DEVELOPMENT OF SPECIFICATIONS FOR ENGINEERED CEMENTITIOUS COMPOSITES FOR USE IN BRIDGE DECK OVERLAYS

TASK 1: LITERATURE REVIEW

NEVADA DEPARTMENT OF TRASPORTATION
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for

NDOT Project 13-39

Submitted to
Nevada Department of Transportation

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CHAPTER 1: INTRODUCTION

Concrete is one of the most used construction materials, both domestically and internationally. A relatively new class of concrete is engineered cementitious composites (ECC). ECC is a high-performance fiber-reinforced mixture of cement, water, fine sand, fibers, and chemical admixtures. The fibers are typically polyvinyl alcohol fibers (PVA). ECC performs very similar to concrete in compression; ECC can reach the same compressive strengths as concrete. However, ECC has superior tensile properties. ECC can have a tensile strain capacity of 5%, about 500 times larger than that of concrete. The same ECC mix can have a tensile strength of over 725 psi (5 MPa). Tests performed on ECC show the material has many characteristics that engineers desire: high corrosion resistance, high resistance to reflective cracking, low permeability, high freeze-thaw resistance, and high ductility. The use of ECC has grown as engineers have seen the benefits of ECC.

ECC is already being used as a construction material. It has been used to construct reinforced ECC structural members in seismic areas. ECC beams show exceptional performance when subjected to earthquake loadings. Several studies conducted at the University of Nevada, Reno, showed that ECC performed much better in bridge columns than standard concrete. These studies also showed that ECC can be produced in Nevada by local contractors. ECC has also been applied in the transportation field. Michigan has already placed multiple bridge deck link slabs constructed with ECC. It has also been used in Japan as the road bed for the Mihara Bridge.

The objective of this Nevada DOT research project is to determine whether or not ECC can be produced consistently and reliably from multiple sources of Nevada aggregates and batched on a large scale for highway construction projects. This research project will investigate the mix design, production, performance, and application of ECC on a large scale for bridge deck overlays. Testing carried out on the ECC will evaluate the material's mechanical properties. The durability of ECC will also be evaluated to determine if the material can perform at a high level for many years as a bridge deck overlay. Once the material has been tested and a mix has been chosen for field testing, two different bridge deck overlays in Nevada will be constructed to validate the results of laboratory testing on ECC. The project will conclude by developing specifications for designing, producing, placing, and finishing ECC for bridge deck overlays in Nevada.

This report is a comprehensive literature review and is the final product of Task 1 of NDOT project 13-39. The report has been divided into chapters that address the key aspects of ECC. Each chapter will provide an introduction and then summarize the ECC literature. It covers all aspects of ECC, from mix design and testing to production and application of the material. Several different ECC mixes from the literature were evaluated to determine the optimal mix proportions for the material. Several studies presented herein evaluated the durability of ECC under conditions that would be expected for bridge deck overlays. In side by side testing, ECC samples have been shown to withstand these harsh conditions whereas concrete samples were destroyed during the tests. The production of large-scale ECC batches was investigated where multiple batching sequences were evaluated until to find sequences that produced consistent ECC with sufficient mechanical properties. The application of ECC, specifically as bridge deck link slabs, was performed to evaluate the feasibility of ECC as a construction material. The field demonstrations of ECC were used to validate laboratory test results and determine if ECC could be produced and applied as frequency and as easily as concrete.

CHAPTER 2: REVIEW OF ECC MIX DESIGN AND PROPERTIES

2.1 Introduction

This chapter summarizes the information compiled from an extensive literature review on the available research studies, mix design and mix compositions, as well as well as fresh and hardened properties of ECC. Several mix design variables were evaluated in the literature: sand-to-cement ratio (S/C), water-to-cement ratio (W/C), fly-ash-to-cement (FA/C), and different amounts of chemical admixtures. Different types of cement, fly ash, and fibers were also evaluated. The interface between the fibers and matrix was studied by several researchers and the results from the literature are presented. Many different mechanical and performance properties were evaluated and reported such as tensile strength, tensile strain capacity, compressive strength, flexural strength, and fatigue resistance. The durability and resistance of ECC to freeze-thaw and environmental conditions as found in the literature are also summarized in this chapter.

