 53 Three-Day Tensile Strengths for Additional MECC Mixes.

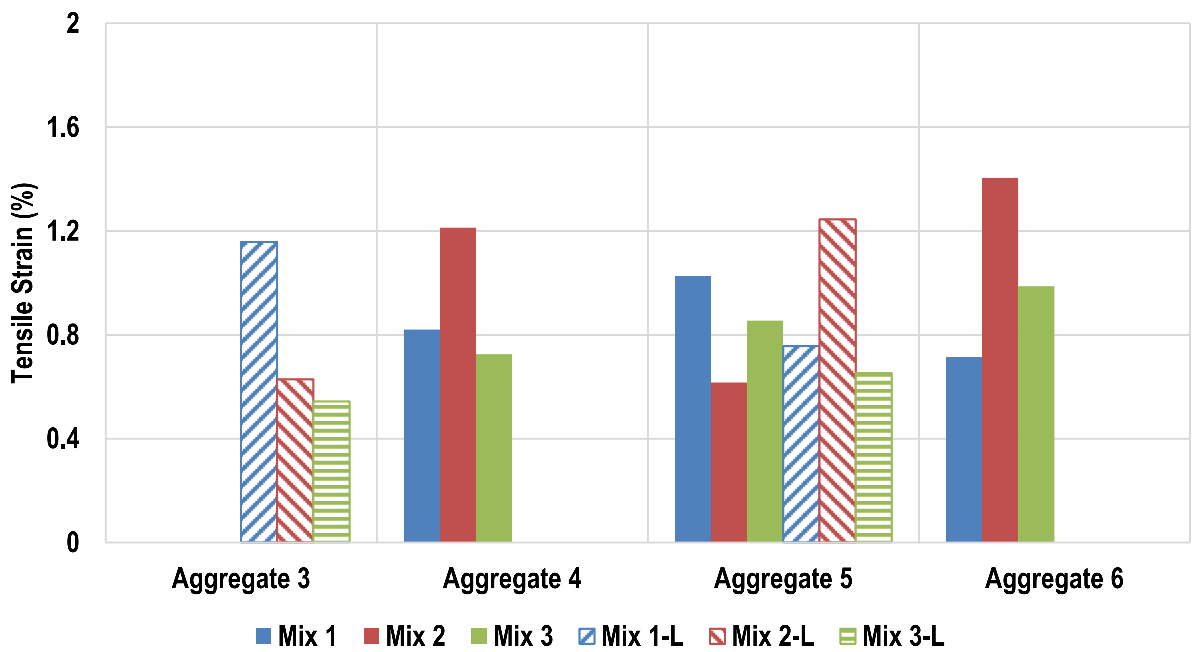

Figure 54Three-Day Tensile Strain Values for Additional MECC Mixes.

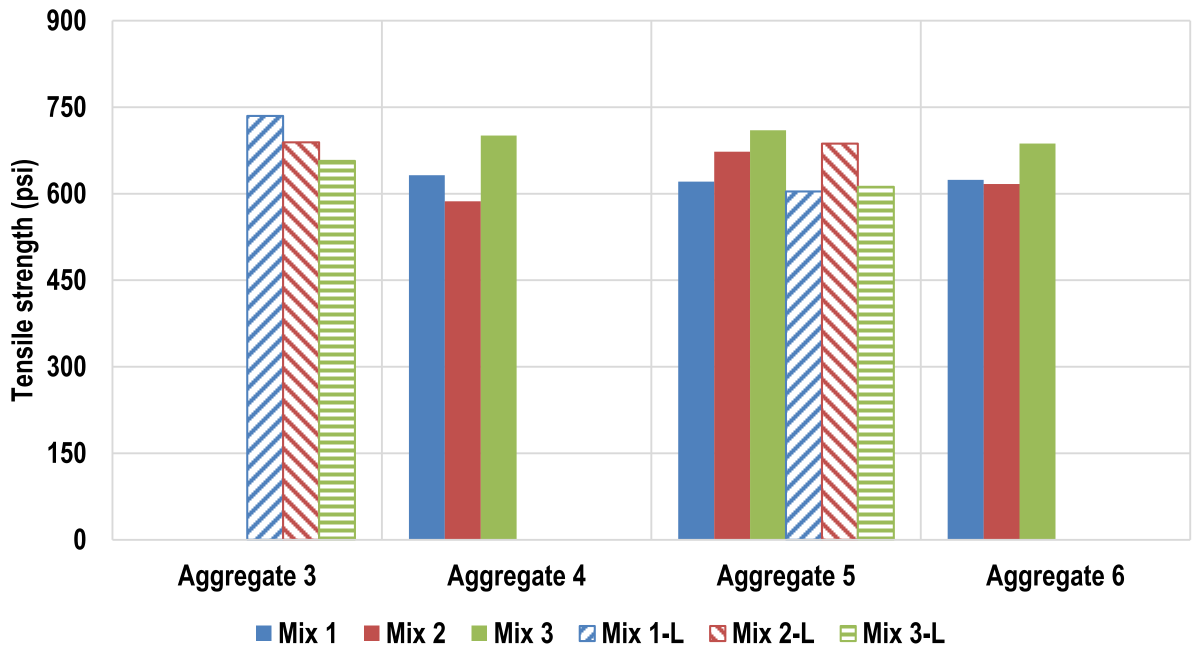

Figure 55 Twenty-Eight Day Tensile Strengths for Additional MECC Mixes.

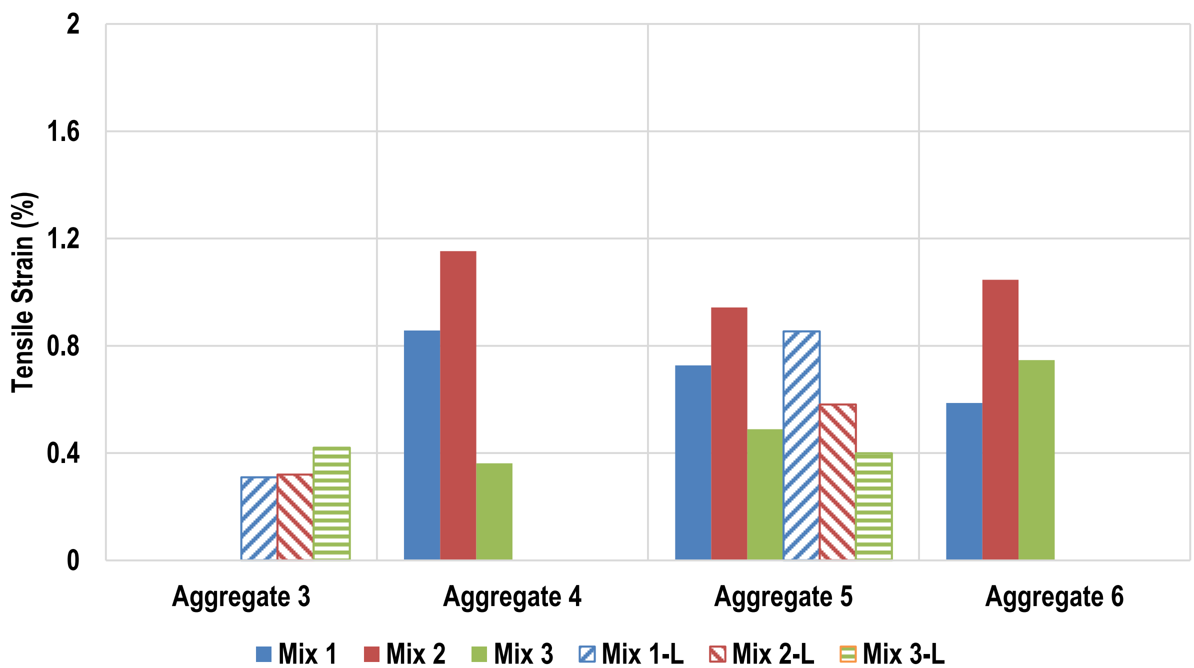

Figure 56 Twenty-Eight Day Tensile Strain Values for Additional MECC Mixes.

Table 24 Tensile Properties for Additional MECC Mixes.

Mix ID	Three Days		Twenty-Eight Days	
	Tensile Strength (psi)	**Tensile Strain (%)**	**Tensile Strength (psi)**	**Tensile Strain (%)**
M1-A4-U	521	0.82	632	0.857
M2-A4-U	460	1.213	587	1.153
M3-A4-U	587	0.725	701	0.362
M1-A5-U	515	1.027	621	0.727
M2-A5-U	486	0.616	673	0.943
M3-A5-U	557	0.855	710	0.489
M1-A6-U	521	0.714	624	0.587
M2-A6-U	550	1.405	617	1.046
M2-A6-U	589	0.987	687	0.747
M1-A3-U-L	567	1.158	735	0.315
M2-A3-U-L	605	0.628	689	0.320
M3-A3-U-L	624	0.543	657	0.426
M1-A5-U-L	536	0.756	604	0.854
M2-A5-U-L	592	1.245	687	0.581
M3-A5-U-L	615	0.652	612	0.399

4.5 Additional Laboratory Evaluations

Following the conclusion of this study, representatives of NDOT recommended the research team conduct two small experiments in the laboratory on the MECC material. The first was to evaluate how the addition of a bonding agent would affect the bond strength between an MECC overlay and an existing PCC bridge deck. The second was to evaluate how changing the curing regiment of the MECC material would affect the material's properties. In this experiment, two different curing methods were selected.

For evaluating the bond strength, SikaDur 32 Hi-Mod LPL was identified as the bonding agent to be used. This bonding agent was mixed up and applied to PCC samples that had been shot-blasted. The amount of bonding agent applied was approximately 1 gallon per 80 square feet, which is in accordance with the manufacturer's recommendations. The bonding agent was applied to the PCC samples and then the MECC material was immediately placed on top of the fresh bonding agent. Samples were stored in a cure room at 100% R.H. until time of test. Samples were tested after 1, 2, 3, and 4 days of curing. The pull-off test was used to determine the bond strength.

For the influence of curing regiment, the first curing method consisted of storing the MECC samples in a cure room at 100% R.H. for 24 hours. After which, the samples were demolded, removed from the cure room, and a wax-based curing compound was applied to the samples. The samples were then stored in the laboratory environment at approximately 30% R.H. until time of test. The second curing method consisted of placing the samples in the cure room at 100% R.H. for 10 days, with samples being demolded after 24 hours. After 10 days, the samples were removed from the cure room and a wax-based curing compound was applied to these samples. The samples were then stored in the laboratory environment at approximately 30% R.H. until time of test. Here, the compressive strength, tensile properties, and shrinkage were evaluated.

The test results for these additional laboratory evaluations are shown in Appendix E.

CHAPTER 5: OVERALL STATISTICAL ANALYSES

5.1 Introduction

This section discusses the statistical analyses that were conducted on the laboratory test results. For each test, the results were analyzed and the mixes were grouped based on the statistical differences between each other. Mixes belonging to the same group did not have statistically significant differences between them. These groups can quantify how the MECC mixes perform relative to each other, as well as how they perform compared to the polymer concrete and traditional PCC. This chapter also included the influence of the different variables and how they influence the MECC's performance. Lastly, the statistical analysis was used to determine which fine aggregate properties influenced the MECC properties.

5.2 Methodology

There were two different statistical analyses conducted on the test results presented in this study.

1. *Differences between Mixes*: The differences between the mixes was conducted using a pairwise comparison using Stata 14 statistical software *(9)*. The Tukey range test was selected as the pairwise comparison method because it was developed to determine the differences between several groups of data, and would ensure the analysis was being conducted at a true 95% confidence level. This analysis is the equivalent of running multiple t-tests, but all is included in a singular analysis. This analysis was conducted on the original eighteen MECC mixes. In this analysis, the results of each mix were compared with the results of all other mixes. For instance, Mix 1 was compared with Mixes 2 thru 18 as well as with the Polymer and PCC where applicable. The analysis provided the differences between mixes as well as the p-value, which is used to determine if the difference is statistically significant or not. A p-value less than 0.05 means the difference is significant, whereas a p-value greater than 0.05 indicates the difference is not statistically significant when considering the variability of the test results. For the grouping, mixes within the same group did not have a statistically significant difference between them. Thus, mixes within Group A are considered to have the same level of performance, even though there might be differences between the mixes' average values.

2. *Influence of Variables*: The influence of the different variables (fiber type, mix proportions, aggregate properties, etc.) was conducted using a linear regression analysis using Stata 14 statistical software *(9)*. In this analysis, the standardized beta coefficients were calculated for each of the variables. These beta coefficients are used to show the relative importance of each variable on the various MECC properties. A beta coefficient (greater than 0.2) means the variable has a moderate influence on the MECC's performance, while a lower beta coefficient (less than 0.1) means the variable has very little or no influence on the MECC's performance. High beta coefficients, greater than 0.3, mean that the variable has a high influence on the material's performance. This analysis was used on the original eighteen MECC mixes, as well as to determine the influence of cement type and the aggregate properties. For the fine aggregates properties analysis, several iterations were carried out. The first iteration contained all five of the fine aggregates properties being

evaluated, with the lease influential aggregate property being removed from the next iteration. This process continued until only the most influential fine aggregates properties remained.

5.3 Statistical Differences and Mix Groupings

5.3.1 Compressive Strengths

The statistical analysis to group the compressive strength test results focused on the early-age (0.5-day and 1-day) and late-age (28-day) compressive strength test results. Tables 25 thru 27 summarize which mixes did not have statistically significant differences between them. These tables are sorted by the average values from lowest at the top to the highest at the bottom. This means mixes at the top had the lowest compressive strengths while mixes at the bottom had the highest strengths.

Table 25 summarizes that the 6 mixes with the lowest compressive strengths all had Aggregate 1, the next six mixes all had Aggregate 3, and the six mixes with the highest strengths all had Aggregate 2. This shows that the influence of the aggregate on the 0.5-day compressive strengths is much higher than the fiber type or mix proportions. Looking at the groups, it becomes apparent that the mixes without statistically significant differences all had the same aggregate. This means that mixes within each group had the same fine aggregates, meaning the influence of fine aggregates is significant, that it is most likely the only variable that influences the compressive strengths. This table also shows the polymer concrete had much higher compressive strengths than any of the eighteen evaluated MECC mixes.

Table 26 summarizes the statistical analysis results for the 1-day compressive strengths. Like with the half-day compressive strengths, the polymer concrete had compressive strengths that were higher than any of the MECC mixes. Again, the six mixes with the lowest compressive strengths all had Aggregate 1, showing the influence the aggregate has on the MECC property. However, the table summarizes that all three fine aggregates source were represented in Group B. Within this group there are two mixes with Aggregate 1, one mix with Aggregate 2, and all six mixes with Aggregate 3. This indicates that over time, the influence of the aggregate may decrease, at which point mixes with different fine aggregates sources can exhibit the same compressive strengths.

Table 27 summarizes the 28-day compressive strengths. Again, the six mixes with the lowest compressive strengths all had Aggregate 1. However, mixes with Aggregate 2 and Aggregate 3 are intermingles, indicating the same level of performance can be obtained for these two fine aggregates. Unlike with early-age compressive strengths, the polymer concrete now had the lowest compressive strengths, with a statistically significant difference as well.

Table 25 Statistical Groupings of Half Day Compressive Strength Test Results.

Mix ID	Average Value	Statistical Group							
M1A1U	1028								
M3A1O	1090	A							
M2A1U	1096	A							
M2A1O	1112	A							
M1A1O	1116	A							
M3A1U	1212								
M2A3O	2183		B						
M3A3O	2210		B						
M1A3O	2214		B						
M3A3U	2303			C					
M1A3U	2347			C					
M1A2O	2349			C					
M3A2O	2410				D				
M1A2U	2414				D				
M2A3U	2416				D				
M3A2U	2514								
M2A2O	2587								
M2A2U	2660								
Polymer	3609								

Table 26 Statistical Grouping of One Day Compressive Strength Test Results.

Mix ID	Average Value	Statistical Group							
M3A1O	2630	A							
M1A1O	2706	A							
M2A1O	2718	A							
M2A1U	2864	A							
M3A1U	3286		B						
M1A1U	3302		B						
M1A3U	3324		B						
M1A2U	3370		B						
M2A3U	3422		B	C					
M1A3O	3442		B	C					
M2A3O	3453		B	C					
M3A3O	3522		B	C	D				
M3A3U	3537		B	C	D				
M3A2O	3614			C	D	E			
M2A2O	3717				D	E	F		
M3A2U	3719				D	E	F		
M1A2O	3820					E	F		
M2A2U	3960						F		
Polymer	4753								

Table 27 Statistical Grouping of Twenty-Eight Day Compressive Strength Test Results.

Mix ID	Average Value	Statistical Group							
Polymer	6140								
M1A1O	7104	A							
M3A1O	7115	A							
M1A1U	7230								
M2A1U	7369		B						
M2A1O	7465		B						
M3A1U	7605								
M3A2O	7894								
M2A3O	8163								
M1A3U	8400			C					
M1A2O	8405			C					
M3A3O	8405			C					
M3A2U	8431			C					
M3A3U	8513			C	D				
M2A2O	8561				D				
M2A3U	8591				D				
M1A3O	8716					E			
M2A2U	8763					E	F		
M1A2U	8858						F		

5.3.2 Tensile Properties

Tables 28 to 31 show the statistical groupings for the tensile properties of the MECC and polymer concrete. Again, these tables are sorted so that the mixes with the lowest tensile strengths and tensile strains are at the bottom while the mixes with the highest values are at the bottom. Table 28 summarizes the 3-day tensile strengths. This table shows that there are four MECC mixes with the same performance as the polymer concrete, four mixes that had higher strengths, and ten mixes that had lower strengths than the polymer concrete. This indicates that almost 50% of the mixes had similar to better performance than the polymer concrete. Additionally, we see that the mixes with the lower tensile strengths had unoiled fibers whereas the mixes with the higher strengths had oiled fibers.

Table 29 summarizes the 3-day tensile strains. This table shows that there were two MECC mixes that had similar tensile strains as the polymer concrete, with the remaining sixteen having statistically significantly higher tensile strains. This indicates that the MECC material as a whole has much better performance than the polymer concrete. This table shows that mixes with tensile strains between about 0.4% and about 0.8% had the same performance. This means that having a minimum required 3-day tensile strain of 0.4% would take into account the variability with the tensile test while still ensuring that an MECC mix that meets this criteria would have sufficient performance.

Table 30 summarizes the 28-day tensile strength values. The groupings show that there are five MECC mixes that had comparable strengths with the polymer concrete and five mixes that had higher strengths. This indicates that almost 60% of the MECC mixes had similar to better performance than the polymer concrete. The groupings show that MECC mixes with strengths between about 615 psi and 730 psi had the same performance. This would suggest that having a minimum required 28-day tensile strength of 600 would account for the variability of this test, yet still provide a quality MECC mix.

Table 31 summarizes the 28-day tensile strain values. Like with the 3-day tensile strains, the polymer concrete had the lowest tensile strain values. In fact, all eighteen mixes exhibited significantly better performance than the polymer concrete. Looking at the groupings, there is a better differentiation between the mixes. Mixes with values between 0.4% and 0.6% had roughly the same performance, which would indicate that a 28-day minimum tensile strain value of 0.4% can account for the test variability, but still ensure that the MECC mix would have sufficient performance.

Table 28 Statistical Grouping of Three-Day Tensile Strength Test Results.

Mix ID	**Average Value**	**Statistical Grouping**									
M2A3O	449	A									
M2A2U	492	A	B								
M2A3U	498	A	B								
M1A3U	516		B	C							
M3A2U	528		B	C							
M3A3U	531		B	C	D						
M2A1O	532		B	C	D						
M1A3O	535		B	C	D						
M1A2U	556			C	D	E					
M1A1O	566			C	D	E	F				
M3A3O	588				D	E	F	G			
M1A1U	595					E	F	G			
M3A1U	611						F	G			
Polymer	645							G	H		
M3A1O	676								H	I	
M2A1U	707									I	J
M1A2O	710									I	J
M3A2O	712									I	J
M2A2O	738										J

Table 29 Statistical Grouping of Three-Day Tensile Strain Test Results.

Mix ID	Average Value	Statistical Grouping									
Polymer	0.23							G			
M1A3U	0.32				D			G			
M2A3O	0.42			C	D			G			
M2A3U	0.43	A		C	D						
M3A3U	0.46	A	B	C	D						
M3A2O	0.63	A	B	C	D						
M1A2O	0.64	A	B	C	D						
M2A1U	0.69	A	B	C	D						
M3A1U	0.70	A	B	C		E					
M2A2U	0.70	A	B	C		E					
M1A2U	0.73	A	B			E					
M3A3O	0.79	A	B			E					
M3A2U	0.88		B			E					
M2A2O	0.92					E					
M1A3O	0.95						F				
M3A1O	1.05						F				
M2A1O	1.15						F				
M1A1O	1.31						F				
M1A1U	1.34										

Table 30 Statistical Grouping of Twenty-Eight Day Tensile Strength Test Results.