2.2 Tensile Strain-Hardening Behavior of Polyvinyl Alcohol ECC

In 2001, Li et al. *(1)* discussed how engineered cementitious composites (ECC) with polyvinyl alcohol (PVA) fibers were designed and tested. The parameters that are needed for the ECC mixture to undergo strain-hardening were investigated in a laboratory setting. There were two variables in the experiment: the amount of fiber surface coating (by % weight fibers) and the sand content. In total there were twelve different ECC mix designs using the REC fibers. A fiber reinforced concrete (FRC) mix with a different type of fiber was used as the reference mix. Table 1 shows the ECC mix proportions while Table 2 shows the properties of the two different PVA fibers used in this experiment.

Table 1: Mix proportions (by weight) for ECC and FRC (0% oiling agent content) mixes.

ECC Mix No.	Oiling Agent Content %	Fiber Volume %	Cement	Water	Sand	MC[1]	SP[2]
1	0.3	2.0	1.0	0.45	0.5	0.0020	None
2	0.3	2.0	1.0	0.45	0.6	0.0020	0.02
3	0.3	2.0	1.0	0.45	0.8	0.0015	0.03
4	0.3	2.0	1.0	0.45	1.0	0.0015	0.03
5	0.5	2.0	1.0	0.45	0.6	0.0015	0.03
6	0.5	2.0	1.0	0.45	0.8	0.0015	0.03
7	0.5	2.0	1.0	0.45	1.0	0.0015	0.03
8	0.5	2.0	1.0	0.45	1.2	0.0015	0.03
9	0.8	2.0	1.0	0.45	0.6	0.0015	0.03
10	0.8	2.0	1.0	0.45	1.0	0.0015	0.03
11	0.8	2.0	1.0	0.45	1.2	0.0015	0.03
12	0.8	2.5	1.0	0.45	1.2	0.0015	0.03
PVA-FRC w/RMU Fibers		2.0	1.0	0.45	0.6	0.0015	0.03

[1] Hydroxypropyl methlcellulose to cement ratio
[2] High range water reducing admixture

Table 2: Properties of PVA fibers used in the tensile-strain-hardening behavior study.

Fiber Type	Nominal Strength	Fiber Diameter	Fiber length	Young's Modulus	Elongation, %
REC	235 ksi (1,620 MPa)	1.5 mil (39 μm)	0.5 inch (12 mm)	6,210 ksi (42.8 GPa)	6.0
RMU	241 ksi (1,660 MPa)	0.5 mil (14 μm)	0.25 inch (6 mm)	8,700 ksi (60.0 GPa)	6.0

The mixes were cast into samples and were tested at 28 days using a uniaxial tensile test (testing procedure explained in report). This is because some types of fiber reinforced concretes might show signs of strain-hardening under flexural loading even though the material is brittle or quasi-brittle. Thus, the uniaxial tensile test is the most accurate method to characterize the material properties in tension.

The results of the test showed that all mixes (except for the reference mix, i.e., FRC w/RMU) exhibited strain-hardening behavior. The ultimate tensile strain capacities varied between 5.5% and 15%, the ultimate tensile strengths fell between 536 psi (3.7 MPa) and 725 psi (5.0 MPa), and the first crack tensile strengths fell between 377 psi (2.6 MPa) and 565 psi (3.9 MPa). Failure in the samples showed that fracture localization was not present after first crack strengths were exceeded, meaning multiple cracking behavior was observed. Fracture localization was present once ultimate strengths were reached, leading to a crack to develop at the weakest section that will cause the specimen to fail.

Table 3 summarizes the findings from the experiment. The tensile first crack strength and tensile ultimate strength increased as sand content increased for a constant oiling content. Both strengths were largest at oiling content of 0.3%. The ultimate tensile strain capacity increased as the oiling content increased and was largest for an oiling content of 0.5%. Lastly, an increase in the amount of fibers from 2% to 2.5% by volume caused huge increases in strengths.

Table 3: Summary of the findings from the tensile-strain-hardening behavior study.

Property	Findings
First Crack Tensile Strength	• Significant Factors: Oiling agent content, sand-to-cement ratio (s/c), fiber content. • The first crack strength decreased as the oiling agent increased. Highest strengths were achieved at oiling agent content of 0.3%. • The first crack strength increased as the s/c ratio increased with constant oiling agent content. • Increased fiber content of 2.5% (by volume) increased strength by 30% compared with fiber content of 2%.
Ultimate Tensile Strength	• Significant Factors: Oiling agent content, sand-to-cement ratio (s/c), fiber content. • The ultimate strength decreased as the oiling agent increased. Highest strengths were achieved at oiling agent content of 0.3%. • The ultimate strength was highest at medium s/c ratios for each oil agent content. • Increased fiber content of 2.5% (by volume) increased strength by 16% compared with fiber content of 2%.
Ultimate Tensile Strain Capacity	• Significant Factors: Oiling agent content, sand-to-cement ratio (s/c), fiber content. • The ultimate tensile strain was highest at oiling agent content of 0.5%. • Increased fiber content of 2.5% (by volume) increased strain by 85% with compared with content of 2%.

Modifying the fiber-matrix interface properties is a major component of ECC. Strain-hardening behavior is dependent on the interface properties between the cement and fibers. This was demonstrated with the reference mix as it did not experience multiple cracking behavior because there was no oiling agent used in the mix. Higher surface coating content led to more consistent performance of the material. High coating content also increased the optimal sand content, leading to a more economical mix.

2.3 Monotonic and Fatigue Performance in Bending of Fiber-Reinforced ECC in Overlay System

Zhang and Li *(2)* evaluated the monotonic and fatigue performance of a PVA-ECC using a composite beam in bending. The study offers a theoretical analysis of ECC material being used in an overlay system.

A beam was constructed that consisted of a concrete bridge deck and an ECC overlay. Table 4 shows the mix proportions for the ECC and concrete materials evaluated. Table 5 shows the properties of the PVA fibers used. Beam dimensions are given in Figure 1. The beam was tested using a three-point bending load and was performed in accordance with ASTM C1018. The beams were cast such that only the overlay was being subjected to the load. There were five test beams used in this experiment: one beam consisting of a Portland cement (PC) overlay and four beams consisting of an ECC overlay. The test took into account the interface condition between the ECC and PC beam. Two of ECC overlay beams and the PC overlay beam were prepared with diamond saw cut (smooth) surfaces where the overlay was placed onto the beam. The other two ECC overlay beams were prepared by sand blasting the cut surface (rough) where the overlay was placed onto the beam.

Table 4: Mix proportions (by weigh) for PC and ECC mixes evaluated in overlay system fatigue study.

Component	**PC**	**ECC**
Cement (Type 1)	1.00	1.00
Natural Sand	1.62	1.00
Crushed Stone	1.62	---
Water	0.45	0.434
Superplasticizer	0.005	0.025
Methyl Cellulose	---	0.002
PVA Fibers	---	2% by volume

Notes: Superplasticizer has water content of 66%;
Natural River sand has particle sizes of (0.011-0.16 inches (0.3-4 mm).
Crushed stone has maximum particle size of 0.4 inches (10 mm).
The additional Superplasticizer in the ECC is to increase the workability of the mix.

Table 5: Properties of PVA fiber evaluated in overlay system fatigue study.