Mix ID	Average Value	Statistical Grouping									
M1A1U	516							G			
M2A2U	614				D			G			
M3A1U	615			C	D			G			
M3A3O	646	A		C	D						
M2A3O	647	A	B	C	D						
M1A2U	663	A	B	C	D						
M3A2U	686	A	B	C	D						
M2A1U	692	A	B	C	D						
M3A3U	693	A	B	C		E					
M2A3U	697	A	B	C		E					
M1A3U	732	A	B			E					
M1A3O	737	A	B			E					
M1A1O	759		B			E					
Polymer	770					E					
M1A2O	796						F				
M3A2O	797						F				
M2A1O	802						F				
M3A1O	809						F				
M2A2O	817										

Table 31 Statistical Grouping of Twenty-Eight Day Tensile Strain Test Results.

Mix ID	Average Value	Statistical Grouping									
Polymer	0.06										
M2A1O	0.27	A									
M1A3U	0.42	A	B								
M2A2O	0.42	A	B								
M3A3O	0.52		B								
M2A3U	0.55		B	C							
M2A3O	0.57		B	C							
M1A1U	0.58		B	C							
M2A2U	0.77			C	D						
M1A3O	0.80				D						
M3A3U	0.80				D						
M1A2U	0.85				D						
M3A1U	1.11					E					
M3A2U	1.13					E					
M2A1U	1.22					E	F				
M3A1O	1.23					E	F				
M1A2O	1.34						F				
M3A2O	1.35						F				
M1A1O	1.80										

5.3.3 Ductility

Tables 32 and 33 show the groupings for the flexural strength from the ductility test. The statistical groupings for the ductility test were only conducted on the flexural strengths. For the 3-day test results, the statistical analysis results showed that the MECC mixes are broken down into three groups, with average group values of 740 psi, 840 psi, and 980 psi for group A, B, and C, respectively. The polymer concrete had much higher flexural strengths than all of the MECC mixes tested. The mixes are primarily grouped by the aggregate, indicating the aggregate may be the more influential variable.

For the 28-day flexural strengths, there are again three groups. The polymer concrete had again significantly higher flexural strength values compared to the MECC mixes. However, all 18 MECC mixes had higher flexural strengths than the PCC did. It does not appear that the mixes are grouped by aggregate or mix proportions, indicating that both variables may have similar influence on the 28-day flexural strengths for the MECC material.

Table 32 Statistical Grouping of 3-Day Flexural Strength Test Results.

Mix ID	Average Value	Statistical Grouping		
M2A3U	726	A		
M1A3U	728	A		
M2A2U	745	A		
M3A2U	767	A		
M1A1U	783	A	B	
M1A2U	863		B	
M3A3U	863		B	
M3A1U	964			C
M2A1U	999			C
Polymer	1261			

Table 33 Statistical Grouping of 28-Day Flexural Strength Test Results.

Mix ID	Average Value	Statistical Grouping		
PCC	411			
M3A1U	753			
M2A2U	860		B	
M2A3U	882		B	
M3A2U	925		B	
M1A3U	1015			C
M1A1U	1065	A		C
M2A1U	1069	A		C
M1A2U	1095	A		
M3A3U	1119	A		
Polymer	1695			

5.3.4 Drying Shrinkage

Tables 34 and 35 show the statistical groupings for the shrinkage test results. The statistical groupings were conducted for the 7-day and 28-day shrinkage values. The groupings for the 7-day shrinkage values show that there are four MECC mixes with comparable shrinkage as the PCC, five mixes with lower shrinkage, and nine mixes with higher shrinkage values. The mixes with the lowest shrinkage typically had Aggregate 2, while the mixes with Aggregate 1 and Aggregate 3 had the highest shrinkage values. Because of the low variability within this test, most of the differences were found to be statistically significant.

For the 28-day shrinkage values, there were three MECC mixes with comparable shrinkage values to the PCC, and only one mix with higher shrinkage values. That means there were fourteen MECC mixes (about 80%) with lower shrinkage values at 28-days than the PCC. While the mixes with shrinkage values between 0.037% and 0.043% were found to have comparable performance, all thirteen of these mixes had a statistically significant difference with the PCC's shrinkage. This indicates that while MECC has a higher potential for shrinkage, if cured properly, MECC in general should have lower shrinkage values than traditional PCC mixes.

Table 34 Statistical Grouping of Seven-Day Shrinkage Test Results.

Mix ID	**Average Value**	**Statistical Group**									
M1A2O	0.011										
M1A2U	0.012	A									
M1A1O	0.012	A									
M3A2U	0.012	A									
M3A2O	0.013						F				
M2A2O	0.014		B				F				
M2A1U	0.014		B								
PCC	0.015		B	C							
M2A2U	0.015			C	D						
M3A3O	0.015			C	D						
M3A3U	0.016				D			G			
M2A1O	0.016							G			
M3A1O	0.017					E					
M1A1U	0.017					E					
M1A3O	0.017					E			H		
M3A1U	0.018								H	I	
M1A3U	0.018									I	
M2A3O	0.020										J
M2A3U	0.020										J

Table 35 Statistical Grouping of Twenty-Eight Day Shrinkage Test Results.

Mix ID	**Average Value**	**Statistical Group**									
M3A2U	0.037							G			
M3A2O	0.037				D			G			
M1A2O	0.037			C	D			G			
M1A2U	0.038	A		C	D						
M3A3O	0.039	A	B	C	D						
M3A3U	0.040	A	B	C	D						
M2A1U	0.040	A	B	C	D						
M2A3O	0.042	A	B	C	D						
M1A1O	0.042	A	B	C		E					
M2A2U	0.043	A	B	D		E					
M2A3U	0.043	A	B			E					
M2A1O	0.043	A	B			E					
M3A1O	0.043		B			E					
M2A2O	0.043					E					
PCC	0.044						F				
M1A1U	0.044						F				
M3A1U	0.044						F				
M1A3O	0.045						F				
M1A3U	0.046								H		

5.3.5 Abrasion Resistance

The abrasion resistance values were statistically grouped after two cycles and five cycles. Table 36 and 37 show the statistical groupings for the abrasion resistance test results. After two abrasion cycles, the statistical groupings show that there were two MECC mixes with similar performance to the polymer concrete, with two mixes having lower mass loss, but forteen mixes having higher mass loss. However, all eighteen MECC mixes had lower mass loss values than the PCC. The test results did not have much variability, so most of the differences between the mixes were found to be statistically significant.

The statistical groupings for the abrasion resistance values after five cycles show a similar trend. There was only one MECC mix with comparable performance to the polymer concrete, with the remaining seventeen mixes having higher mass loss values. However, all eighteen MECC mixes had lower mass loss values compared to the PCC. Like with the mass loss values after two abrasion cycles, there was low variability with the mass loss values after five abrasion cycles, so most of the differences between the mixes were statistically significant.

Table 36 Statistical Grouping of Abrasion Resistance Test Results after Two Cycles.

Mix ID	**Average Value**	**Statistical Group**							
M1A2U	1.0				D				
M1A2O	1.1				D				
M3A3O	1.3			C					
M2A2U	1.3			C					
Polymer	1.4			C					
M3A3U	1.5					E			
M2A2O	1.6					E	F		
M1A1O	1.7		B				F		
M2A3U	1.8	A	B						
M1A1U	1.8	A	B						
M3A1O	1.8	A	B						
M1A3O	1.8	A	B						
M2A3O	1.8	A							
M3A2O	1.8	A							
M2A1U	1.8	A							
M2A1O	1.9	A							
M3A1U	2.1							G	
M1A3U	2.1							G	
M3A2U	2.2								
PCC	3.5								

Table 37 Statistical Grouping of Abrasion Resistance Test Results after Five Cycles.

Mix ID	Average Value	Statistical Group							
Polymer	2.1				D				
M2A2U	2.9				D				
M3A3O	3.3			C					
M2A2O	3.3			C					
M3A3U	3.6			C					
M1A2U	3.7					E			
M3A1O	3.7					E	F		
M3A2O	3.8		B				F		
M2A3U	3.9	A	B						
M1A2O	4.0	A	B						
M3A1U	4.2	A	B						
M2A1O	4.3	A	B						
M1A3O	4.4	A							
M3A2U	4.4	A							
M2A3O	4.4	A							
M2A1U	4.7	A							
M1A3U	4.8							G	
M1A1O	5.3							G	
M1A1U	5.5							G	
PCC	8.2								

5.3.6 Resistance to Chloride ion Penetration

Table 38 summarizes the statistical groupings for the chloride ion penetration test. The test results show that all eighteen MECC mixes had much higher penetration values compared to the polymer concrete, but were all lower than the PCC mix. The groupings show that the MECC mixes are grouped primarily based on the mix proportions. MECC mixes with Mix Proportion 2 had the lowest penetration values while mixes with Mix Proportion 3 had the highest values. The results show that the MECC mixes with Mix Proportions 2 all had similar chloride ion penetration resistance. The same holds true for mixes with Mix Proportions 2 and 3, respectively. This indicates that the influence of the mix proportions is very high, otherwise there would be less mixes grouped by the mix proportions and more mixes grouped by aggregate or fiber type. Additionally, the polymer concrete had a statistically significant different with all eighteen MECC mixes, so too did the PCC with the 18 MECC mixes. This indicates that the MECC material had greater resistance to chloride ion penetration than traditional PCC, but not as much as the polymer concrete material.

Table 38 Statistical Grouping of Chloride Ion Penetration Test Results.

Mix ID	**Average Value**	**Statistical Group**									
Polymer	300										
M2A2U	1660		B								
M1A2U	1670		B	C							
M2A2O	1682		B	C	D						
M2A3U	1684		B	C	D						
M2A3O	1699		B	C	D					I	
M2A1U	1711			C	D					I	
M1A2O	1723				D					I	J
M2A1O	1744									I	J
M1A3O	1771					E					J
M1A1O	1782	A				E					J
M1A3U	1784	A				E					J
M3A2O	1801	A				E	F				
M3A2U	1817	A				E	F	G			
M1A1U	1822	A					F	G	H		
M3A3U	1824	A					F	G	H		
M3A3O	1845						F	G	H		
M3A1O	1866							G	H		
M3A1U	1869								H		
PCC	1993										

5.4 Influence of Aggregate, Mix Proportions, and Fiber Type on MECC's Properties

In determining the influence of the fine aggregates source, mix proportions, and fiber type on the MECC material's properties, the beta coefficients from a linear regression analysis were determined. A low beta value (less than 0.1) indicates the variable has little to no influence. A mid-level beta value (between 0.1 and 0.2) indicates a moderate influence. A higher beta value (between 0.2 and 0.3) means the variable has a high influence. Beta values greater than 0.3 indicate a strong influence by the variable on the MECC property. These values were determined and are shown in Table 39.

Figure 57 shows the beta coefficients for the tensile strengths plotted at different curing durations. The analysis shows that the early age tensile strength values are influenced by both the fiber type and the fine aggregates used. The mix proportions had very little influence on the 3-day tensile strengths. However, at 28 days, the influence of the fine aggregates source has decreased while the influence of the fiber type increased. This indicates that the fiber type was the most influential variable, while the fine aggregates source influenced the early-age tensile strengths, and the mix proportions having very little influence on the tensile strengths.

Figure 58 shows the beta coefficients for the tensile strain values plotted at different curing duration. At 3 days, all three variables (i.e., fine aggregates source, mix proportions, and fiber type) influence the tensile strains, with the most influential variable being the aggregate. At 28 days, the influence of all three variables drops. The mix proportions did not influence the tensile strains, while the fiber type had a slight influence. The fine aggregates source still had a very large influence on the tensile strain values. This indicates that the tensile strain values are heavily influenced by the fine aggregates used. The mix proportions only influenced the 3-day strains, while the fiber type had a moderate influence on tensile strain at both 3 days and 28 days.

Table 39 Beta Coefficients for Influence of Aggregate, Mix Proportions, and Fiber Type on MECC Properties.

Property	**0.5 Day**	**1 Day**	**1.5 Days**	**3 Days**	**7 Days**	**28 Days**
Tensile Strength						
Aggregate				0.418		0.026
Mix Prop				0.097		0.027
Fibers				0.296		0.615
Tensile Strain						
Aggregate				0.666		0.415
Mix Prop				0.195		0.023
Fibers				0.287		0.14
Compressive Strength						
Aggregate	0.776	0.523	0.244	0.651	0.637	0.778
Mix Prop	0.024	0.046	0.029	0.083	0.121	0.097
Fibers	0.064	0.141	0.338	0.37	0.493	0.186
Abrasion Resistance						
	Cycle 1	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**	
Aggregate	0	0.158	0.238	0.271	0.338	
Mix Prop	0.456	0.274	0.041	0.231	0.477	
Fibers	0.245	0.155	0.017	0.124	0.113	
Ductility Flexural Strength						
	0.5 Day	**1 Day**	**1.5 Days**	**3 Days**	**7 Days**	**28 Days**
Aggregate				0.577		0.144
Mix Prop				0.296		0.424
Fibers						
Shrinkage						
	4 Days	**7 Days**	**14 Days**	**21 Days**	**28 Days**	
Aggregate	0.292	0.304	0.012	0.018	0.041	
Mix Prop	0.237	0.087	0.057	0.146	0.293	
Fibers	0.204	0.114	0.241	0.126	0.034	
RCP*						
Aggregate						0.183
Mix Prop						0.458
Fibers						0.057

Note: *Resistance to Chloride Ion Penetration test was performed after 56 days of curing at 100% R.H.

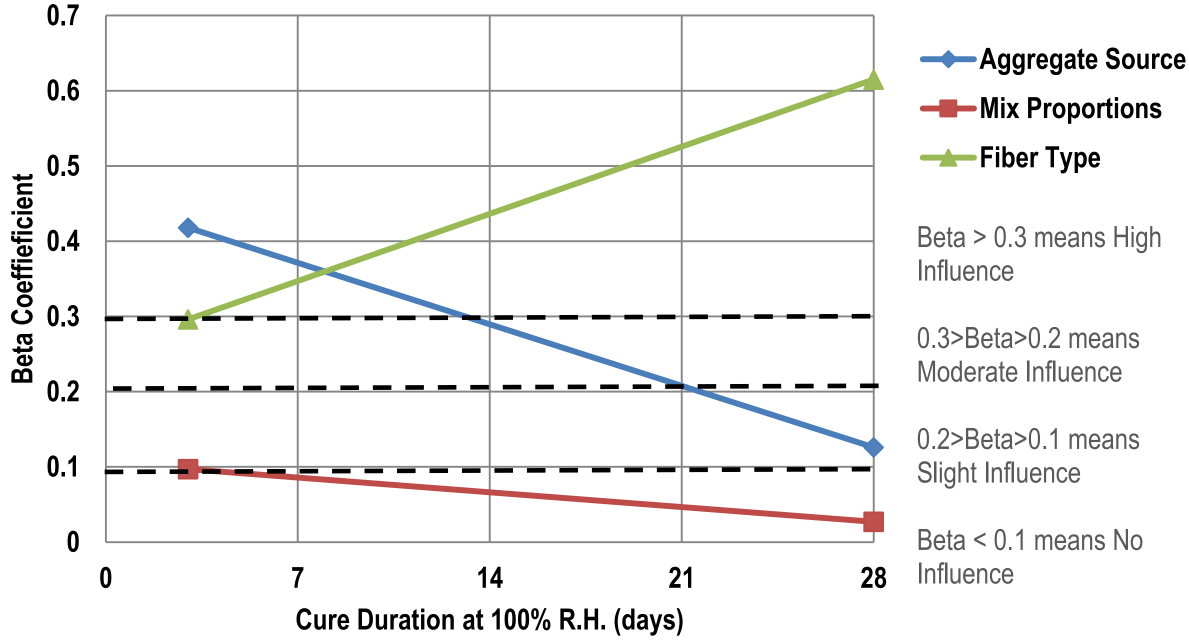

Figure 57 Beta Coefficients for Tensile Strength.

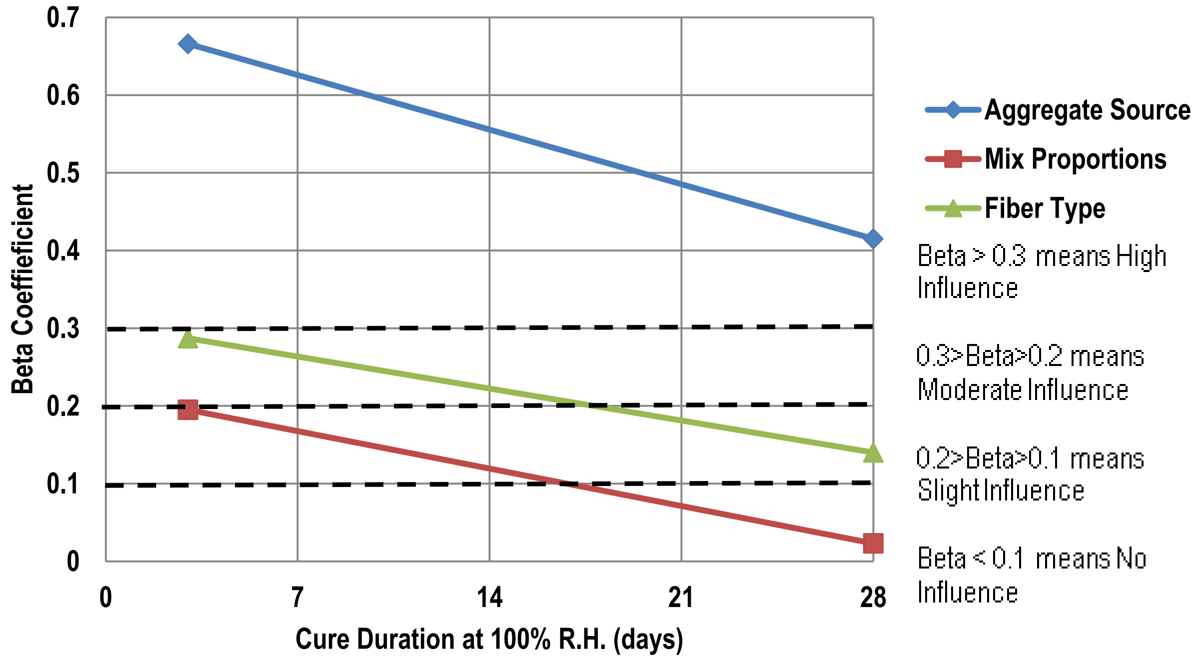

Figure 58 Beta Coefficients for Tensile Strain.

Figure 59 shows the beta coefficients for the compressive strengths plotted for different curing durations. This figure shows that the 12 hours and 1 day compressive strengths are solely influenced by the fine aggregates used. At 1.5, 3, and 7 days, the fine aggregates and the fiber type both influenced the compressive strengths. However, at 28 days, the influence of the fibers decreases such that the fine aggregate becomes the most influential variable. The mix proportions only had little to no influence at all curing durations. This indicates that the compressive strengths will be influenced mainly by the fine aggregates source, with the fiber type influencing the early-age strengths.

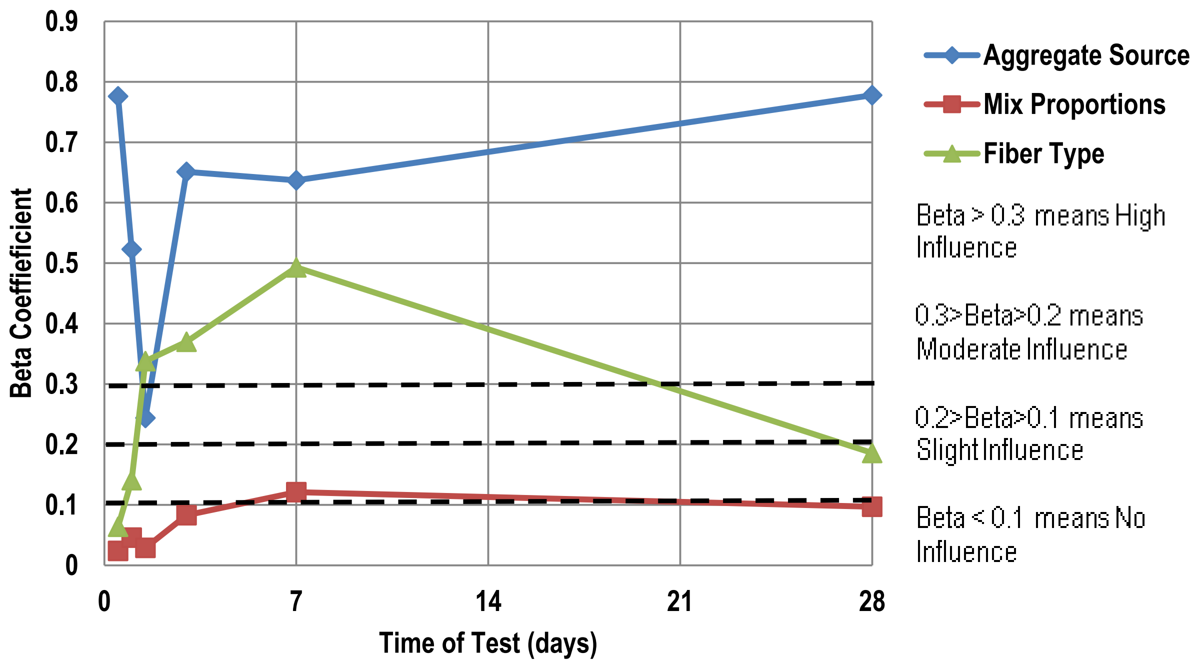

Figure 59 Beta Coefficients for Compressive Strength.