Type	**E_f**	**S_f (MPa)**	**D_f**	**L_f**
PVA (K-II)	6,210 ksi (42.8 GPa)	235 ksi (1,620 MPa)	1.5 mil (39 µm)	0.5 inch (12 mm)

Notes: E_f = fiber modulus; S_f = fiber tensile strength; D_f = fiber diameter; L_f = fiber length

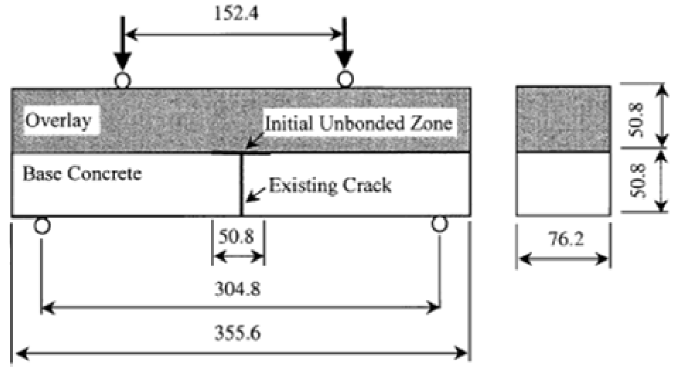

Figure 1: Dimensions for ECC/concrete beam evaluated in overlay system fatigue study. *(2)*

Table 6 summarizes the findings from this study. The ECC overlay had a modulus of rupture (MR) of 1.94 ksi (13.35 MPa) and 1.98 ksi (13.68 MPa) for the rough and smooth beams, respectively. The PC overlay had a MR of 0.9 ksi (6.24 MPa). The beam deflection for the ECC overlay was 0.04 inches (1.05 mm) for the rough interface and 0.088 inches (2.24 mm) for the smooth interface. The smooth surface ECC overlay had a higher load capacity because the smooth interface allowed for the ECC overlay to delaminate over a larger area, which increased the multiple cracking zone within the overlay. The first crack strength was 510 psi (3.5 MPa) for both the smooth and rough interface for the ECC overlay.

Table 6: Summary of findings from overlay system fatigue study.

Property	Findings
Modulus of Rupture	• Significant factors: Overlay/bridge deck interface conditions • Smooth interface surface between overlay layer and bridge deck will cause the ECC to have a higher modulus of rupture.
First Crack Strength	• No significant factors. • Both smooth and rough interface surface between overlay layer and bridge deck layer had the same first crack strength.
Beam Deflecton	• Significant factors: Overlay/bridge deck interface conditions • Smooth interface surface between overlay layer and bridge deck will cause the beam to have a higher vertical deflection under four-point bending.
Overlay Delamination	• Significant factors: Overlay/bridge deck interface conditions • The ECC overlay layer will delaminate from the bridge deck under bending load. Smooth surface interface allows ECC layer to delaminate over a larger area, which causes the beam to deflect more and the modulus of rupture for the ECC layer to be higher than those of the rough surface interface.

2.4 Interface Tailoring for Strain-Hardening Polyvinyl Alcohol ECC

In 2002, Li et al. *(3)* investigated the influence of fiber/matrix interface on the tensile strain capacity of a PVA-ECC mixture. The objective was to adjust the oiling agent content (% weight of fibers) such that the fiber/matrix interface properties fell within the range of optimal values calculated. Three critical parameters for the fiber/matrix interface were identified: (1) chemical bond; (2) slip-hardening coefficient; and (3) the interface frictional bond. A single ECC mix was used in this study. Table 7 shows the mix proportions of the ECC while Table 8 shows the properties of the PVA fibers used in this experiment. Five different oiling agent contents were tested: 0.0, 0.3, 0.5, 0.8, and 1.2%. To assess the three interface parameters, a single fiber pullout test was conducted at 21 days. Fibers were placed protruding out from the ECC sample and these fibers were pulled out at an angle normal to the sample using a load cell. To determine the tensile strain capacity of the mixes, a uniaxial tension test was also performed at 14 days.

Table 9 summarizes the findings for this study. The results from the pullout test showed that all three of the interface parameters decreased as the oiling agent content increased. It was found that oil content between 0.8% and 1.2% allowed the fiber/matrix interface to be within the range of optimal values. The results of the tension test showed that the first crack strength decreased with increasing oil content. However, the tensile strain capacity greatly increased as the oil content increased. This study showed that ECC can achieve tensile strain capacity of 4.88% by modifying the interface properties between the cement and fiber using an oiling agent.