Figure 60 shows the beta coefficients for the abrasion resistance plotted against the abrasion cycle number. The figure shows that the early-age abrasion resistance is influenced primarily by the fiber type and mix proportions, with the fine aggregate source having no influence at all. However, after 2 and 3 cycles, the mix proportions and fiber type both had a decreased influence, while the fine aggregates source had an increased influence. After 4 and 5 cycles, both the aggregate and mix proportions had an increased influence on the abrasion resistance while the influence of the fibers remained minimal.

Figure 61 shows the beta coefficients for the ductility flexural strengths plotted for different curing durations. Because only unoiled fibers were used during this test, the influence of the fiber type could not be determined. The figure shows that both the fine aggregates source and mix proportions had high influences on the 3-day flexural strengths. However, at 28 days, the influence of the aggregate severely decreases while the mix proportions increases. This suggests that the early-age flexural strengths are primarily influenced by the fine aggregates source, but the 28-day strengths are more influenced by the mix proportions with the fine aggregates source having only a small influence.

Figure 62 shows the beta coefficients for the drying shrinkage test results for different curing durations. This figures shows that the 4-day shrinkage values are influenced by all three variables. At 7 days, the shrinkage is primarily influenced by the fine aggregates source, with the fibers and mix proportions providing only a small influence. At 14 days, the influence of the fine aggregates source becomes insignificant, and remains that way for the higher curing durations. However, the influence of the fibers increased and is the primary influential variable on the shrinkage values. At 21 days, the mix proportions and fiber type both had a moderate influence on the shrinkage. At 28 days, the mix proportions were the only variable influencing the shrinkage values, while the fine aggregates source and fiber type both had no influence on the shrinkage properties of MECC.

Figure 63 shows the beta coefficients for the resistance to chloride ion penetration. The fiber type had no influence on the material's resistance to chloride ion penetration while the fine aggregates source had a moderate influence. The mix proportions had the highest influence on the MECC's resistance to chloride ion penetration. This suggests that sufficient resistance to chloride ion penetration can be achieved by adjusting the mix proportions.

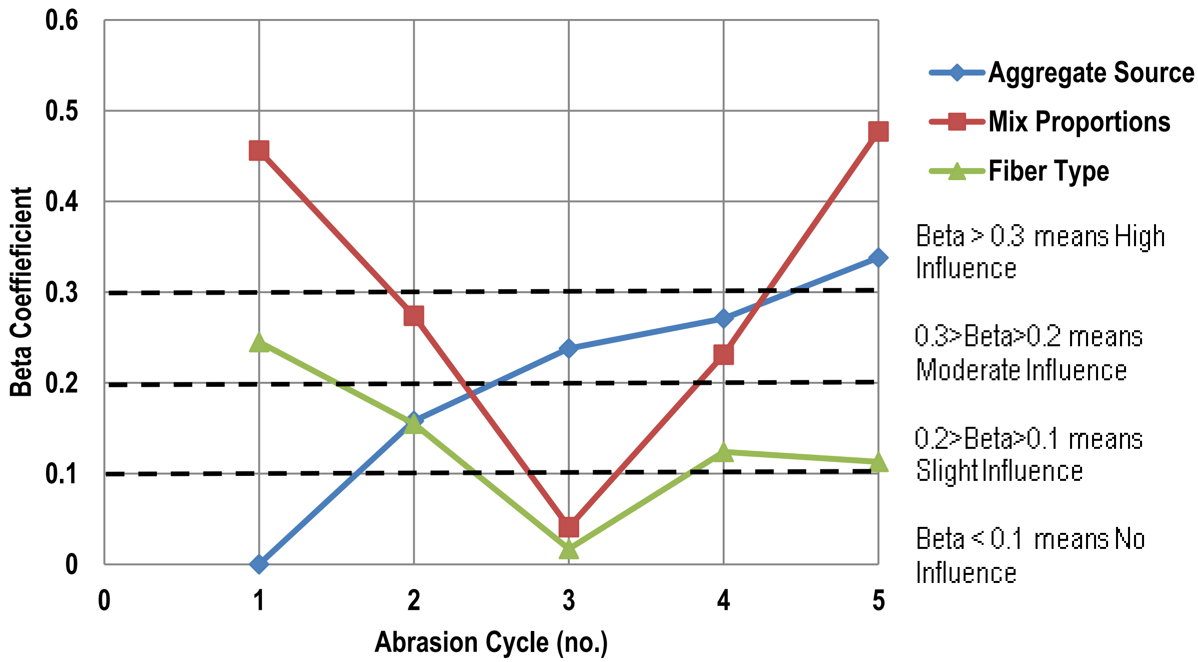

Figure 60 Beta Coefficients for Abrasion Resistance.

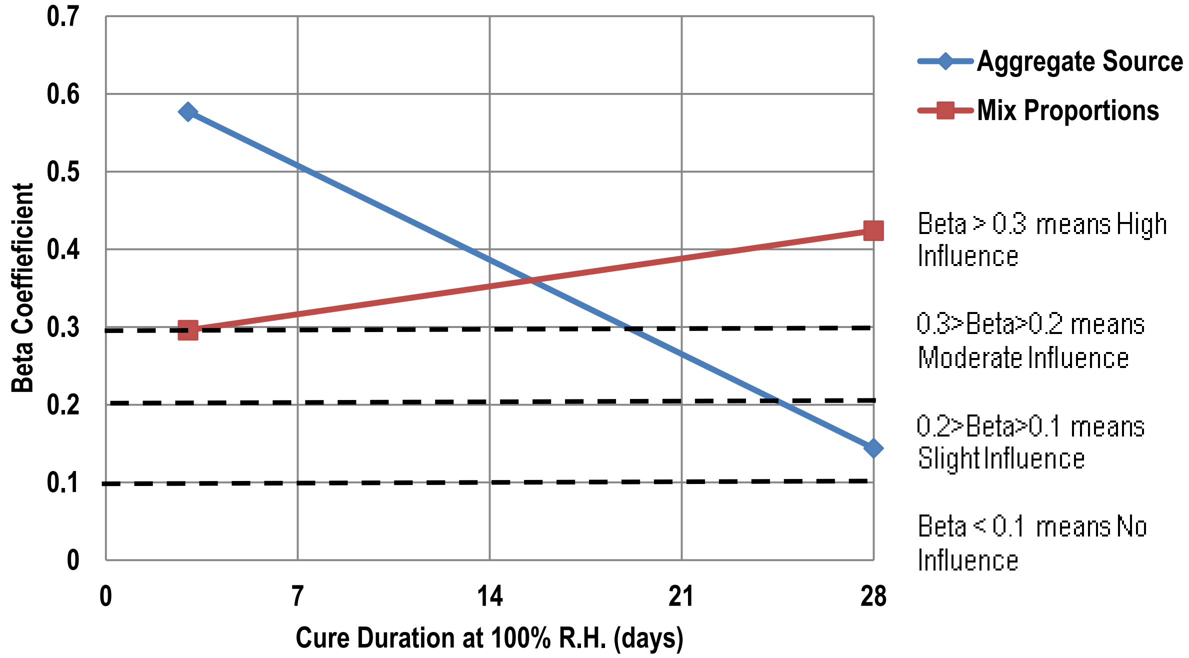

Figure 61 Beta Coefficients for Flexural Strength.

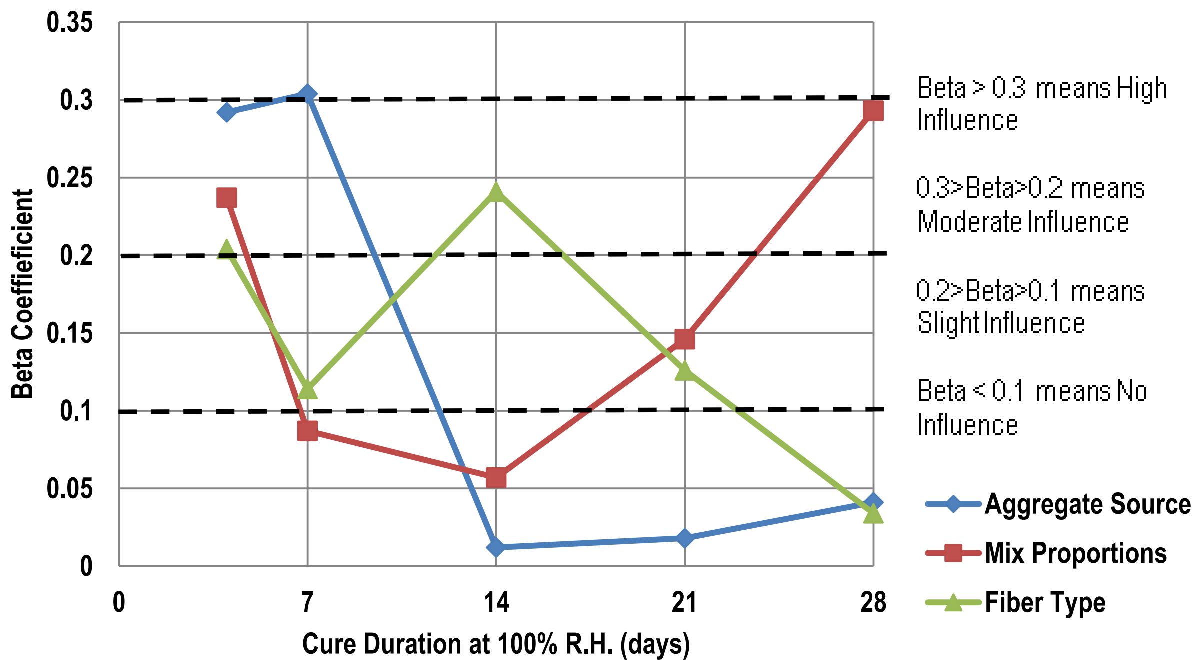

Figure 62 Beta Coefficients for Drying Shrinkage.

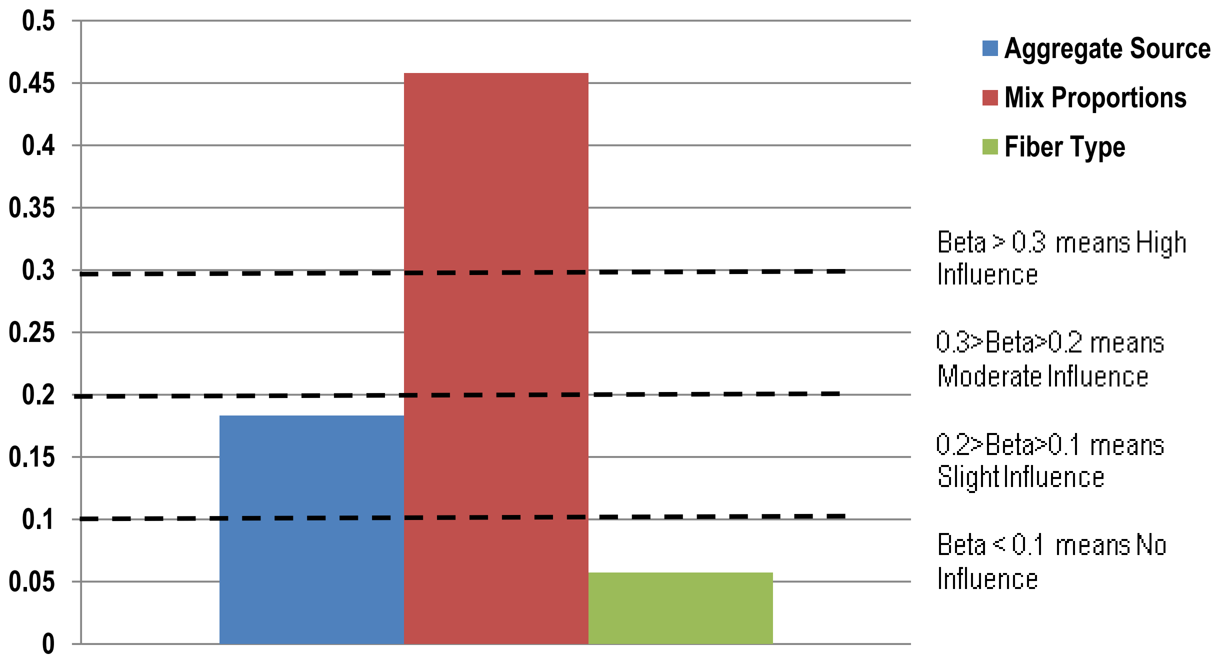

Figure 63 Beta Coefficients for Resistance to Chloride Ion Penetration.

5.5 Influence of Cement Type

When looking at the influence of cement, there were two different analyses conducted. First, t-tests were conducted to determine the differences in performance between the mixes with Lehigh Cement and Nevada Cement, and whether or not this difference was statistically significant. Second, a linear regression was conducted to determine the beta coefficients, which were used to determine how much influence the cement had on the MECC's properties.

Table 40 summarizes the change in performance associated with using different cements. This table shows how the substitution of Lehigh Cement for Nevada Cement affected the MECC mix properties. For example, using Lehigh Cement instead of Nevada Cement caused an increase of 3-day tensile strength values by 6.5 psi. The results show that the Lehigh Cement did produce a large change in the 3-day tensile strengths. While the addition of Lehigh Cement caused 28-day strengths to be 50 psi higher and the difference was not statistically significant. However, the Lehigh Cement caused significant decreases in the tensile strain values at both 3 and 28 days. These differences were also statistically significant, signifying that the use of Lehigh Cement can cause a negative impact on the MECC properties compared to the Nevada Cement. The half-day compressive strengths were increased by about 100 psi compared to the Nevada Cement, which was a statistically significant difference. While the compressive strengths afterwards were higher with the Lehigh Cement, these differences were not statistically significant; suggesting the use of Nevada Cement gave the MECC similar performance when using the Lehigh Cement.

Table 40 Summary of MECC's Performance Change with Different Cements (Lehigh Cement compared to Nevada Cement).

Property	0.5 Day	1 Day	1.5 Days	3 Days	7 Days	28 Days
Tensile Strength (psi)						
Difference				6.5		51
P-value				0.7021		0.1016
Significant?				No		No
Tensile Strain (%)						
Difference				-0.272		-0.194
P-value				0.0426		0.0425
Significant?				Yes		Yes
Compressive Strength (psi)						
Difference	97	96	171	89	199	191
P-value	0.0337	0.209	0.1222	0.5724	0.3452	0.2836
Significant?	Yes	No	No	No	No	No

Table 41 summarizes the beta coefficients from the linear regression. The results show that the cement type had the highest influence on the 3-day tensile strains, with the mix proportions also having a large influence. However, at 28 days, the influence of the cement type dropped to moderate levels, while the influence of the fine aggregate source increased and became the most influential variable. At 28 days, the mix proportions had no influence on the tensile strengths. For the tensile strains, the cement type had a moderate influence for both the 3-day and 28-day test results. The cement type had almost the same influence on tensile strain as the fine aggregates source. For the compressive strengths, the cement type had a high influence at 0.5 days and a moderate influence at 1 and 1.5 days. However, after 3 days the influence of the cement type dropped to very low levels. Figures 64 thru 66 show the beta coefficients plotted for different curing durations.

Table 41 Beta Coefficients for Cement Influence.

Property	0.5 Day	1 Day	1.5 Days	3 Days	7 Days	28 Days
Tensile Strength						
Aggregate				0.057		0.489
Mix Prop.				0.341		0.021
Cement				0.635		0.227
Tensile Strain						
Aggregate				0.441		0.404
Mix Prop.				0.255		0.086
Cement				0.349		0.359
Compressive Strength						
Aggregate	0.488	0.901	0.877	0.959	0.44	0.889
Mix Prop.	0.31	0.219	0.155	0.084	0.139	0.252
Cement	0.3	0.185	0.226	0.044	0.117	0.036

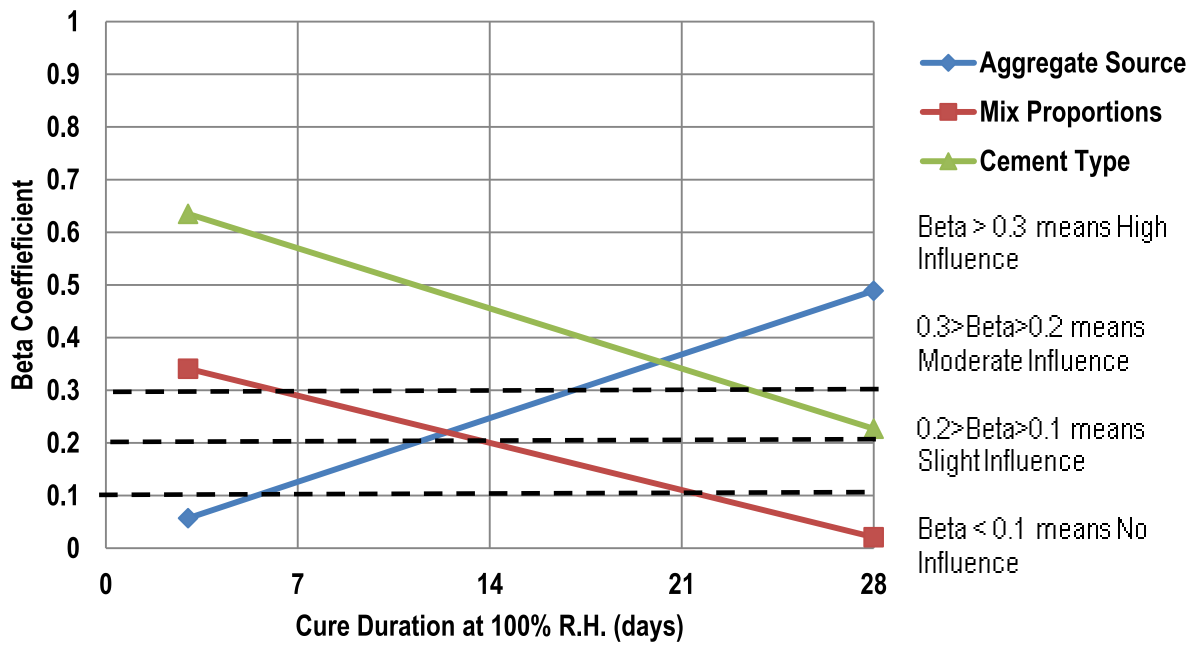

Figure 64 Beta Coefficients for Influence of Cement on Tensile Strengths.

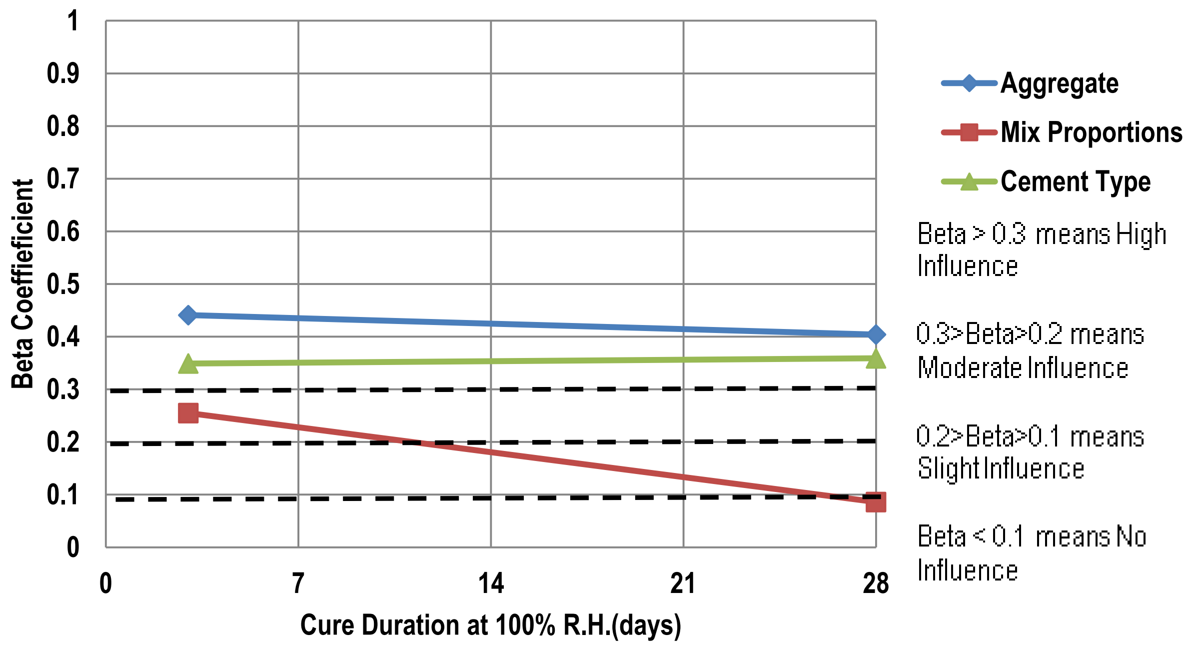

Figure 65 Beta Coefficients for Influence of Cement on Tensile Strains.