Table 7: Mix proportion for the ECC used in the fiber/matrix interface evaluation study.

W/C ratio by weight	S/C ratio by weight	Superplasticizer, %	Viscosity agent (Methyl Cellulose)	De-foamer, %
0.45	0.6	2.0	0.15	0.05

Note: Type I cement; Fiber content was 2% by volume; F110 sand used

Table 8: Properties of PVA fibers used in the fiber/matrix interface evaluation study.

Nominal strength	Apparent strength	Diameter	Fiber length,	Young's Modulus	Elongation, %
235 ksi (1,620 MPa)	158 ksi (1,092 MPa)	1.5 mils (39 μm)	0.5 inch (12 mm)	6,210 ksi (42.8 GPa)	6.0

Table 9: Summary of findings from the fiber/matrix interface evaluation study.

Property	Findings
First Crack Tensile Strength	• Significant Factors: Oiling agent content • The first crack strength decreased and then increased as the oiling agent increased. Highest strength of 420 psi (2.9 MPa) was achieved at oiling agent content of 1.2%
Ultimate Tensile Strength	• Significant Factors: Oiling agent content • The ultimate tensile strength decreased and then increased as oiling agent content increased. • Highest strength of 667 psi (4.6 MPa) was achieved at oiling agent content of 0.8%.
Ultimate Tensile Strain Capacity	• Significant Factors: Oiling agent content • The ultimate tensile strain capacity increased as the oiling content increased. Tensile strain of 4.88% was achieved with 1.2% oiling agent content.

2.5 Design of ECC for Processing and Workability Requirements

Fischer et al. *(4)* investigated in a 2003 study how to design an ECC mix that can be mixed in conventional gravity-based drum mixers. The focus was to create an ECC mix in a laboratory setting that will be densely packed and well-dispersed. This mix would reach a fluid state when water is added to achieve a high workability.

To achieve a dense mix, the ideal gradation for the composition of cement, sand, and fly ash (Type C and Type F) was determined using Equation 1. A blend of these components that best matched the ideal gradation was found to be: 1 part cement, 0.8 sand, 0.5 fly ash F, and 0.3 fly ash C by weight. In this experiment, the water content of the mix was varied and five different water-to-cement (w/c) ratios were tested. Table 10 shows the mix proportions for the five high-workability ECC mixes and for the reference ECC mix.

$$f_d = 100 * (\frac{d}{d_{max}})^{0.5} \quad \text{(Eq. 1)}$$

where f_d is the fraction of particles smaller than d, d is the particle size smaller than D in mm, and d_{max} is the maximum particle size in mm.

Table 10: Mix proportions for the five high workability and the traditional (M-ref) ECC mixes.

Components	**M-ref**	**M-1**	**M-1**	**M-3**	**M-4**	**M-5**
Cement	1.00	1.00	1.00	1.00	1.00	1.00
Sand	0.60	0.80	0.80	0.80	0.80	0.80
Fly Ash (F)	0.00	0.50	0.50	0.50	0.50	0.50
Fly Ash (C)	0.15	0.30	0.30	0.30	0.30	0.30
Ratios						
W/C	0.45	0.36	0.37	0.38	0.40	0.42
W/(CM)	0.450	0.195	0.202	0.207	0.220	0.230
W/Solids	0.260	0.134	0.138	0.142	0.150	0.158
MFS[2]/C	0.020	0.030	0.030	0.030	0.030	0.030
HPMC[3]/C	0.00150	0	0	0	0	0

[1] CM = cementitious material = (cement + fly ash)
[2] MFS is a superplasticizer.
[3] HPMC is hydroxypropyl methlcellulose.

Using Equation 1, the ideal gradation was determined. This gradation is ideal because it gives the highest density by optimizing the particle packing of all dry particles in the mix. Figure 2 shows the gradations of the dry components of the ECC (cement, sand, and fly ash). Figure 3 shows how the ECC gradation compares with the ideal gradation. The mix designs were determined based on trial and error testing in the laboratory. The water content was increased until the ECC mix was fluid enough to be mixed in a drum mixer. Mix M-5 exhibited all of the desired properties of a workable ECC mix that can be mixed in a drum mixer. The air content of the fresh ECC was measured. The flowability index (Γ) was also calculated (Equation 2). D_0 is the diameter of the bottom of slump cone, which measured 0.78 inches (20 cm) and D_f is the diameter of ECC after slump cone is removed in cm.

$$\Gamma = \frac{{D_f}^2 - {D_0}^2}{{D_0}^2} \quad \text{(Eq. 2)}$$

A certain mixing procedure was implemented to achieve a homogenous mixture. Sand, fly ash, and 1/3 of the cement were dry mixed for one minute, followed by 80% of the water. Next, the remaining water, cement, and superplasticizer were added. Lastly, the PVA fibers were added. Samples were mixed in a planetary mixer first, then in a drum mixer. After the samples were mixed, they underwent a direct tensile test to determine the strength of the ECC mixes.

Table 11 summarizes the findings from this study. Mix M-5 was successfully mixed in a gravity-based drum mixer. M-5 mix showed a tensile strain of 4% and an ultimate strength of 6 MPa. It was also shown that M-5 did not undergo segregation during mixing and remained homogeneous throughout mixing. M-5 also had an air content of 4.3% and a flowability index of 19.25.

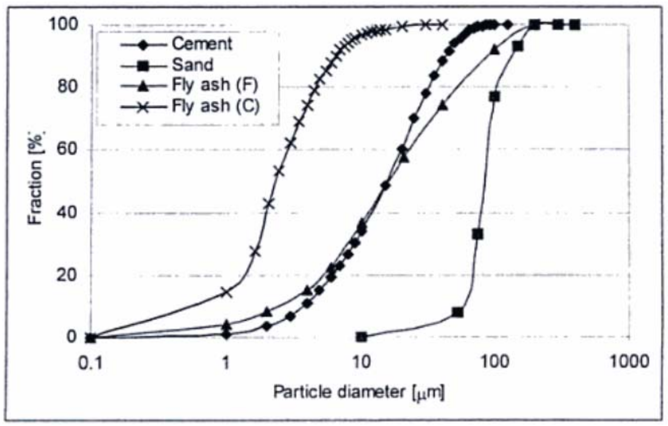

Figure 2: Gradations for all dry components in the ECC mixtures. *(4)*

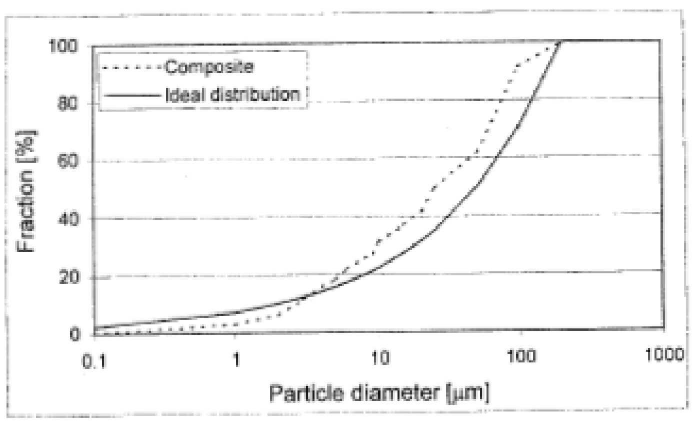

Figure 3: Gradation of ECC mixtures (sand, fly ash, and cement particles). *(4)*

Table 11: Summary of findings from processing and workability study.