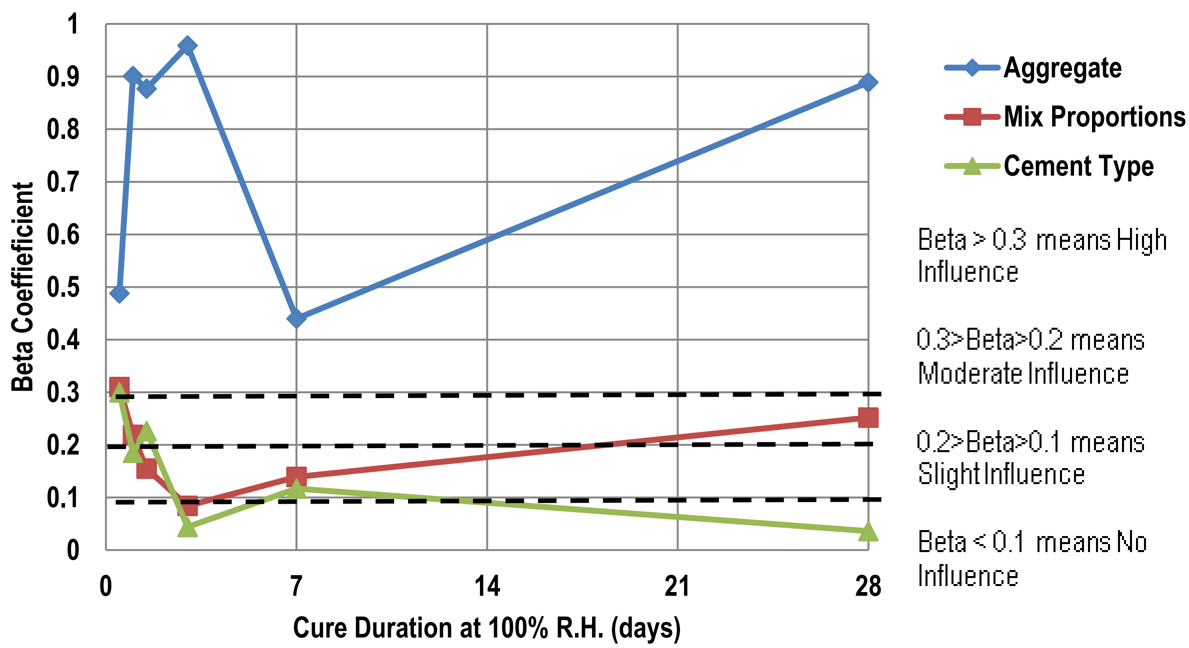

Figure 66 Beta Coefficients for Influence of Cement on Compressive Strengths.

5.6 Influence of Fine Aggregates Properties

The influence of fine aggregates properties analysis was carried out to help identify what desirable properties a fine aggregates should have for use in MECC mixes. By identifying which fine aggregates properties influenced the performance of MECC helps identifying which concrete sands would be ideal for use in MECC. Tables 42 and 43 show the results of this analysis. The fine aggregates properties used in this analysis were the fineness modulus (FM), bulk SSD specific gravity (SG), absorption (Abs), sand equivalent (SE), and uncompacted voids (Uncomp). The tables present the beta coefficients for each variable and the R-squared value, which shows how strong the fine aggregates properties can predict the MECC performance. The analysis was performed in iterations, where all five aggregate properties were included in the first iteration, and the fine aggregate property with the lowest influence was removed for the next iteration. These iterations were continued until all of the fine aggregate properties remaining would have a significant influence on the MECC material properties.

For the compressive strengths, it appears that the uncompacted voids of the fine aggregates had the highest influence on the compressive strengths at all curing durations. For the early-age compressive strengths (half- and one-day), a high fineness modulus is also desired to achieve high strengths. The half-day compressive strengths were also higher for mixes with high specific gravity (SSD) of fine aggregates. At one-day, the specific gravity (SSD) loses its influence, while the sand equivalent becomes more influential; a higher value is desired. At 28 days, the uncompacted voids are the only influential fine aggregates property. While the absorption is also shown to be influential, the absorption values and uncompacted void values may be collinear; meaning a change in the uncompacted voids would cause a change in the absorption. Because these properties are not completely independent, the influence of the absorption may not be as high as the analysis suggested. However, a medium absorption value of 2% would be the desired for fine aggregates to achieve high 28-day strengths.

For the 3-day tensile strengths, a high specific gravity (SSD), a medium absorption value (2%), and medium sand equivalent values (85-90) were found desirable fine aggregate properties to achieve high tensile strengths. Unlike the compressive strengths, a low uncompacted void value would give MECC mixes higher tensile strengths. This shows that balancing the compressive strengths and tensile strengths is critical when selecting the fine aggregates stockpile. For the 3-day tensile strain values, a high fineness modulus, medium specific gravity (2.6), and a low uncompacted void value resulted in a MECC mix with higher tensile strains. For the 28-day tensile strengths, a high fineness modulus, low specific gravity (SSD), and medium uncompacted void (40) values were found desired to achieve high tensile strengths. The 28-day tensile strains were highest when the fine aggregates had a high fineness modulus, high specific gravity (SSD), and either low or high uncompacted void values (35 or 45).

It is important to note that the findings for the fine aggregate properties are a function of the aggregate sources evaluated. This means that the influences of the individual aggregate properties (fineness modulus, sand equivalent, etc.) were limited to the ranges and variations of these values used in this study. If additional fine aggregate sources were evaluated, or different aggregate sources were evaluated instead of the six within this study, then the results of the statistical analyses would be different. Hence, the observations found in this study might not be applicable for materials that are outside the range of values available for this study.

Table 42 Influence of Aggregate Properties on Compressive Strengths of MECC.

One Day Compressive Strength					
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	4th Iteration	Desired Value
FM	0.534	0.52	0.676		High
SG	0.482	0.5	0.624		High
Abs	0.312	0.25	---		
SE	0.0895	---	---		
Uncomp	1.452	1.446	1.457		High
R-sqrd	0.951	0.947	0.905		
One Day Compressive Strength					
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	4th Iteration	Desired Value
FM	0.476	0.514	0.564		High
SG	0.026	---	---		
Abs	0.127	0.137	---		
SE	0.521	0.517	0.588		High
Uncomp	0.783	0.813	0.901		High
R-sqrd	0.683	0.688	0.683		
Twenty-Eight Day Compressive Strength					
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	4th Iteration	Desired Value
FM	0.111	---	---	---	
SG	0.244	0.284	0.223	---	
Abs	0.355	0.347	0.325	0.368	2%
SE	0.215	0.212	---	---	
Uncomp	0.8	0.894	0.88	0.916	High
R-sqrd	0.838	0.84	0.816	0.773	

Table 43 Influence of Aggregate Properties on Tensile Properties of MECC.

Three Day Tensile Strength				
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	Desired Value
FM	0.179	---		
SG	0.493	0.557		High
Abs	0.430	0.443		2
SE	0.398	0.393		85-90
Uncomp	0.244	0.396		Low
R-sqrd	0.423	0.430		
Three Day Tensile Strain				
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	Desired Value
FM	1.695	1.656	1.404	High
SG	0.867	0.815	0.779	2.6
Abs	0.118	---	---	
SE	0.398	0.457	---	
Uncomp	1.540	1.545	1.503	Low
R-sqrd	0.475	0.478	0.310	
Twenty-Eight Day Tensile Strength				
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	Desired Value
FM	0.871	0.821	0.927	High
SG	0.607	0.679	0.762	Low
Abs	0.373	0.173	---	
SE	0.311	---	---	
Uncomp	1.024	1.002	1.009	40
R-sqrd	0.333	0.288	0.280	
Twenty-Eight Day Tensile Strain				
Agg. Property	1st Iteration	2nd Iteration	3rd Iteration	Desired Value
FM	1.199	1.166	1.427	High
SG	0.586	0.635	0.841	High
Abs	0.566	0.429	---	
SE	0.215	---	---	
Uncomp	1.219	1.204	1.222	45 or 35
R-sqrd	0.429	0.413	0.302	

5.7 Summary of Findings from Statistical Analyses

The statistical analyses performed in this study were used to identify which variables would influence the performance of the MECC mix. Table 44 summarizes how the fine aggregates source (Agg), mix proportions (Mix), and fiber type (Fiber) influenced each of the material's properties. The beta factors showed that the most influential variable was the fine aggregates source. This indicates that selecting the appropriate fine aggregates for use in MECC is critical in developing a quality MECC mix. The decision of whether to use oiled or unoiled fibers may be driven primarily by cost; oiled fibers cost considerably more than the unoiled fibers. However, using low-quality fine aggregates may require the use of oiled fibers to achieve the required MECC material properties. The mix proportions are also an important factor on the MECC mixture's performance. While there is no substitute for a quality fine aggregates, performing several trial batches to optimize the mix proportions is imperative in developing a cost-effective MECC mix.

Table 44 Summary of Variable Influences on MECC's Properties.

MECC Property	**Condition**	**High Influence (Beta > 0.3)**	**Moderate Influence (0.3 > Beta > 0.2)**	**Low Influence (0.2 > Beta > 0.1)**	**No Influence (0.1 > Beta)**
Tensile Strength	3-Day Curing	Agg	Fiber		Mix
	28-Day Curing	Fiber			Agg, Mix
Tensile Strain	3-Day Curing	Agg	Fiber	Mix	
	28-Day Curing	Agg		Fiber	Mix
Compressive Strength	0.5-Day Curing	Agg			Mix, Fiber
	1-Day Curing	Agg		fiber	Mix
	1.5-Day Curing	Fiber	Agg		Mix
	3-Day Curing	Agg, Fiber			Mix
	7-Day Curing	Agg, Fiber		Mix	
	28-Day Curing	Agg		Fiber	Mix
Abrasion Resistance	Cycle 1	Mix	Fiber		Agg
	Cycle 2		Mix	Agg, Fiber	
	Cycle 3		Agg		Mix, Fiber
	Cycle 4		Agg, Mix	Fiber	
	Cycle 5	Agg, Mix		Fiber	
Flexural Strength	3-Day Curing	Agg, Mix			
	28-Day Curing	Mix		Agg	
Shrinkage	4-Day Curing		Agg, Mix, Fiber		
	7-Day Curing	Agg		Fiber	Mix
	14-Day Curing		Fiber	Mix	Agg
	21-Day Curing			Mix, Fiber	Agg
	28-Day Curing	Mix			Agg, Fiber
Chloride Ion Penetration	56-Day Curing	Mix		Agg	Fiber

Notes: “Agg” denotes Fine Aggregates Source; “Mix” denotes Mix Proportions; “Fiber” denotes Fiber Type

The statistical analysis showed that while different cement types may give higher compressive strengths, these differences were only statistically significant for the 0.5-day compressive strengths. However, by using a different cement type, the tensile strains dropped considerably, indicating there will be trade-offs when evaluating multiple cement types or fine aggregates sources.

The statistical analysis was able to determine what kind of fine aggregates would produce the most desirable MECC mix. Table 45 summarizes the desired properties for a fine aggregates source to be used in a MECC mix. The table shows that a fine aggregates having a high fineness modulus, high specific gravity (SSD), high sand equivalent, and high uncompacted voids would be the desirable material to use in MECC. While the absorption was found to have some influence, this may be because the absorption values could be collinear with some other aggregate properties (for instance, aggregates with higher uncompacted voids had lower absorption values). Because of the high amount of water typically in MECC mixes (500 lbs per cubic yard), an aggregate with a low water demand would be desirable.

Table 45 Summary of Desirable Aggregate Properties for use in MECC.

Aggregate Property	Relative Desired Value
Fineness Modulus	High
Bulk Specific Gravity (SSD)	High
Absorption (%)	2%
Sand Equivalent	High
Uncompacted Voids (%)	High

CHAPTER 6: FIELD TRIALS

6.1 Introduction

This chapter presents the field trials conducted during this study. Two large-scale trial batches were conducted to determine if the MECC material could be mixed at a traditional concrete batch plant and transported in typical concrete trucks. A third large-scale trial was performed to construct a small MECC overlay on top of an existing concrete slab to determine if standard concrete placement techniques could be used to construct an MECC overlay. Additionally, a full-scale trial project was commissioned by NDOT in August 2015 to construct a trial bridge deck overlay in the Reno area. The NDOT project will be constructed after the completion of this report.

6.2 Large-Scale Trial Batches

In the trials, six cubic yards of MECC were batched. Trial A was conducted at American Ready Mix in Sparks, Nevada on May 8, 2014. It consisted of using a central-mix plant setup where all of the raw dry materials (concrete sand, cement, fly ash, and fibers) were added into a large gravity-based mixing drum while the water and HRWR admixture were simultaneously sprayed into the drum. The various components were mixed together for a short time and then discharged into a front-end discharge concrete truck.

Trial B was conducted at 3D Concrete in Sparks, Nevada on September 25, 2014. It consisted of using a truck-mixed plant setup where the water and HRWR were added into a back-end discharge concrete truck. The raw dry materials (concrete sand, cement, and fly ash) were added one by one to and mixed in the concrete truck with the fibers added to the truck as the last step. All mixing took place inside of the concrete truck. Table 46 summarizes the mix proportions of the MECC for the two trials. Table 47 summarizes the mixing sequences used during these two large-scale trial batches.

In both trials, the MECC material was homogeneous and well-mixed, with excellent fiber distribution. Visual survey of the MECC showed some minor cement clumping, but these were small and uncommon. The material appeared to be the same quality as the MECC produced in the laboratory. At both trials, the MECC material was used to construct trial slabs to simulate the placement of an MECC overlay. Prior to both trials, several unsuccessful attempts were made to utilize local construction contractors to assist in the finishing these trial slabs. Figures 67 thru 72 show the MECC material from the large-scale trial-batches, along with the plant configurations for each trial.

Table 46 MECC Mix Proportions for Large-Scale Trial Batches.

Material	**Trial A**	**Trial B**
Mix ID:	M3-A5-U-L	M1-A4-U
Cement (lb/yd^3)	869	976
Fly Ash (lb/yd^3)	1217	1171
Sand (Dry) (lb/yd^3)	869	781
Water (lb/yd^3)	501	516
Type of HRWR Admixture	MasterGlenium 7500	Plastol 6200 EXT
HRWR Dosage (oz/cwt)	4.4	3.8
Initial Slump (inch)	6 ¼	3 ½

Figure 67 Central Mix Plant Setup for Trial Batch A.

Figure 68 MECC Material from Trial Batch A after Mixing and Discharge from Concrete Truck.

Figure 69 Slump of Fresh MECC Material from Trial Batch A.

Figure 70 Completed Trial Slab from Trial Batch A.

Figure 71 Plant Setup for Truck-Mixed MECC from Trial Batch B.

Figure 72 Completed Trial Slab from Trial Batch B.

Table 47 Mixing Sequences used for Large-Scale Trial Batches.

Trial A (Wet Process)	Time (min)	Trial B (Dry Process)	Time (min)
Cement, fly ash, and sand were weighted out onto conveyor belt.	2	HRWR was added directly into concrete truck.	1
Conveyor belt was stopped and 75% of fibers were manually added onto belt.	2	90% of water was added to concrete truck.	1
Water and HRWR was sprayed into mix drum as materials were being loaded via conveyor belt.	1	Sand was added to concrete truck.	1
Material was mixed until homogeneous.	7	Fly Ash was added to concrete truck.	2
Remaining 25% of fibers were added to empty concrete truck.	1	Cement was added to concrete truck.	3
MECC was discharged into truck and mixed for approximately 60 revolutions at high speed.	2	Remaining 10% of water was used to wash off fins inside concrete truck drum.	3
		All fibers were added to concrete truck and mixed for approximately 90 revolutions at high speed.	5
Total Time (min)	15	Total Time (min)	16

Samples were cast using MECC from both trials and brought back to the laboratory and later tested to determine the properties of the material. These test results showed that field-mixed MECC had slightly lower tensile and compressive strengths compared with the corresponding laboratory-mixed MECC. However, the field-mixed MECC had higher tensile strain values. This showed the properties of MECC do not significantly change when the material is batched at a concrete plant compared to the small-scale procedure in the laboratory. Table 48 summarizes the test results for the large-scale trial batches and the corresponding laboratory test results.

A third large-scale trial took place on March 25, 2015 at 3D Concrete in Sparks, Nevada. The purpose was to determine how easy the MECC material would be to place and finish. The research team had discussions with representatives of Granite Construction, who agreed to help with placing a 1-inch thick overlay of MECC. The overlay would be placed over an existing concrete slab, and the surface of the slab would be shot-blasted prior to the overlay construction. The overlay measured 10 feet by 10 feet and was placed inside of a wooden form approximately 1-inch high. A total of three cubic yards of MECC material was mixed by 3D Concrete and delivered in a rear-end concrete truck. Visual inspection of this MECC mix showed some minor cement clumping throughout the material, but these clumps were small and uncommon. The fibers appeared to be well distributed and the material looked well-mixed and homogeneous.

During the placement of the MECC, the contractors spread out the material with shovels to fill the form. Next, a vibratory screed was used to level out the material to produce a thickness of 1 inch. During the screeding process, it was observed that the MECC material would not move when subjected to the vibrations from the screed. The screed would ride on top of the MECC instead of consolidating the material. In order for the screed to strike off the MECC, two people had to push down on the screed while a third person would pull the screed along the surface of the material. While this method was able to level off the MECC, the surface of the overlay was not very smooth. The surface had visible tears throughout the overlay from the screeding process. The contractors then used hand finishing tools to smooth out the surface of the trial overlay. While the contractors were successful in producing a smooth, level-surfaced MECC overlay, they believed that the amount of effort needed to construct this trial overlay would make the construction of a full-scale bridge deck overlay difficult.

Table 48 Large-Scale Trial Batch Test Results.

Property	Trial A		Trial B	
	Lab Results	Field Results	Lab Results	Field Results
Slump (in.)	6	6 ¼	5 ½	3 ½
1-Day Compressive Strength (psi)	3,147	1,962*	2,649	2,157
3-Day Compressive Strength (psi)	4,984	3,708*	4,389	3,824
7-Day Compressive Strength (psi)	6,459	4,812*	5,942	5,549
28-Day Compressive Strength (psi)	9,550	8,602*	7,918	7,885
3-Day Tensile Strength (psi)	615	542	521	---
3-Day Tensile Strain (%)	0.652	0.587	0.820	---
28-Day Tensile Strength (psi)	612	561	632	---
28-Day Tensile Strain (%)	0.399	0.681	0.857	---
28-Day Flexural Strength (psi)	---	---	862	771
Abrasion Resistance (After 5 Cycles, g)	---	---	4.3	4.7
RCP (coulombs)	1,835	2,084	1,745	2,106

Note: *Compressive strength cube samples for Trial A were left overnight at the American Ready Mix batch plant. As a result, these samples lost moisture and were not properly cured. The 1-day, 3-day, and 7-day reported values are from these samples. Cylinder samples were cast and sealed during the trial, and compressive strength cubes were cut and tested from these cylinders. These samples were tested and used for the 28-day compressive strength values reported in the table.

6.3 Workability Adjustments

Using feedback from representatives of Granite Construction and 3D Concrete, the research team evaluated different methods to produce a more workable MECC material in the laboratory. The research team met with representatives of Euclid Chemical Company to discuss the use of different types of water-reducing admixtures in the MECC material. These discussions led to the evaluation of four different water-reducing admixtures which are presented in Table 49.

Table 49 Additional Water-Reducing Admixtures Evaluated in MECC Mixes.

Product Name	ASTM C494 Classification	Admixture Chemistry
Eucon X15	A and F	Lignosulfonate
MRX	A and F	Lignosulfonate/Polycarboxylate
Eucon 37	A and F	Naphthalene
Plastol 6400	A and F	Polycarboxylate

Samples of these admixtures were obtained from Euclid Chemical and evaluated in laboratory-produced MECC mixes. Table 50 summarizes the different combinations of water-reducing admixtures evaluated in the laboratory. The Eucon 1037 and Plastol 6400 are incompatible and were not evaluated. The X15 and MRX were not able to provide enough workability to the MECC material individually, or when combined together. When either the MRX or X15 was used with the 37 admixture, it required a very high dosage of admixture to provide the necessary workability and also delayed the strength gain of the MECC. When used alone, the 37 admixture was not able to provide enough workability to the MECC material.

While the 6400 by itself was able to produce MECC with a 6 inch slump, the material was still sticky, as was the case when using the Glenium 7500 admixture. However, because of the effectiveness of the polycarboxylate molecules, the 6400 admixture was needed to produce a workable MECC material. When combined with either the MRX or X15, the MECC material was not as sticky as mixes with just the 6400 admixture. By reducing the amount of polycarboxylate admixture within the mix, the MECC material became easier to place and finish. By performing several small-scale laboratory batches, it appeared that the combination of the Plastol 6400 and the Eucon MRX produced an MECC material that was easier to place and finish than any other combination of admixtures. By targeting a slump of about 8 inches, the material was easier to place, while not having the stickiness that would cause an excessive amount of work to finish the surface of the MECC. Accordingly, the recommended admixture combination for use in MECC would be a small dosage of polycarboxylate HRWR and a large dosage of a lignosulfonate HRWR.

Table 50 Evaluated Combinations of Water-Reducing Admixtures.

Admixtures	X15	MRX	37	6400
X15	Not Mixable	Not Mixable	Excessive Admixture	Not as Sticky
MRX	---	Not Mixable	Excessive Admixture	Not as Sticky
37	---	---	Not Mixable	Incompatible
6400	---	---	---	Sticky

6.4 NDOT Field Project

Task 6 of this research project was the construction of a demonstration bridge deck overlay. This field application would determine the short-term and long-term performance of an MECC bridge deck overlay. Additionally, it would provide valuable information regarding the placement, finishing, and QC/QA testing of the MECC material during construction. NDOT had originally found a potential bridge for a trial MECC overlay during early 2014. However, due to financial constraints, the MECC trial overlay was not approved. During 2015, NDOT continued its search for a prospective bridge for a trial overlay. The research team was informed that NDOT had found a bridge where an MECC overlay could be constructed. NDOT decided to move forward with the MECC trial overlay project, but not until after the conclusion of the research project.

The MECC overlay will be placed on the Lockwood Interchange Bridge to the east of Sparks, Nevada. The bridge carries a two lane road that has a low amount of average daily car traffic but very high amount of truck traffic. Granite Construction uses the bridge to access the Lockwood Quarry. The bridge is approximately 140 feet long and 28 feet wide. The trial overlay will be four inches thick to match with the barrier rail. The MECC trial overlay would be included in NDOT Contract 3606. On August 13, 2015, NDOT Contract 3606 was opened for bidding by contractors. The project was awarded to Granite Construction on August 17, 2015. The construction of the MECC overlay is scheduled for early spring of 2016. The MECC specification used for this trial overlay followed the recommendations and developed specifications from this study. Refer to chapter 7 for more information regarding the development of the MECC specification.

CHAPTER 7: PROPOSED SPECIFICATION AND COST ESTIMATION

7.1 Introduction

This chapter presents the draft MECC Specification that the research team developed with input from the NDOT project panel. This specification was written as a performance-based specification that had a few limitations on the raw materials used and instead focused on the MECC mix properties. By having a performance-based specification, it allows for contractors and material suppliers to be innovative when it comes to the MECC mix designs. This will keep MECC a cost-effective option for bridge deck overlay. This chapter also discusses how the specification was developed and the methodology behind its development. The proposed MECC specification is shown in its entirety in Appendix D. An initial cost estimation for the MECC material is also presented at the end of this chapter.

7.2 Development of MECC Specification

There are several different sections included in the MECC specification. The materials section discusses the requirements for the raw materials (sand, fibers) as well as requirements for the MECC mixtures (mix proportions, required strengths). It also discusses performing large-scale trial batches and construction of trial slabs prior to any use of MECC on a NDOT bridge deck overlay project. The construction section discusses the requirements for handling, placing, curing, and finishing the MECC material during the construction of an MECC overlay. As the laboratory study progressed and additional test results became available, multiple revisions and updates were performed on the proposed specification. This report presents the final version of the specification as recommended by the research team based on the overall findings from this study.

Starting with the materials section, the material requirements were put in place to ensure that the fibers used in a MECC mix would have the same characteristics as the fibers used in this laboratory study. Additionally, the same admixtures and cement type were also specified to match the kinds used in this study. The mix design requirements are in line with the mix proportions evaluated. The minimum amounts of cement, fly ash, and fibers were incorporated to prevent the contractors from using a MECC mix with very low amounts of such raw materials. The maximum water-to-cementitious material ratio, amount of cement, and amount of fly ash were based on the comprehensive literature review conducted as part of this study. Mixes that had higher proportion values than the ones listed in the specification were found to have inadequate performance.

The required mix design properties were developed based on the laboratory results of this study. The minimum slump was implemented because the MECC material is can be difficult to place, so specifying a high slump should help address this problem. High-slump MECC mixes (and MECC mixes that have fresh properties similar to self-consolidating concrete) are allowed, but must be tested using the appropriate methods. The air content was implemented to limit the amount of entrapped air that is introduced into the material. The laboratory test results showed that the MECC mixes developed as part of this study were able to achieve the desirable maximum air content of 3%.

The selection of the required MECC material's properties was determined by balancing both appropriate and achievable performance. For instance, MECC mixes should gain strength quickly to minimize the time a bridge is closed to traffic, but the specification must also be achievable. This was done by first establishing the specification performance levels for the

MECC's properties. Next, the laboratory test results were compared with this specification to determine if the specification limit obtainable. The final specification limits (which are present in the draft specification) for the MECC properties are values that would provide sufficient performance, but also performance levels that were achievable with the MECC mixes evaluated.

When considering the early-age compressive strengths, the focus was on minimizing the time the bridge deck would be closed to traffic. The laboratory tests showed that the developed mixes had good compressive strengths at 12 hours, but there was a high variability in the test results. On the other hand, the testing variability was reduced after 24 hours of curing. Therefore, a 1-day compressive strength was selected and included in the specification. The research team determined, in consultation with NDOT, that a 2,000 psi compressive strength would allow the bridge to be opened to traffic. This value is also the minimum compressive strength for opening a PCC pavement to traffic as specified in the 2001 NDOT Standard Specifications *(10)*. The laboratory test results showed that all eighteen of the original mixes were able to meet this criteria. Depending on project requirements, performance levels can be changed depending on future project conditions.

At 7 days, the minimum compressive strength was chosen as 5,000 psi because this value would be greater than most typical PCC mixes, which have demonstrated sufficient strength performance. The test results showed that seventeen of the eighteen MECC mixes were able to pass his criteria. The one MECC mix that failed had a compressive strength of 4,995 psi. The 28-day compressive strength limit for the MECC material was set to 7,000 psi. Having a 7,000 psi minimum would ensure that a MECC mix would have higher compressive strengths than most PCC mixes *(11)*. Most of the MECC mixes developed as part of this project did meet these design objectives.

The tensile properties were specified to be tested at 3 and 28 days to match up with the days selected for the compression tests. The laboratory test results showed that both the tensile strength and tensile strain properties were very sporadic within the first 36 hours, but stabilize at 3 days. It was determined by the researchers and NDOT that after 3 days of curing a tensile strength of 400 psi is anticipated to give a satisfactory-performing material. A 2003 study by Swaddiwudhipong *(12)* showed that the average tensile strength of traditional PCC mixes subjected to a direct, uniaxial tensile load were about 365 psi. Because MECC is expected to have higher performance than PCC, a minimum tensile strength of 400 psi would ensure that all MECC mixes would have better performance than traditional PCC mixes. The lab results showed that the eighteen MECC mixes developed as part of this study met this minimum tensile strength limit at 3 days.

The 3-day tensile strain value was set to the desirable strain level of 0.5%. Traditional PCC mixes have in general a tensile strain of only 0.01%, indicating MECC would have 5,000% higher performance. The test results showed that fourteen of the eighteen MECC mixes evaluated met this minimum set value for tensile strain at 3 days. However, since the polymer concrete had tensile strains of only 0.057%, the research team believe that a lower tensile strain value of 0.4% could be specified for a satisfactory-performing material. This lower value was passed by all but one of the eighteen MECC mixes evaluated in this study. The selected value is anticipated to ensure good ductility within the slab when compared to the polymer and PCC materials.

The 28-day tensile strength value was determined in the same manner as the 3-day tensile strength limit. The Swaddiwudhipong study *(12)* showed that the highest tensile strength of the PCC samples was about 500 psi. However, MECC is expected to have higher tensile strengths than traditional PCC, so the limit was raised to 600 psi. After testing, the laboratory results showed that all but one MECC mix were able to meet this specification limit. The 28-day tensile strain value was left at 0.4% to match with the 3-day tensile strain limit. This is because the laboratory results indicated that on average, the tensile strain value of the MECC mixes is roughly the same at both 3 days and 28 days. While some MECC mixes gained tensile strain capacity, other mixes lost capacity. When compared to the tensile strain of PCC (0.01%), the MECC tensile strain limit of 0.4% indicates all MECC mixes must have at least 40 times the tensile strain capacity of traditional PCC.

In addition to the compressive and tensile properties, there were other specified tests on the hardened MECC material, but no minimum values were selected. The drying shrinkage values would be desirable to know during field projects to determine if a MECC mixture is experiencing excessive shrinkage during the use phase of a MECC overlay. But because the MECC shrinkage values were generally lower than that of traditional PCC *(11)*, the research team concluded that maximum shrinkage value limits will be waved at this time. A revision to the shrinkage requirement may be needed as additional data is being collected from actual bridge deck field projects. The split cylinder tensile strength values are desirable to know to understand how these values relate with the uniaxial tensile strength values. Also, split cylinder tensile strengths would allow for more direct comparisons with traditional PCC tensile strength values. Not to mention, the split cylinder test would be much easier to run than the direct tensile test. Lastly, the flexural strengths at 1 day were set to report to help NDOT understand how early traffic can be turned out onto the overlay after construction. It should be noted that the current 2014 NDOT Standard Specifications uses the flexural strength as the main indicator when determining if a PCC pavement can be opened to traffic. The 28-day flexural strength was set to report to help understand and predict the performance of the MECC overlay. But because the flexural strengths of the MECC were much higher than the PCC strengths, the research team concluded that a minimum 28-day flexural strength value was not necessary at this time.

The large-scale trial batch and test slab were required for a number of reasons. First, the material does not behave like traditional PCC, so it is imperative that the contractor try to place a test slab prior to any field project to avoid surprises during construction. The specification allows for the contractor to test out several different construction methods for a MECC overlay and get approval to use these alternative methods during construction. Second, mixing MECC on a large-scale may require special mixing sequences at the batch plant, depending on the available equipment and plant setup. Performing a trial batch would allow for the contractor to determine whether or not the MECC material could be mixed or if any changes are necessary prior to constructing any field project. Lastly, because the properties of the MECC appear to be slightly different between laboratory-produced and field-produced, the large-scale trial batch will help the contractor determine if changes to the mix design may be needed so the MECC material will pass the minimum material requirements specified in the specification during construction.

Most of the construction section in the proposed specification was written by NDOT so that the construction of the MECC overlay would closely follow the NDOT Standard Specifications. The results of the bond strength tests showed that water-blasting did not produce a strong bond; thus, the water-blasting surface preparation should not be the primary surface preparation method used.

7.3 Initial Cost Estimation

One of the reasons for the potential use of MECC instead of the proprietary polymer concrete for bridge deck overlays was the high cost for the polymer concrete material, about $1,600 per cubic yard of the material. By determining the cost of the MECC material, it would provide a tangible piece of information to determine the economic benefits of using MECC versus the polymer concrete.

The cost of the MECC was determined by finding the unit costs of the constituent materials. Once unit costs were established, the MECC mix proportions were selected. The Mix Proportion 1 was selected because this mix had the highest amount of cementitious materials (cement and fly ash), which are more expensive than the concrete sand or water. Mix Proportion 1 was also selected because this MECC mix would meet the mix design requirements that are specified in the draft MECC Specification. The amount of PVA fibers was set at 44 lbs per cubic yard, which was held constant throughout this research study. Table 51 summarizes the tabulated cost breakdown.

Table 51 Tabulated MECC Cost Estimation (per cubic yard).

Raw Material	**MECC Mix Proportions (lbs)**	**Unit Cost ($ per 2,000 lbs)**	**Cost per cubic yard ($)**
Cement	970	180	87
Fly Ash	1171	100	59
Concrete Sand	781	20	8
Water	515	0	0
Fibers	44	264 (per 40 lbs)	290
HRWR	0.75 (gal.)	75 (per gal.)	56
		Total:	**$500**
	Quoted Price from a Local Concrete Supplier:		**$460**

The unit costs for the cement and fly ash were found from an internet search. Prices for the sand were obtained from a local aggregate pit. It was assumed that the amount of water would not have a significant effect on the cost of MECC, and was excluded. The cost of the fibers is $264 for a 40 lbs box of the unoiled fibers, which does not include the shipping and handling costs. The shipping and handling costs were not included because it was assumed that this cost would be greatly reduced if the fibers were ordered in large quantities. The large fiber quantities could also reduce the fiber costs if the fibers were purchased in bulk. The price of the HRWR was estimated at $75 per gallon based on conversations with representatives of concrete admixture companies. The total cost for the MECC was estimated to be $500 per cubic yard based on these prices. Additionally, the research team asked a local concrete supplier to provide a quote for the same MECC mixture. The supplier estimated the cost of the MECC material to be around $460 per cubic yard. Both of these unit costs for MECC are 66% less than the polymer concrete, indicating that using MECC instead of polymer concrete would save over $1,000 per cubic yard without jeopardizing performance.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to evaluate the performance of Engineered Cementitious Composites (ECC) made with locally sourced raw materials, now called Modified Engineered Cementitious Composite (MECC). The objective was to determine if MECC can provide an alternative to the currently used polymer concrete as an overlay. Three different concrete sands, three different mix proportions, and two different fibers were used to develop eighteen different MECC mixes. The performance of MECC was compared to that of a typical PCC mix and the polymer concrete mix currently used for bridge deck overlays in Nevada. Based on the findings from this study the following observations can be made:

1. The laboratory test results showed that MECC performed better than PCC in almost every test. Furthermore, MECC had comparable performance to the polymer concrete in most of the tests. The ductile behavior of MECC, combined with the material's superior durability and mechanical properties make MECC a feasible alternative material for bridge deck overlays in Nevada.

2. The large-scale trial batches showed that six cubic yard batches of MECC could be mixed in both a central-mix and dry-mix plant configurations. MECC batched on the large scale also had very similar properties to laboratory-mixed MECC, showing the material does not lose its hardened properties when batched on a large scale. These successful trial batches showed that MECC can be transported in commonly available concrete trucks and can be delivered to the jobsite in a timely and uninterrupted manner during construction.

3. The fine aggregates source was the most influential variable in this study, signifying that selecting the appropriate fine aggregates for use in MECC mixes is critical. The fiber type used also provided a great deal of influence on the MECC performance. While the unoiled fibers cost less than the oiled fibers, the oiled fibers may be needed to produce an MECC mix meeting the required properties if lower quality fine aggregates are used. The mix proportions for any MECC mixture need to be optimized for each fine aggregates. A certain mix proportion may work for one fine aggregates source, but not necessarily for another fine aggregates source.

4. The type of cement used can have a large influence on certain properties of the MECC. While different cement may provide higher compressive strengths, the MECC mixture may have reduced tensile properties. Additionally, the increase in compressive strengths may not necessarily be statistically significant when taking into account the test variability. When evaluating multiple cements, fine aggregates, or fiber types, there will be trade-offs. Multiple laboratory trial batches may be needed to fully understand how different fine aggregates, cements, and mix proportions will influence the MECC mix properties.

The findings from this study showed that MECC has many desirable properties that make it an ideal material for bridge deck overlays. A full-scale trial MECC overlay is currently planned for construction in 2016 to fully evaluate the short-term and long-term performance of MECC overlays to determine if MECC is suitable for replacement of the polymer concrete bridge deck overlays in Nevada. Additionally, the development of a performance-based specification for

MECC was completed to allow for the use of variety of fine aggregates sources and mix proportions. The development of an MECC specification will facilitate the implementation of MECC overlays in Nevada.

This research has shown that MECC made with locally available concrete sands is a material that exhibits many desirable properties. While this study attempted to determine the level of expected performance of MECC, there were many factors that could be further explored. Recommendations for future research on the MECC material include the following topics:

1. The primary source of cost associated with MECC are the fibers. While the fiber content was kept constant at 2% by volume throughout the study, it may be possible to achieve the same level of performance with lower volumes of fiber in the MECC mix. Additionally, while two types of fibers were evaluated, the only difference was the presence of the oiling agent on the oiled fibers. There are many different fiber properties that could be changed (length, chemical composition, use of multiple types of fibers) which could not only produce quality MECC mixes, but mixes that are also cost-effective.

2. While the MECC material was being evaluated to determine its applicability for use in bridge-deck overlays, the material may be used elsewhere. There are numerous potential applications for MECC within Nevada (bridge columns, concrete pavement patching). While some of these applications will require high-performing MECC mixes, others may not need high-strength MECC mixes, but rather high-ductility mixes. By evaluating the applicability of MECC for other uses, NDOT could use MECC to further replace proprietary products and save money with cost-effective MECC mixes.

3. The groundwork for the MECC specification was completed within this study. However, this study will conclude before the MECC trial overlay is completed in the spring of 2016. The outcome of the MECC trial overlay may require modifications to the specification. For instance, while MECC had less shrinkage than PCC, there may need to be a limit on the shrinkage values for MECC to perform well in the field. There may also need to be additions to the specification to address any issues that arise from the trial overlay, such as changes to the placement and finishing techniques, to ensure that future MECC overlays will have good performance.

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APPENDIX A: TASK 1 LITERATURE REVIEW

APPENDIX B: LABORATORY TESTS DESCRIPTIONS

Introduction

The following are descriptions of how each of the laboratory tests that were conducted for this research project. Many of the tests were performed in accordance with NDOT Test Methods. However, if there was no NDOT Test Method, ASTM or AASHTO Test Standards were used. There were some tests which did not have any test standard at the time of this research project. Instead, the research team worked to develop testing procedures to ensure that these tests would be consistently conducted in the same manner for the duration of the project. The purpose of this section is to help the reader understand how each test is performed and to provide details about how the test samples were cast, cured, and tested.

Compressive Strength

This test was conducted in accordance with ASTM C78.

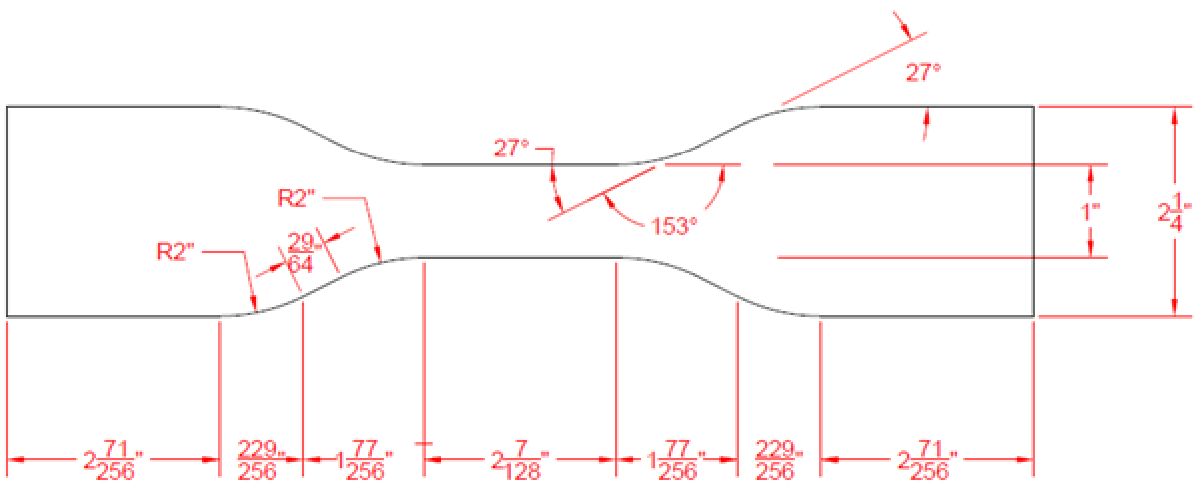
Cube samples measuring 2 in. by 2 in. by 2 in. were cast in reusable molds. Molds were filled in two approximate equal layer with each layer being tamped. After tamping the second (top) layer, the surface was smoothed out to make the samples flush with the mold. Once filled, the molds were immediately moved into the humidity chamber at 100% relative humidity (R.H.) for 24 hours. After 24 hours, the samples were removed from the molds and left in the humidity chamber until time of testing. Samples tested at 12 hours were removed from molds after 12 hours and immediately tested.

Samples were tested by applying a compressive load at a rate of about 300 pounds per second. This rate of loading was held constant until the applied load was approximately 50% of the estimated peak load the sample would experience during testing. After this point, no adjustments to the rate of loading were made to the testing machine. Samples were tested until applied load was 50% of the peak load. The peak load for each sample was recorded, and each samples was measured prior to testing. The peak compressive strength for each sample was then calculated and recorded. Four samples were tested and the average value was reported.