Property	Findings
Workability	• Significant factors: w/c ratio • Higher w/c ratio will cause higher workability of ECC mixes. • Fresh sample of mix M-5 had spread of 35 inches (90 cm) after slump cone was removed. • Fresh sample of mix M-5 had flowability index of 19.25
Tensile Strength	• Mix M-5 had a tensile strength of 870 psi after being mixed in drum mixer.
Tensile Strain Capacity	• Mix M-5 had a tensile strain of 4% after being mixed in drum mixer.
Air Content	• Significant factors: w/c ratio • Higher w/c ratio will cause lower air content. • Mix M-5 had air content of 4.3% after being mixed in drum mixer.

2.6 Evaluation Method for PVA Fiber Distribution in ECC

In 2003, Torigoe et al. *(5)* evaluated how the fiber distribution in ECC can be quantified as well as its influence on the strain capacity of the material. Several ECC specimens were cast and subjected to a uniaxial tensile test. After testing, the specimen was cut such that the cross section at the location of the largest crack was exposed. A mercury light, filtered through a Green Flourescent Protein (GFP) filter, was shined onto the sample. This caused the fibers in the cross section to show as green to yellow dots against the black background of the ECC. The images were analyzed using a compter software (Media Cybernetics). These images were split into various amounts of equally sized pieces. The number of fibers inside each of the pieces was counted manually. Using statitical analysis, the "distribution coefficient" was calculated for each sample at each of the seven different number of pieces. For reference, a distribution coefficient of 1 means there are an equal number of fibers in all of the pieces of the cross section.

Table 12 summarizes the laboratory test results and findings. The distribution coefficient was most accurate between 56 and 270 pieces. 270 pieces is the optimal number of pieces (evaluated in this study) because it provides a larger population for the statistical analysis. There was a strong linear correlation between the distribution coefficient and the strain capaity of the ECC samples. Based on these results, the distribution of fibers in the ECC was identified critical to the mechanical properties of the material.

Table 12: Summary of findings from evaluation of fiber distribution in ECC study.

Property	Findings
Distribution Coefficient	• No significant different in distribution coefficient between 56 and 270 number of pieces. • Maximum value of distribution coeffecient occurred at 72 number of pieces. • Higher number of pieces will reduce the sensativity of the distribution coefficient. • Standard deviation of distribution coefficient is not affected by the ultimate tensile strain of ECC samples.
Tensile Strain Capacity	• The tensile strain capacity of samples increased as the distribution coefficient increased. • Distribution coefficient of 0.7 represents strain capacity of 7% while distriution coefficient of 0.65 represents strain capacity of only 2%.

2.7 Micromechanics-Based Durability Study of Polyvinyl Alcohol ECC

In 2004, Li et. al. *(6)* evaluated the long-term mechanical and micromechanical properties of laboratory produced ECC. The evaluation focused on how the tensile and fiber/matrix interface properties of ECC change with time by subjecting ECC samples to accelerated aging and then performing a uniaxial tension testing.

A single ECC mix was evaluated in this study. Table 13 shows the mix proportions for the ECC mix while Table 14 shows the properties of the PVA fibers used. ECC samples were cured in water at 68°F (20°C) for 28 days. Samples were then submerged in water at 140°F (60°C) for 0, 4, 13, and 26 weeks before they were subjected to a single fiber pullout test and a uniaxial tensile test. In addition, fibers were placed in 140°F (60°C) water for 0, 4, 13, and 26 weeks and pulled until rupture occurred.

Table 13: ECC mix proportions (by weight) for micromechanics-based durability study.

W/C	S/C	FA/C	Superplasticizer (%)	Viscosity agent (%)	De-foamer (%)	Fiber (% vol.)
0.42	1.0	0.11	1.2	0.049	0.048	2.0

Note: FA = fly ash Type II; S = sand; C = cement Type I

Table 14: Properties of the PVA fibers evaluated in micromechanics-based durability study.