Tensile Properties

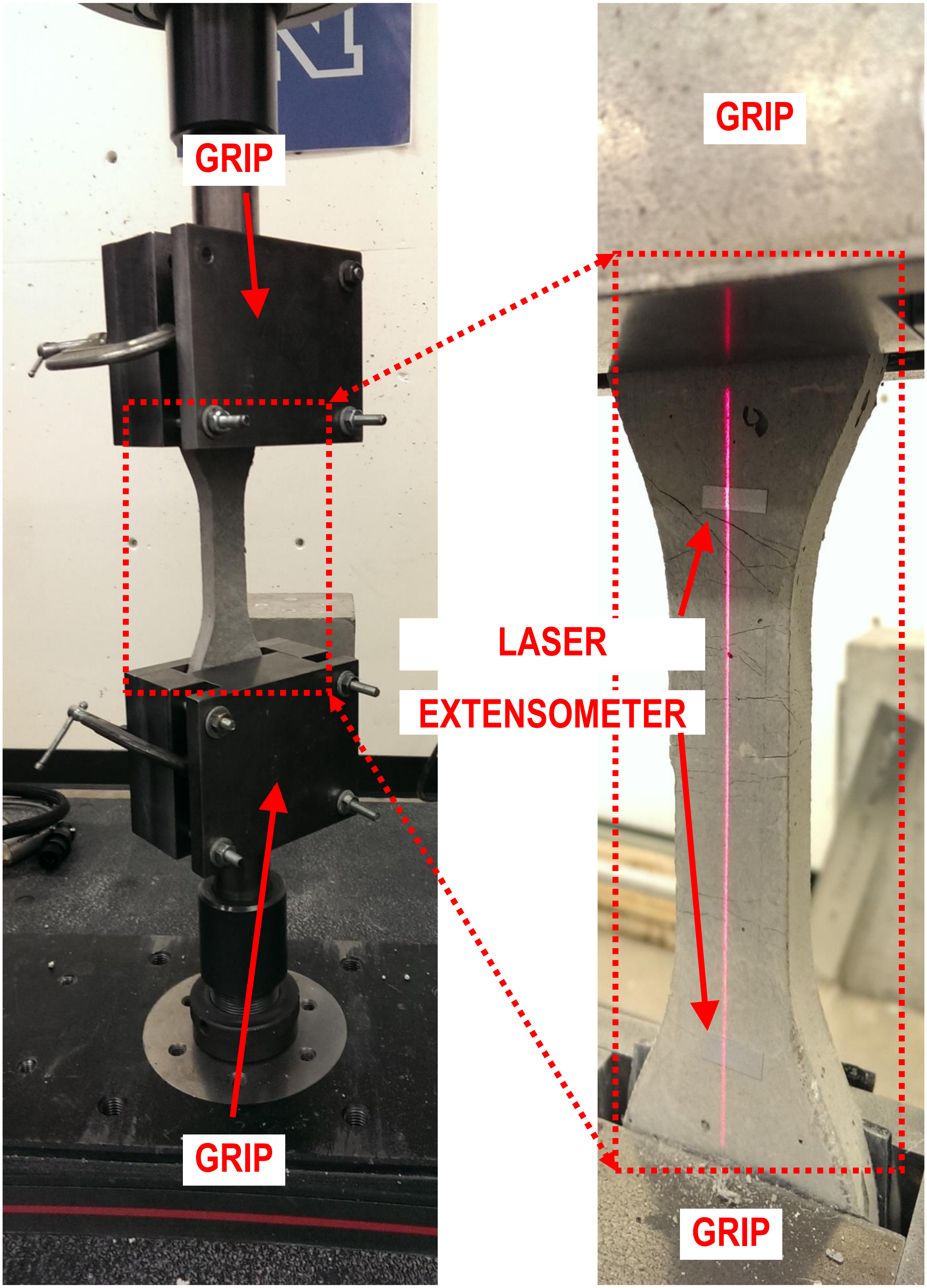
There is currently no test standard for this test. The research team developed this test procedure to closely mimic the test procedures found in the literature review, which were used to evaluate MECC's tensile properties.

Dog-bone shaped samples measuring 11 in. by 2.25 in. by 0.5 in were cast in reusable molds. Molds were filled in one layer that was tamped 25 times. After tamping, the surface was smoothed out to make the samples flush with the mold. Once filled, the molds were immediately moved into the humidity chamber at 100% R.H. for 24 hours. After 24 hours, the samples were removed from the molds and left in the humidity chamber until time of testing.



Specimen Thickness = 0.5 inches

Samples were tested by placing each end of the sample into steel grips. One grip was fixed, while the other was allowed to move and apply the tensile load. A tensile load was applied to the samples at a rate of about 2 pounds per second. Samples were loaded until the applied load was 10% of the peak load. Tachometer tape was placed on the sample and a laser extensometer was used to measure the displacement of the middle 3.5 inches of the sample. The load and displacement were measure continuously throughout the duration of the test. The thickness and width of the middle section of each sample was measured prior to testing. The stress-strain curve for each samples was then calculated and plotted. The peak tensile strength was identified and recorded. The tensile strain for each samples was determined by looking for a sudden drop in the stress-strain curve. That is, the tensile strain was the strain at which the sample experienced a significant drop in tensile strength. Four samples were tested and the average value was reported.

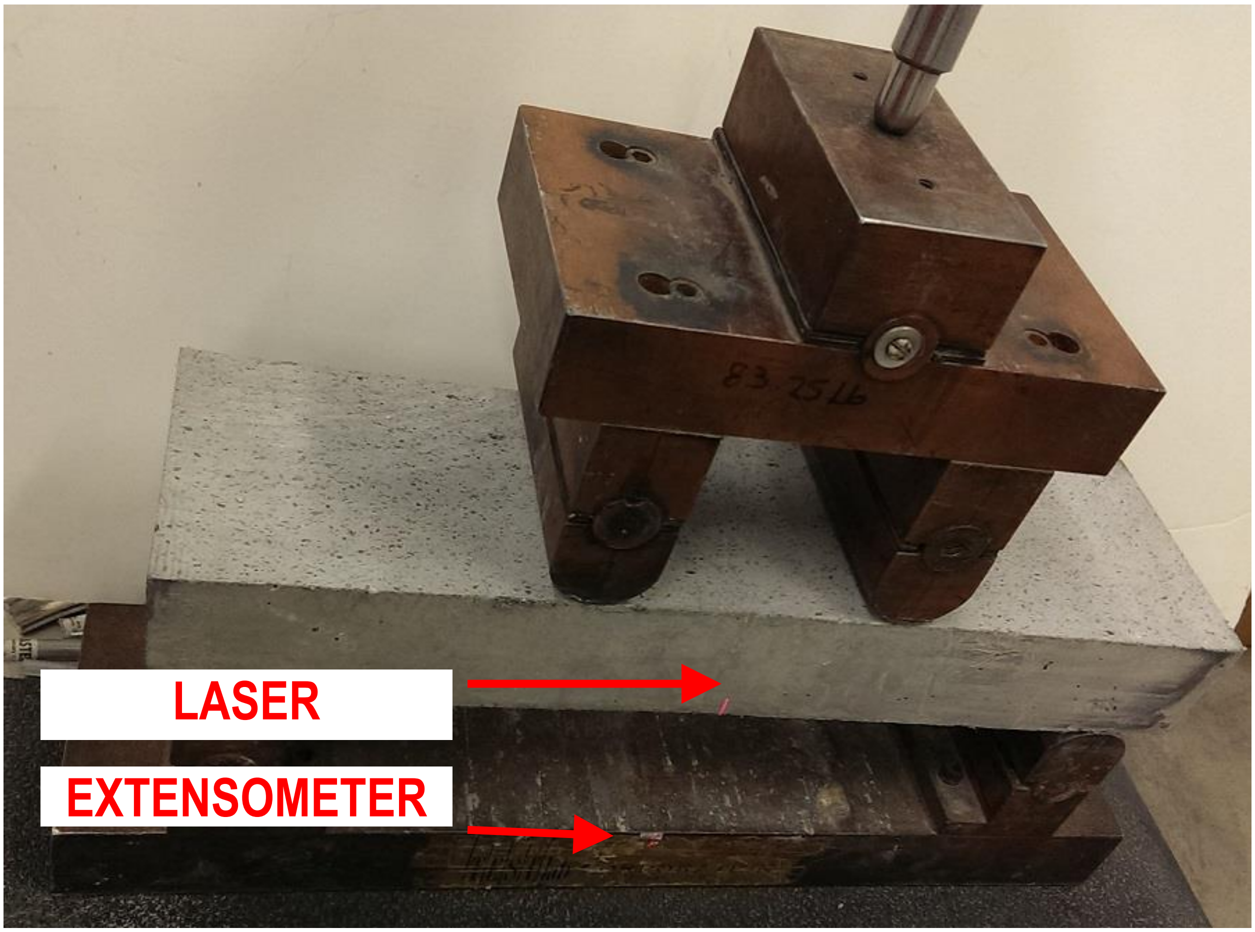

GRIP
GRIP
LASER
EXTENSOMETER
GRIP
GRIP

Ductility

This test was conducted in accordance with Nev. Test Method 442G.

Beams measuring 6 in. by 6 in. by 21 in. were cast in reusable flexural strength beam molds. Molds were filled in two approximate equal layers with each layer being rodded. After rodding the second (top) layer, the surface was smoothed out to make the samples flush with the mold. Once filled, the molds were immediately moved into the humidity chamber at 100% relative humidity (R.H.) for 24 hours. After 24 hours, the samples were removed from the molds and were cut using concrete saws. Samples measuring 6 in. by 3 in. by 21 in. were cut from the middle of the cast beam. These samples were then placed in the humidity chamber until time of testing.

Samples were tested by applying a compressive load at a rate of about 450 pounds per second. This rate of loading was held constant over the duration of the test. Samples were tested until applied load was 50% of the peak load. The peak load for each sample was recorded, and each samples was measured prior to testing. The peak flexural strength for each sample was then calculated and recorded. Two samples were tested and the average value was reported.

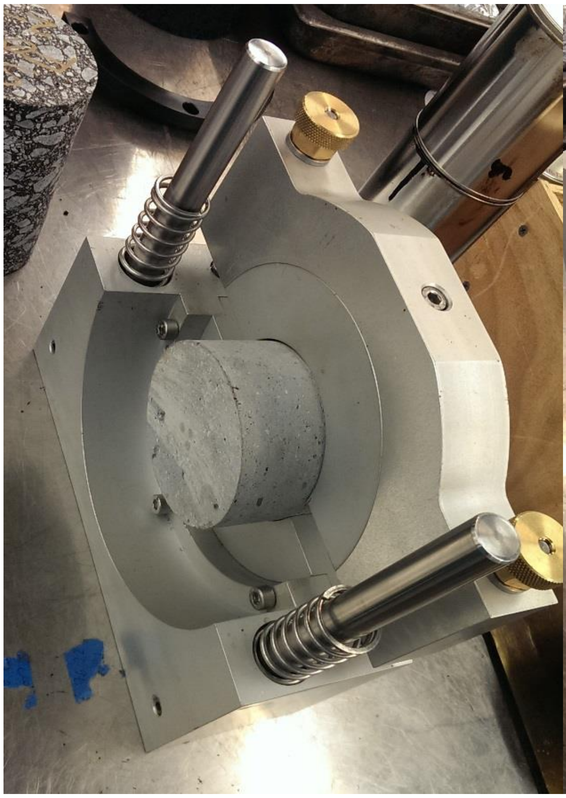
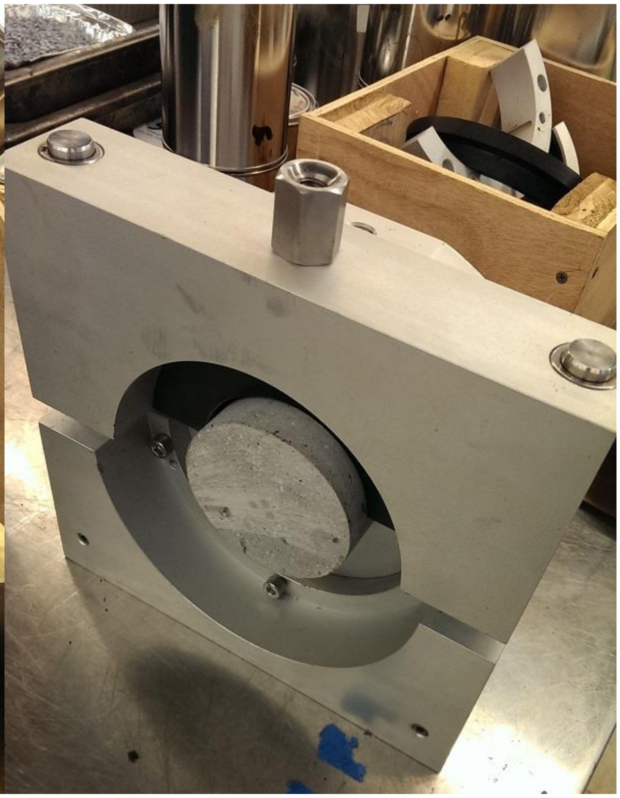


Louisiana Interlayer Shear Strength Tester (L.I.S.S.T.)

This test was conducted in accordance with a Draft AASHTO Test Procedure *(13).*

Cylindrical samples measuring 6 in. diameter and 2 in. height of traditional Portland cement concrete (PCC) were cast in disposable plastic molds. These molds were placed in the humidity chamber at 100% R.H. for 28 days, after which the samples were removed from the molds. The top of these samples were prepared with either shot-blasting or water-blasting. The shot-blasting consisted of using aluminum beads to remove the mortar and expose the coarse aggregates of the top of the sample to a depth of approximately ¼ inch. The water-blasting consisted of using a 4,000 psi pressure washer to remove the mortar and expose the coarse aggregate. However, the pressure washer was only able to lightly texture the surface. After the surface preparation, 2 in. of MECC was placed on top of the PCC samples. These samples were placed in the humidity chamber and removed from the molds after 24 hours. Samples not tested after 24 hours were placed back into the cure room until time of testing.

Samples were tested by being placed on the side in the L.I.S.S.T. apparatus. The bottom part (PCC) was fastened to resist movement. A shear load is applied to the top part (MECC) of the specimen only. The load is applied to the sample by applying a displacement of 0.1 inch per minute to the top of the sample. The peak load was recorded and the sample diameter was measured to calculate the bond strength. Three samples were tested and the average value was reported.

Slant-Shear

This test was conducted in accordance with ASTM C882.

Cylinder samples measuring 3 in. diameter and 6 in. height of PCC were cast in disposable plastic molds. These molds were placed in the humidity chamber at 100% R.H. for 28 days, after which the samples were removed from the molds. These samples were saw cut at a 45 degree angle to cut the specimen into two equal parts. Afterwards, the saw-cut surface was subjected to one of the surface treatments evaluated, either shot-blasting or water-blasting. Once the surface preparation was complete, these samples were placed back into disposable plastic molds, and MECC was added to the molds, on top of the treated PCC surface. These samples were then placed in the humidity chamber and removed from the molds after 24 hours. Samples not tested after 24 hours were placed back into the cure room until time of testing.

Samples were tested by applying a compressive load to the cylinders. These samples were tested in a similar fashion to typical compressive strength cylinder samples for concrete. The compressive load was applied at a rate of 35 pounds per second. The load was applied until the samples failed. The peak load was recorded and the area of the bond interface was measured and used to calculate the bond strength. Three samples were tested and the average value was reported.

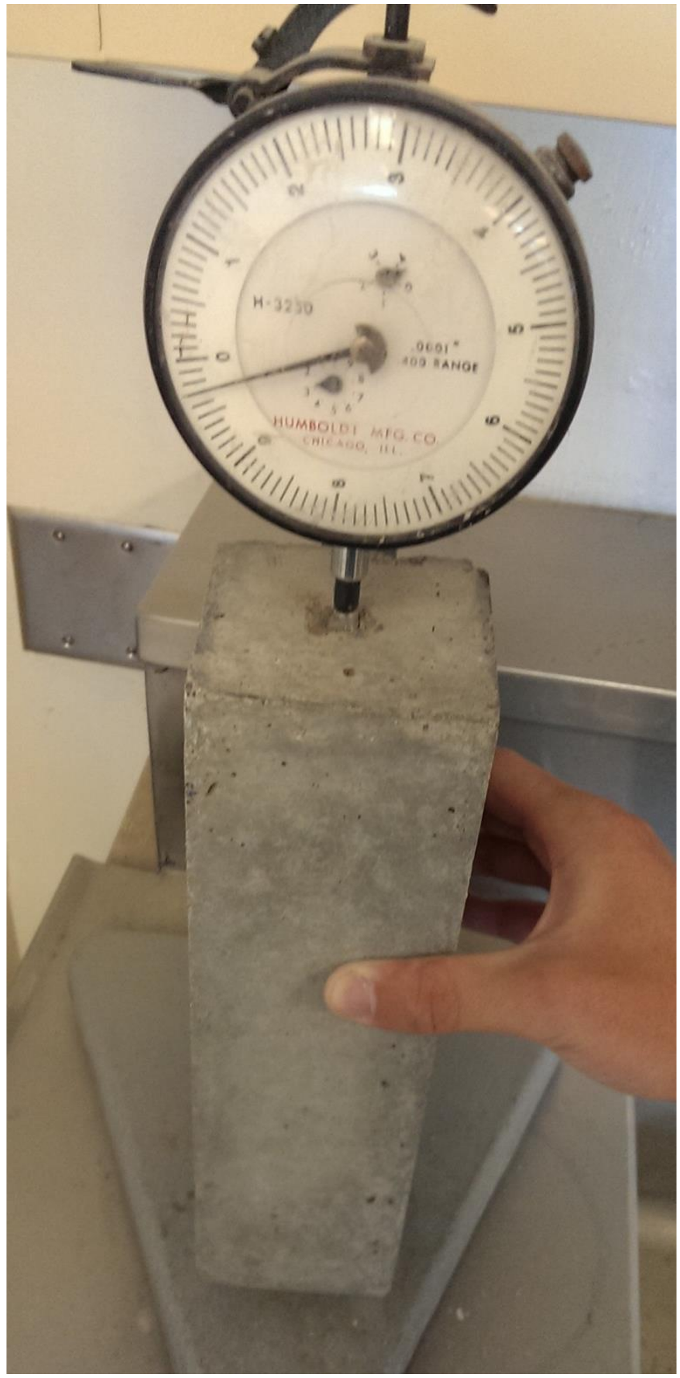
Pull-off Test

This test was conducted in accordance with ASTM C1583

Cylinder samples measuring 6 in. diameter and 3 in. height of PCC were cast in disposable plastic molds. These molds were placed in the humidity chamber at 100% R.H. for 28 days, after which the samples were removed from the molds. Afterwards, the surface was subjected to one of the surface treatments evaluated, either shot-blasting or water-blasting. Once the surface preparation was complete, these samples were placed back into disposable plastic molds, and 3 inches of MECC were added to the molds, on top of the treated PCC surface. These samples were then placed in the humidity chamber and removed from the molds after 24 hours. Samples not tested after 24 hours were placed back into the cure room until time of testing. Just prior to testing, a 2 in. diameter core-bit was used to core the middle of the sample, completely through the MECC layer and about ¼ inch into the PCC layer. The top of the MECC layer was dried off using compressed air prior to testing.

Two in. diameter metal caps were glued to the top of the cored MECC layer. The glue was given two hours to dry before testing began. Using the pull-off tester, a tensile load was applied to the metal cap, which would pull the MECC layer from the PCC layer. This tensile load was applied at a rate of 5 psi per second. The load was applied until the sample failed. The failure type was recorded, as well as the peak tensile load applied. The surface area at the bond interface was measured and used to calculate the bond strength. All samples experienced failure at the MECC/PCC bond interface. Three samples were tested and the average value was reported.

Drying Shrinkage



This test was conducted in accordance with ASTM C157.

Beam samples measuring 3 in. by 3 in. by 11 in. were cast in reusable metal molds. MECC was added to the molds in two equal layers, each layer was rodded with the top layer also smoothed off to produce a very uniform sample. Samples were placed in the humidity chamber at 100% R.H. for 24 hours, after which the samples were removed from the molds. These samples were then submerged in a lime-saturated water bath for 27 days. Afterwards, the samples were removed from the 100% R.H. chamber and placed in a second humidity chamber set to 50% R.H. Shrinkage values were measured at 4, 7, 14, 21, and 28 days after the samples were placed in the second humidity chamber at 50% R.H.

The shrinkage values were determined by using a comparator. The samples were placed in the comparator immediately after being removed from the molds; this value would serve as the initial measurement. Subsequent measurements taken after the beams were placed in the second humidity chamber were recorded and compared to the initial measurement. By performing the calculations described in the ASTM test methods, these comparator measurements were converted into shrinkage values. Two samples were tested with the average value being reported.

Abrasion Resistance

This test was performed in accordance with ASTM C944.

Cylindrical samples measuring 6 in. diameter by 2 in. height were cast in disposable plastic molds. Samples were placed in the humidity chamber at 100% R.H. for 24 hours, after which the samples were removed from the molds and the top ½ inch was saw cut from the sample and would serve as the test specimen. These specimens were then returned to the humidity chamber and cured for 27 days. After curing, the samples were removed from the cure room and allowed to air-dry in the laboratory environment for 3 hours prior to testing.

Samples were tested by the use of a rotating cutter wheel. This cutter wheel was affixed to a mounted drill press, and would be in contact with the samples and grind away at the samples. 22 pounds of force was the applied load that the cutter wheel had with the samples. This cutter wheel also rotated at a speed of 220 rotations per minute. There were five abrasion cycles performed for each sample, which lasted for two minutes each. The samples were wiped down and weighed before and after each abrasion to determine the amount of mass each sample lost for each cycle. Two samples were tested and the average value was reported.

Freeze-thaw Durability

This test was performed in accordance with ASTM C666.

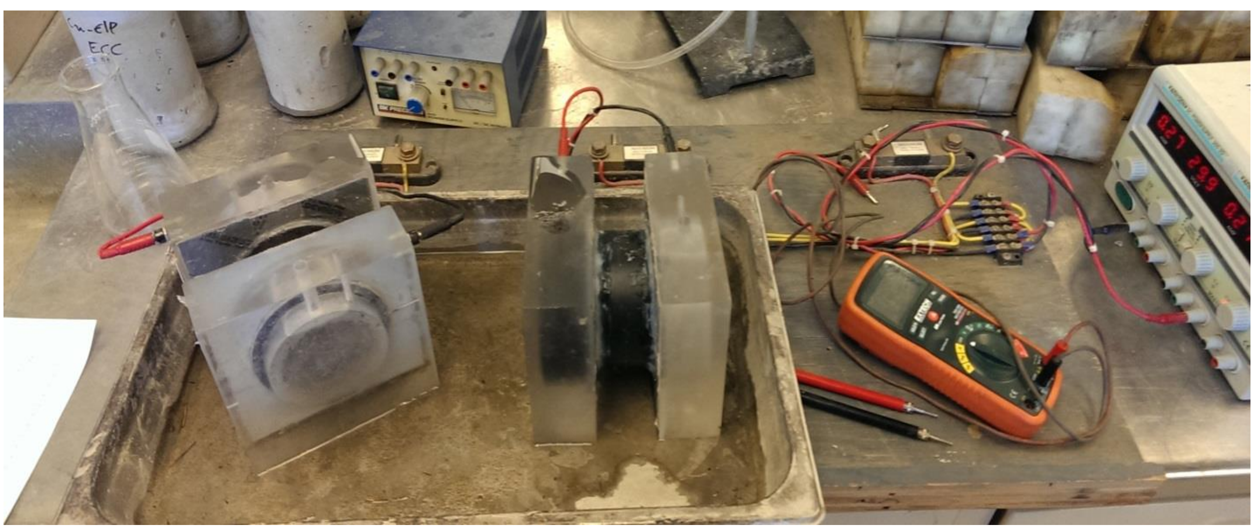
Beam samples measuring 3 in. by 4 in. by 11 in. were cast in reusable metal molds. MECC was added to the molds in two equal layers, each layer was rodded with the top layer also smoothed off to produce a very uniform sample. Samples were placed in the humidity chamber at 100% R.H. for 24 hours, after which the samples were removed from the molds. These samples were then submerged in a lime-saturated water bath for 13 days. Afterwards, these samples were removed from the water bath, wrapped in plastic sheeting, and placed in a freezer at 0 degrees Fahrenheit. This test was performed by CTL Thompson in Denver, Colorado, so the beam samples were shipped frozen in a cooler to their laboratory. After CTL Thompson had completed the test, the laboratory prepared a report summarizing the test results and sent it to the research team. Two samples were tested and the average value was reported.

Resistance to Chloride Ion Penetration

This test was performed in accordance with ASTM C1202.

Samples measuring 4 in. diameter by 8 in. height were cast in disposable plastic molds. MECC was added to the molds in three equal layers, each layer was rodded with the top layer also smoothed off. Samples were placed in the humidity chamber at 100% R.H. for 24 hours, after which the samples were removed from the molds. Two specimens measuring 4 in. diameter by 2 in. height were cut from the middle of the cylinder and would serve as the test specimens. These specimens were returned to the cure room for to cure for an additional 55 days. The samples were removed and allowed to air-dry in the laboratory for one hour, after which the circumferential side of each samples was sprayed with an aerosol plastic coating. Two applications of this spray was applied, which each application having 30 minutes to dry. Afterwards, the specimens were placed in a vacuum chamber for 3 hours. The vacuum was stopped and water was added to completely cover the samples. The vacuum was then restarted and run for an additional 18 hours.

The samples were removed from the vacuum and quickly dried off with a towel. Each sample was placed between two plastic test blocks and a silicone gel was used to seal the edge of the samples with the test blocks. This gel was given about one hour to dry. A solution of NaCl was added to one test block while a solution of NaOH was added to the other test block for each sample. After, a power supply unit was connected to the test blocks and a 60 volt charge was applied to each specimen. Using a multi-meter, the voltage was measured for each specimen at a maximum of 30 minute intervals. The test was run for 6 hours. Afterwards, the voltage measurements were then used to calculate the total number of coulombs that had passed through the specimen. Two samples were tested and the average value was reported.



APPENDIX C: FREEZE-THAW DURABILITY TEST RESULTS

TABLE 1
Resistance of Concrete to Rapid Freezing and Thawing
ASTM C 666, Procedure A

Client: University of Nevada, Reno
Project: ASTM C 666 Testing
Project No. CT15810.000-400

Date Cast: Undisclosed
Date Received: June 24, 2014
Age When F/T Started: Unknown

Mix ID: Research
Date Started: 8/1/2014
Date Finished: 10/10/2014

Date	Period Cycles	Cumulative Cycles	Weight (lbs)				Resonant Frequency				Weight Loss (%)					Relative Dynamic Modulus of Elasticity (%)				
			#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	Avg.	#1	#2	#3	#4	Avg.
08/01/14	0	0	13.86	13.81	13.69	13.80	1553	1538	1530	1508	-	-	-		-	-	-	-		-
08/08/14	30	30	13.94	13.90	13.78	13.91	1553	1537	1530	1508	-0.5%	-0.7%	-0.7%	-0.8%	-0.7%	#####	99.9%	#####	#####	#####
08/15/14	30	60	13.94	13.91	13.79	13.93	1553	1537	1530	1508	-0.6%	-0.7%	-0.7%	-0.9%	-0.7%	#####	99.9%	#####	#####	#####
08/22/14	30	90	13.94	13.91	13.79	13.93	1553	1537	1530	1508	-0.6%	-0.7%	-0.7%	-0.9%	-0.7%	#####	99.9%	#####	#####	#####
08/29/14	30	120	13.95	13.92	13.79	13.94	1553	1537	1530	1508	-0.6%	-0.8%	-0.7%	-1.0%	-0.8%	#####	99.9%	#####	#####	#####
09/05/14	30	150	13.95	13.92	13.80	13.94	1553	1537	1530	1508	-0.6%	-0.8%	-0.8%	-1.0%	-0.8%	#####	99.9%	#####	#####	#####
09/12/14	30	180	13.95	13.93	13.80	13.95	1553	1537	1530	1508	-0.6%	-0.8%	-0.8%	-1.1%	-0.8%	#####	99.9%	#####	#####	#####
09/19/14	30	210	13.95	13.93	13.79	13.95	1553	1537	1530	1508	-0.6%	-0.8%	-0.7%	-1.1%	-0.8%	#####	99.9%	#####	#####	#####
09/26/14	30	240	13.94	13.97	13.82	13.96	1553	1537	1530	1508	-0.6%	-1.1%	-0.9%	-1.2%	-1.0%	#####	99.9%	#####	#####	#####
10/03/14	30	270	13.95	13.97	13.82	13.96	1553	1537	1530	1508	-0.6%	-1.2%	-1.0%	-1.2%	-1.0%	#####	99.9%	#####	#####	#####
10/10/14	30	300	13.93	13.95	13.81	13.94	1553	1537	1530	1508	-0.5%	-1.0%	-0.9%	-1.0%	-0.8%	#####	99.9%	#####	#####	#####
											Average at 300 cycles:				-0.8%					100.0%
											Durability Factor					100	100	100		100

Notes:

APPENDIX D: PROPOSED ECC SPECIFICATION

SECTION 496 – DECK SEAL CONCRETE

DESCRIPTION

496.01.01 General. This work consists of overlaying existing concrete slabs with Engineered Cementitious Composite (ECC).

MATERIALS

496.02.01 General. No coarse aggregates are to be used for the ECC material. Fine aggregates shall conform to Subsection 706.03.03.

Fibers to be used for ECC material shall be manufactured of polyvinyl-alcohol (PVA) with a fiber diameter of 0.04 mm (1.5 mils) and a length of between 8 mm (0.3 inch) and 13 mm (0.5 inch). The surface of the fiber may be oiled by the manufacture with 0.8% (by weight) hydrophobic oiling compound along the length of the fiber. Fiber strength shall be a minimum of 1.6 GPa (232 ksi) with a tensile elastic modulus of at least 40 GPa (5,800 ksi).

Water reducing, high range admixture (superplasticizer) shall conform to ASTM C 494 Type F or G and ASTM C1017 Type 1 or 2. The selected water reducing, high range admixture shall be comprised of a polycarboxylate chemical composition. Hydration stabilizing admixtures shall conform to ASTM C494, Type D. Viscosity modifying admixtures (VMA) shall conform to ASTM C494, Type S.

Type II cement shall be used in all ECC mixes. Fly ash shall be an ASTM C618 Class F fly ash.

496.02.02 Mix Design Requirements. The ECC mixture requirements are shown in

Table. For the mixture proportions listed, the assumed specific gravity for the fibers is 1.3. Adjustments to the weight of fiber may be allowed to meet the required 2% by volume. The amount of High Range Water Reducer (HRWR) may be adjusted to reach the target workability of the mix. Additional HRWR may be added at the construction site to adjust the workability of the mix in small quantities if proven through demonstration to be effective. Water additions are not allowed at the construction site or in transit.

The combined mass of cement and pozzolan will be considered as the mass of cementitious material when determining compliance with the maximum water-cementitous requirement of Table 1 of Section 496.02.02. The amount of cement only will be considered as the mass of cement when determining compliance with the cement range in Table 1 of Section 496.02.02.

Table 1: Required ECC Mix Design Parameters.

ECC Mix Design Parameter	Value
Polyvinyl-alcohol Fibers (PVA)	Approx. 44 lb/yd^3
	2% by volume
Maximum Water-Cementitious Material Ratio (lb/lb)	0.3
Cement Range (lb/yd^3)	800-1100
Fly Ash Range (lb/yd)	800-1500

The proposed ECC mix design shall be submitted a minimum of 35 working days prior to placement of the ECC material. Mechanical and fresh property requirements for the ECC material are shown in Table 2 and all requirements must be met by proposed ECC mix design. Testing for hardened ECC may be conducted at the Civil Engineering Materials Laboratory at the University of Nevada, Reno under the direction of Professor Elie Y. Hajj (1664 N. Virginia Street, Reno, Nevada 89557, (775) 784-1180). Other testing laboratories shall be approved prior to testing.

Table 2: Required ECC Mix Design Performance.

	Fresh ECC Properties (Lab and Jobsite)					
Property	**Test Method**	**Required Value for Fresh ECC Material**				
Slump (in.)	Nev. Test Method T438C	Minimum of 7				
Slump Flow (in.) (See Note (A) Below)	Nev. Test Method T417B	Maximum of 24				
Air Content (%)	Nev. Test Method T432E	Maximum of 3				
Unit Weight Variation (lb/ft^3)	Nev. Test Method T435D	± 3				
	Hardened ECC Mechanical Properties (See Note (B) Below)					
Property	**Test Method**	**12 hrs**	**1 day**	**3 days**	**7 days**	**28 days**
Minimum Compressive Strength (psi)	ASTM C109	Report	2000	Report	5,000	7000
Minimum Uniaxial Ultimate Tensile Strength (psi)	See Note (C) Below			400		600
Minimum Tensile Rupture Strain Capacity (%)				0.4		0.4
Maximum Free Drying Shrinkage ($\mu\varepsilon$)	ASTM C157				Report	Report
Split Tensile Strength (psi)	ASTM C496				Report	Report
Flexural Strength (psi)	See Note (D) Below		Report			Report

(A) If ECC mix design designates a slump of greater than 10 inches, perform the slump flow test to measure workability. Air content and unit weight shall be determined using Nev. Test Method T416B. The maximum Visual Stability Index for ECC mix shall not exceed 1.
(B) 12 hour and 3 day compressive strength tests are only required for samples cast from the large-scale trial batch and samples retrieved from the corresponding test slab.
(C) Refer to Subsection 496.02.04 for detailed description of test method to obtain uniaxial tensile strength and tensile strain capacity of ECC material.
(D) Specimens shall have modified dimensions of 6 inch width, 21 inch length, and 3 inch depth and shall be saw-cut from the middle of a full 6 inch width, 21 inch length, and 6 inch depth beam immediately after demolding. Cast and test specimens in accordance with Nev. Test Method T442F.

496.02.03 Trial Batch. Appoint a technical representative capable of making adjustments to the batching and mixing of ECC material. This representative shall be familiar with the mixing, batching, and placement of ECC material. The technical representative shall designate a batching sequence of ECC material to ensure uniform fiber dispersion and homogeneity of the material. Table 3 shows the required mixing sequence for small-scale trial batches of workable ECC mixtures. Table 4 shows the suggested mixing sequence for large-scale trial batches; the contractor may modify this sequence to produce a workable mixture with satisfactory fresh properties (as approved by the Engineer). The technical representative shall be present at the trial batch and at the first placement of ECC material to make recommendations and adjustments. A small-scale trial batch may be performed to become familiar with the material. Small-scale trial batches shall be performed using a concrete mixer.

Table 3: Required Small-Scale ECC Mixing Sequence.

Activity No.	Activity	Elapsed Time (min)
1	Charge all sand	1
2	Charge approximately 75% of mixing water, all HRWR, all hydration stabilizer	1
3	Charge all fly ash	2
4	Charge all cement and remaining mixing water intermittently	4
5	Charge fibers	1
6	Mix for 5 minutes or until mixture is homogeneous	5

Table 4: Suggested Large-Scale ECC Mixing Sequence.

Central-Mixed Concrete		Transit-Mixed Concrete	
Activity	Elapsed Time (min)	Activity	Elapsed Time (min)
Weight out all sand, fly ash, cement, and fiber onto weight hopper conveyor belt.	3	Charge all sand.	2
Discharge all dry materials into central mixing drum. Simultaneously, add all mixing water and HRWR to mixing drum.	2	Charge approximately 80-90% of mixing water, all HRWR.	2
Mix for 5 minutes or until mixture is homogeneous.	5	Charge all fly ash.	2
Discharge into concrete truck.	1	Charge all cement.	2
---	---	Charge remaining mixing water to wash drum fins.	3
---	---	Mix at high RPM for 2 minutes or until mixture is homogeneous.	2
---	---	Charge all fibers.	3
---	---	Mix at high RPM for 5 minutes or until mixture is homogeneous.	5

Perform a minimum of 6yd^3 large-scale trial batch at least 35 days prior to full production. The Engineer shall be notified of the time of the trial batch placement a minimum of 48 hours before batching. Quality control specimens shall be cast from this trial batch according to Table 2. The large-scale trial batch shall be prepared following the development of a mix design and with the same materials that will be used for the ECC overlay mixture. For the trial batch to be considered successful, fiber dispersion and both fresh and mechanical material properties shall meet all requirements of this special provision as shown in Table 2. Qualitative judgment will be made by the Engineer as to proper homogeneous fiber dispersion throughout the fresh material. If the trial batch does not meet all of these requirements, the trial batch shall be repeated at no additional cost to the department. The 28-day test results of a successful trial batch shall be received by the Engineer at least 7 days prior to full production.

Using ECC material from a successful large-scale trial batch, place and finish a test slab of approximately 3yd^3 at the mix plant or on the project site, as designated, a minimum of 7 days prior to full production. The slab thickness shall be similar to the thickness that the ECC material will be placed as specified in the contract. The Contractors shall thoroughly moisten surfaces on which ECC will be placed with water immediately before placing concrete. Place ECC to avoid segregation of the material. Consolidate the ECC in accordance with Section 502.03.08. Finish the test slab in accordance with Section 496.03.01 of this special provision. The slab shall be cured using the same method that will be used when curing the ECC during construction. Cure the test slab in accordance with 501.03.09.

The purpose of the test slab is to determine the best way to place, consolidate, finish, and cure the ECC material. A test slab must be placed at the mix plant or on the project site without the ECC segregating and finished to provide a smooth surface free from tears. If a modification of the mix design or batching sequence is necessary, a revised mix design and batching sequence must be prepared and another test slab placed. Repeat the submittal and test slab process until a workable and finished test slab is produced. Test slabs may be poured using material from a large-scale trial batch but shall only be accepted if the corresponding large-scale trial batch is considered successful. Do not place the ECC overlay as specified in the contract until the test slab has been accepted.

If consolidation and/or finishing of the material prove difficult using the methods described in the standard specification and this special provision, the Contractor may make modifications to these methods. Multiple test slabs may need to be placed for the Contractor to become familiar with and to evaluate different methods for consolidating, finishing, and curing the material. All modifications by the Contractor must be demonstrated to the Engineer to show the improvements of the consolidation, curing, and/or finishing qualities of the ECC material. These modified methods must be pre-approved by the Engineer at least 7 days prior to full production.

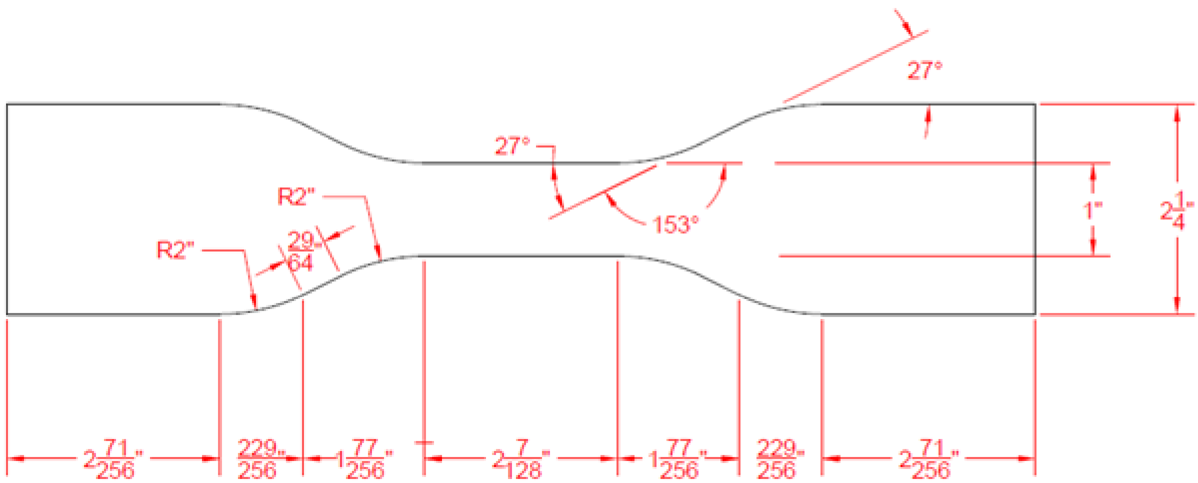
Samples shall be retrieved from the test slab to determine the compressive strength of the ECC. The Contractor can either have core samples taken and cut into 2-inch cubes or have a rectangular piece cut out from the slab and then cut into 2-inch cubes. Samples shall be retrieved at 12 hours, 1 day, and 3 days after the completion of the test slab. Samples shall be tested within 2 hours of being removed from the test slab. These cube samples must meet the requirements for compressive strength in Table 2.

496.02.04 Uniaxial Test. The following is the test method used to determine the uniaxial tensile strength and tensile strain capacity of ECC material

This test method covers the determination of the uniaxial tensile strength and tensile strain capacity of an ECC material when subjected to a uniaxial tensile load.

Uniaxial tension tests shall be run on a servo-hydraulic testing machine capable of operating a displacement controlled test at a test speed of 0.1 mil/sec. The servo-hydraulic testing machine shall be capable to measure the displacement between grips and the applied load at a frequency of 2 measurements per second or greater.

Specimens to be used in this uniaxial tension test shall conform to the dimensions shown in Figure 1. At least 4 replicates shall be tested. Specimens shall be compacted using a tamping rod as mentioned in ASTM C109, tamping the entire surface of the specimens. Finish the specimens with a damp trowel to give the specimen a smooth surface. Place specimens into curing room at a relative humidity of between 96% and 100% until time of test. Demold specimens after 24 hours. Use extreme care when removing specimens from molds. Specimens damaged during removal from molds shall be discarded immediately. Specimens shall be air dried in laboratory for 1 hour prior to uniaxial tension test.



Specimen Thickness = 0.5 inches

Figure 1: Dimensions of specimens for uniaxial tension test.

Measure the width and depth of the specimen at 3 places along the neck of the specimen. Place specimens into the grips of the servo-hydraulic testing machine. Ensure that there is sufficient contact between the grips and the specimen. Apply load to the specimen at a rate not exceeding 3 lb/sec. Continue the test until specimen has failed.

Determine the cross sectional area of the specimen using the average value of the three measurements of specimen's depth and width. Divide the applied load by the area to determine the applied tensile stress. Determine the tensile strain of the specimen using the following equation.

$$\epsilon\ (\%) = \frac{[(\text{Displacement at time} = \text{t}) - (\text{Displacement at time} = 0)]}{(\text{Displacement at time} = 0)} \times 100$$

Report the following results from the uniaxial tensile test for each specimen tested.

Ultimate uniaxial tensile strength of each tested specimen.

Rupture uniaxial tensile strain of each tested specimen.

Average and standard deviation values for both the maximum uniaxial tensile strength and tensile strain.

95% confidence interval for both the maximum uniaxial tensile strength and tensile strain.

Stress-strain graph of each tested specimen.

CONSTRUCTION

496.03.01 Preparation, Placement, and Cure. Prior to placement of the ECC overlay, scarify the existing slab surface by shot blasting or hydroblasting. Use of scabblers, milling machines, or sand blasting will be at the discretion of the Engineer. If shot blasting is utilized, use a 75 hp minimum self-propelled machine equipped with vacuum recovery. If electing to use the hydroblasting method to scarify the existing slab surface, do not exceed a water pressure at the nozzle of 55 MPa (8,000 psi). The scarifying procedure shall produce a uniform rough texture, removing paste and exposing the coarse aggregate to a depth not to exceed 6 mm (1/4 in.). The prepared surface shall be sound.

Trucks delivering ECC material to the project shall be fully discharged within 90 minutes of charging. A request written request to exceed the specified 90 minute time limit for the discharge of the ECC material as specified in Subsection 501.03.06. Because of the high flowability of ECC material and placement on sloping surfaces, any vibration may pose problems with maintaining the location of the ECC material, causing it to flow down grade to the low point of the crown before setting. Care shall be used to not over agitate ECC material to cause excessive flowing.

ECC material shall be placed so as not to segregate the material. The ECC shall be consolidated in accordance with Section 502.03.08. Curing of the ECC overlays shall be in conformance with Subsection 501.03.09. The Contractor can choose to use the alternative methods from the test slab if found to be necessary. These alternative methods must be pre-approved by the Engineer at least 7 days prior to full production.

496.03.02 Surface Finish. In advance of curing operations, use a mechanical steel tine device to form grooves in the ECC overlay parallel to the centerline. Do not perform tining too early, where by the grooves may close up. Make tines of rectangular cross section and of sufficient thickness and resilience to result in grooves spaced 19 mm

(3/4 in.) on center, 2 mm to 3 mm (3/32 in. to 1/8 in.) wide and 3 mm to 5 mm (1/8 in. to 3/16 in.) deep in the finished concrete pavement.

Tine the ECC overlay within 75 mm (3 in.), but no closer than 50 mm (2 in.), of pavement edges.

Maintain the tining device clean and free of encrusted mortar and debris to ensure uniform groove dimensions.

Do not tine pavement which has set, whereas the operation is lifting aggregate out of, or tearing, or causing excessive roughness to the pavement surface. In such case, groove the pavement as directed.

Grind and groove pavement surfaces that do not meet tining requirements. Perform grinding and grooving to meet the tining requirements as directed.

496.03.03 Surface Tolerances. Produce completed surfacing which is smooth and free from ruts, humps, depressions, or irregularities. Eliminate ridges, indentations, or other objectionable marks left in the surface. Discontinue use of equipment that leaves ridges, indentations, or other objectionable marks in the surface, or does not consistently produce a surface meeting the straightedge requirements.

After final finishing the surface shall meet the straightedge measurement.

The Engineer will perform the straightedge measurement. When a straightedge 3.6 m (12 ft) long is laid on the finished surface and parallel with the centerline of the highway, the surface shall not vary more than 7.5 mm (0.3 in.) from the lower edge of the straightedge. When a straightedge 3.6 m (12 ft) long is laid on the finished surface and at right angles with the centerline, the surface shall not vary more than 7.5 mm (0.3 in.) from the lower edge of the straightedge.

Correct defective areas by abrasive grinding, by removal and replacement, or approved methods.

The grinding machine for correcting defective areas shall be power driven, self-propelled and specifically designed to remove, profile, smooth, and texture the overlay. Use grinding machine with a wheel base of not less than 3.6 m (12 ft), equipped with a rotating powered mandrel drum studded with diamond blades with a cutting head not less than 0.9 m (3 ft) wide. Equip the grinding machine with an effective means for controlling dust and other particulate matter.

Perform grinding in a longitudinal direction. Satisfactorily grind to produce a uniform textured surface over the surface areas designated for grinding.

The surface of the ground pavement shall have parallel corduroy-type texture consisting of grooves between 2.3 mm (0.09 in.) and 3.3 mm (0.13 in.) wide. The peaks of the ridges shall be approximately 1.5 mm (1/16 in.) higher than the bottom of the grooves with approximately 170 to 190 evenly spaced grooves per meter (52 to 57 grooves per foot).

Pick up and dispose of grinding materials, including water used for the grinding operation, outside the right of way according to Subsection 107.14.

496.04.01 Quality Assurance. Quality assurance of ECC materials shall be consistent with standard specifications. Compressive strength cube samples, uniaxial tensile test samples, and flexural strength samples shall be cast on site at the time of placement. Tests on the fresh properties of ECC shall be performed concurrently with casting of samples when possible. Samples shall be taken every 100 yd^3 or fraction thereof, and first samples shall be taken within first two loads. Tests to evaluate fresh properties shall be taken every 50 yd3 or fraction thereof, and first tests shall be performed within first two loads.

METHOD OF MEASUREMENT

496.04.01 Measurement. Deck seal concrete will be measured by the square yard.

BASIS OF PAYMENT

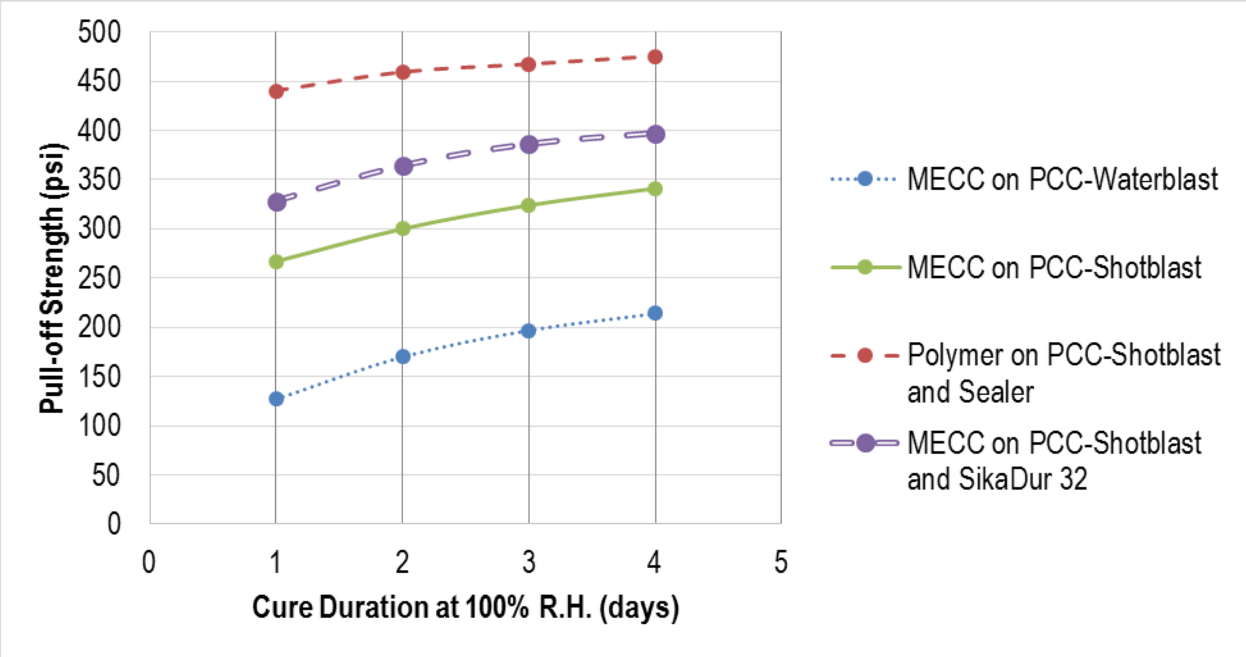
496.05.01 Payment. The accepted quantities, measured as provided above, will be paid for at the contract price per unit of measurement for the pay items listed below that are shown in the proposal. Payment will be full compensation for the work prescribed in this Section.

Payment will be made under:

Pay Item	Pay Unit
Deck Seal Concrete	Square Yard

APPENDIX E: RESULTS OF ADDITIONAL LABORATORY EVALUATIONS

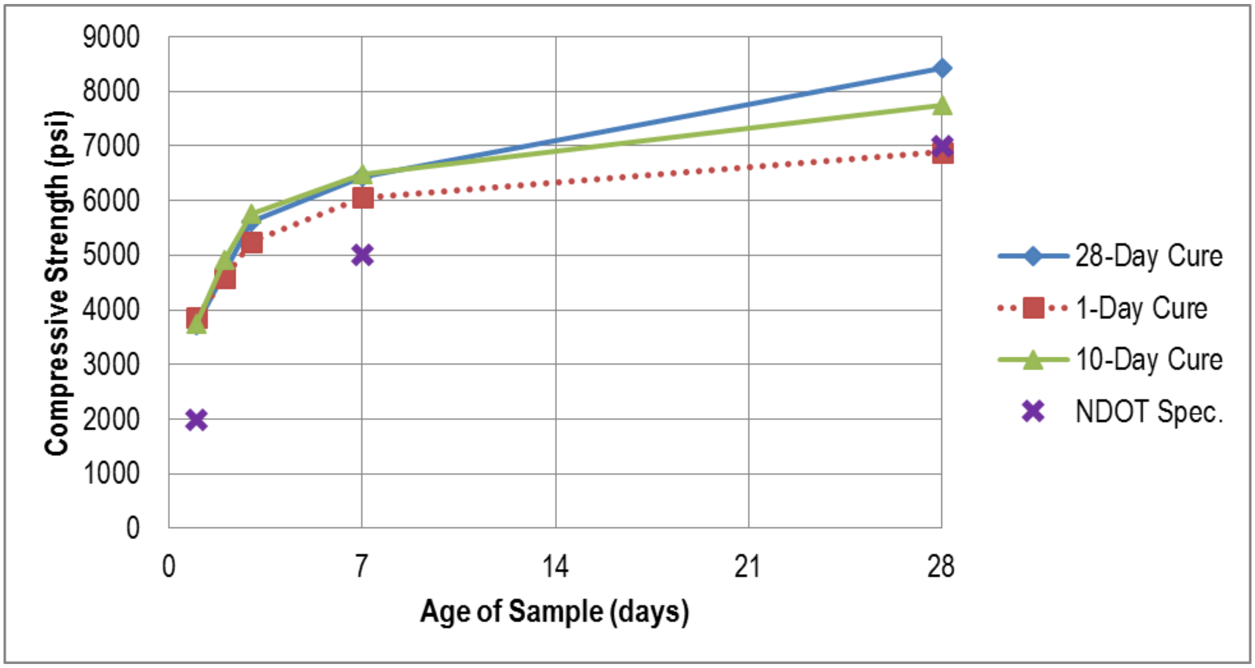
Influence of Bonding Agent on Pull-Off Bond Strength between MECC and PCC.



Sample	1 Day	2 Days	3 Days	4 Days
MECC-WB	127	170	197	214
MECC-SB	267	300	324	341
Polymer	440	459	467	475
SikaDur 32	328	364	386	397

Influence of Curing Regiment on Compressive Strengths of MECC.

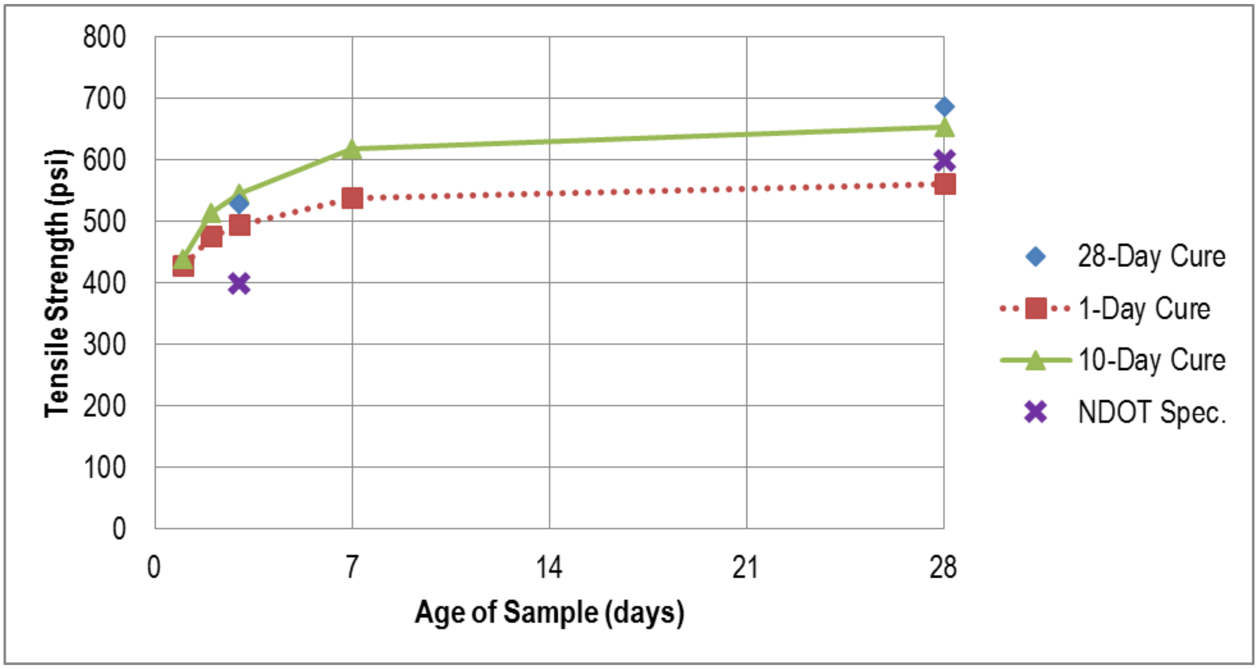
28-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room at 100% R.H. until time of test.
1-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were then removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
10-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room for 10 days in total. Samples were removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
NDOT Spec: Minimum MECC mix's required properties as outlined in NDOT Specifcation.



Cure Regiment:	1 Day (psi)	2 Days (psi)	3 Days (psi)	7 Days (psi)	28 Days (psi)
1-Day Cure	3,778	4,578	5,248	6,057	6,891
10-Day Cure	3,719	4,896	5,691	6,428	7,758
28-Day Cure	3,742	4,925	5,764	6,492	8,431
Specification	2,000	N/A	N/A	5,000	7,000

Influence of Curing Regiment on Tensile Strengths of MECC.

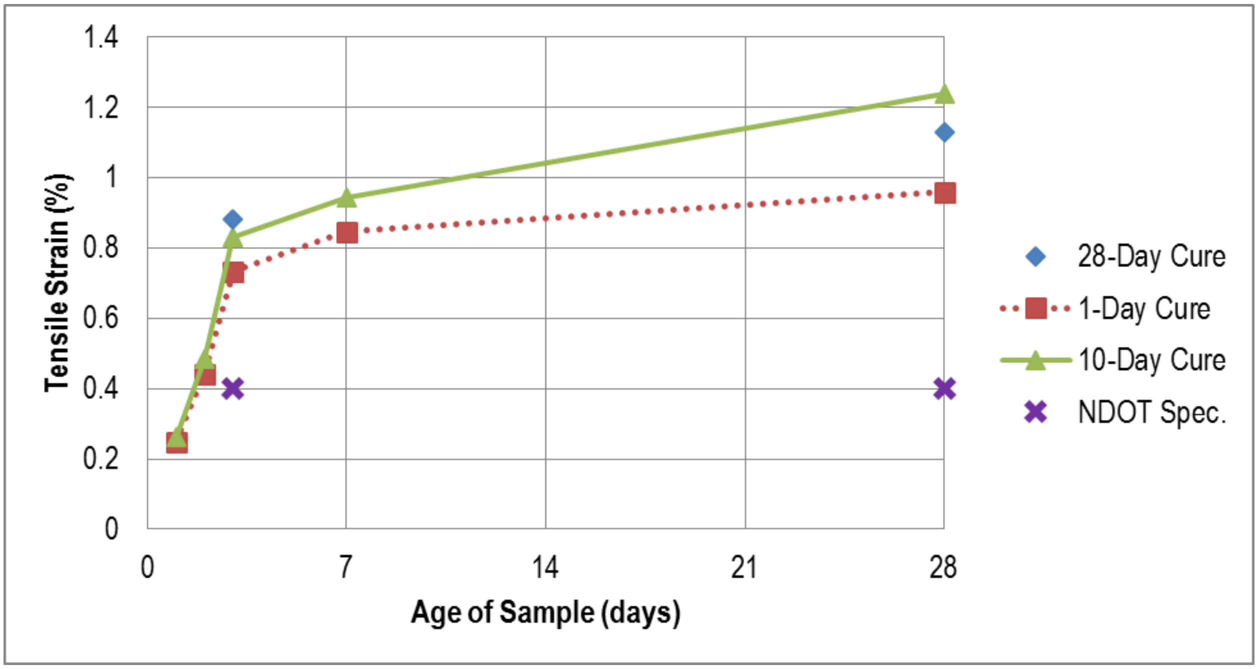
28-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room at 100% R.H. until time of test.
1-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were then removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
10-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room for 10 days in total. Samples were removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
NDOT Spec: Minimum MECC mix's required properties as outlined in NDOT Specifcation.



Cure Regiment:	1 Day (psi)	2 Days (psi)	3 Days (psi)	7 Days (psi)	28 Days (psi)
1-Day Cure	428	476	495	538	561
10-Day Cure	440	514	546	618	654
28-Day Cure	N/A	N/A	538	N/A	686
Specification	N/A	N/A	400	N/A	600

Influence of Curing Regiment on Tensile Strain of MECC.

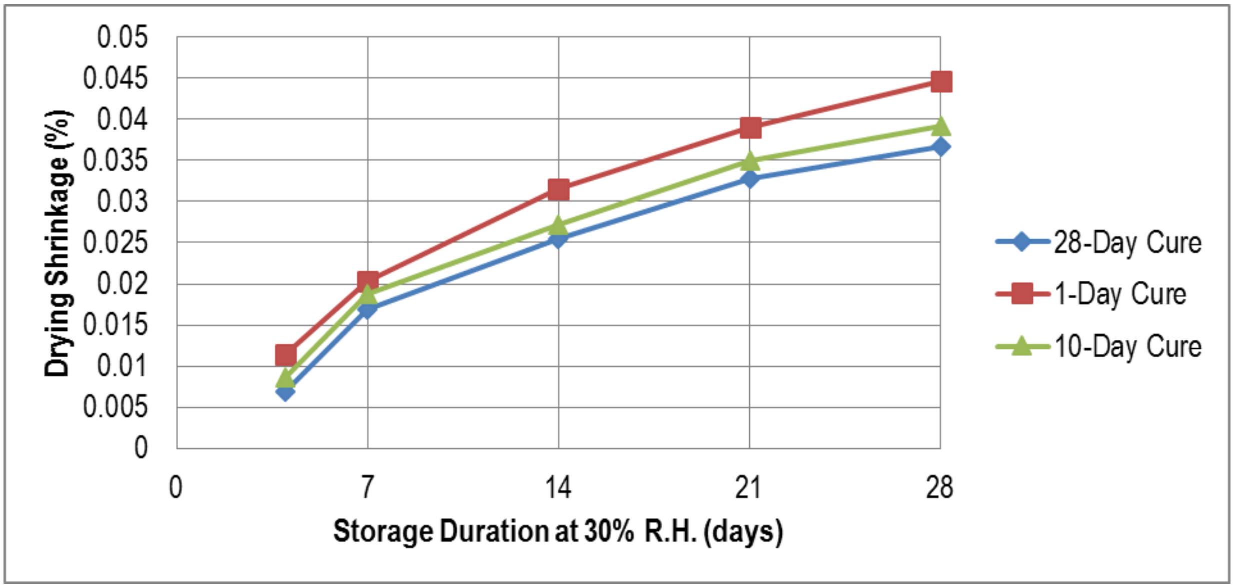
28-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room at 100% R.H. until time of test.
1-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were then removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
10-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room for 10 days in total. Samples were removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. until time of test.
NDOT Spec: Minimum MECC mix's required properties as outlined in NDOT Specifcation.



Cure Regiment:	1 Day (%)	2 Days (%)	3 Days (%)	7 Days (%)	28 Days (%)
1-Day Cure	0.248	0.439	0.732	0.845	0.958
10-Day Cure	0.261	0.486	0.831	0.943	1.24
28-Day Cure	N/A	N/A	0.88	N/A	1.13
Specification	N/A	N/A	0.40	N/A	0.40

Influence of Curing Regiment on Drying Shrinkage of MECC.

28-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room at 100% R.H. for a total of 28 days. After 28 days, samples were then stored at a R.H. of 50% for remainder of test.
1-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were then removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. for remainder of test.
10-Day Cure: Samples were stored in cure room at 100% R.H. Samples were demolded after 24 hours. Samples were left in cure room for10 days in total. Samples were removed from cure room and had wax-based curing compound applied. Samples were left in laboratory at 30% R.H. for remainder of test.



Cure Regiment:	4 Days (%)	7 Days (%)	14 Days (%)	21 Days (%)	28 Days (%)
1-Day Cure	0.01147	0.02037	0.03154	0.03905	0.04457
10-Day Cure	0.00876	0.01875	0.02719	0.03497	0.03912
28-Day Cure	0.00698	0.01684	0.02540	0.03284	0.03670

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