Nominal fiber strength, σ_f^N	Apparent fiber strength, σ_f^{APP}	Diameter, D	Length, L	Young's modulus, E	Elongation (%)
235 ksi (1,631 MPa)	150 ksi (1,035 MPa)	1.5 mil (39 μm)	0.5 inch (12 mm)	5,640 ksi (38.9 GPa)	6.4

Table 15 summarizes the findings from this study. The results of the fiber pullout test showed that fiber/matrix properties changed with time. After 26 weeks of accelerated aging, the frictional bond remained unchanged while the chemical bond incresed by 40% from 0.36 psi (2.5 N/m^2) to 0.5 psi (3.5 N/m^2). The apparent fiber strength also dropped from 145 ksi (1,000 MPa) to 130 ksi (900 MPa) after 26 weeks. The fiber durability test showed that the nominal strength, elastic modulus, and elongation of the PVA fibers remained unchanged after 26 weeks of immersion in 140°F (60°C) water. The results of the tensile test showed the ultimate tensile strain capacity dropped with increased aging, from 4.5% to 3% after 26 weeks. The conclusions reached were that the change in fiber/matrix interface properties are the dominate factors for the long-term durability of PVA-ECC mixes evaluated. The ECC samples retained tensile strains of over 3% after 26 weeks of accelerated aging.

Table 15: Summary of findings from micromechanics-based durability study.

Property	Findings
Fiber/matrix interface properties	• Significant factors: accelerated aging • The friction bond experiences a small increase over time, from 0.29 ksi (2 MPa) to 0.32 ksi (2.2 MPa) after 26 weeks of accelerated aging. • The chemical bond significantly increases over time from 0.36 psi (2.5 N/m^2) to 0.5 psi (3.5 N/m^2) after 26 weeks of aging. • The apparent fiber strength decreases over time from 145 ksi (1,000 MPa) to 130 ksi (900 MPa) after 26 weeks of aging.
Long-term fiber properties	• No significant factors • The nominal strength, elastic modulus, and elongation of the PVA fibers remain unchanged after 26 weeks of immersion in 140°F (60°C) water.
Ultimate tensile strain capacity	• Significant factors: accelerated aging, fiber/matrix interface properties • Ultimate tensile strain capacity decreases over time from 4.5% to 3% after 26 weeks of aging. • Ultimte tensile strain capacity decrease is the result of the change in fiber/matrix properties. This change is a primary factor for long-term durability of PVA ECC. • Changes in fiber/matrix interface properties are dominate factor for long-term durability of PVA-ECC mixes.

2.8 Self-Healing of ECC Under Cyclic Wetting and Drying

Ying-zi et al. *(7)* evaluated how ECC's self-healing properties are affected by wetting and drying cycles. Table 16 shows the mix proportions for the ECC mixes evaluated. Samples of ECC were formed and air cured for 6 months without controlling the humidity or temperature. There were two different wetting and drying cycles: CR1 and CR2. In CR1, the samples were submerged in water at 68°F (20°C) for 24 hours and then left to air dry at 70°F (21°C) for 24 hours. In CR2, the samples were submerged in water at 68°F (20°C) for 24 hours, oven dried at 131°F (55°C) for 22 hours, and air dried at 70F (21°C) for 2 hours. ECC samples were preloaded to different tensile strains (0.3% to 3%) such that the samples exhibited distributed cracking behavior. The self-healing properties of the ECC were determined using ASTM C215. The extent of self-healing was determined by finding the ratio of final to initial frequencies of the sample. The final frequency is from the cracked sample after exposure to 10 wetting and drying cycles and the initial frequency is from the un-cracked sample. The frequency is a measurement of how stiff the ECC material is.

Table 17 shows the summary of findings from this study. Test results showed the samples achieved between 77-90% of the initial frequency. The amount of self-healing within a sample increased as the number of cracks increased. Self-healing appears to be affected by high temperatures. Samples in CR1 recovered more tensile strain capacity than those in CR2. Samples in CR2 recovered more tensile strength than those in CR1. Post self-healing samples reached tensile strain capacities between 1.8% and 3.1%. Samples that were pre-loaded to higher strains did not recover as much tensile strength or tensile strain capacity as those samples pre-loaded to lower strains.

Table 16: Mix proportions for ECC used in self-healing study.

Material:	Cement	Aggregate	Fly ash	Water	High ranger water reducer	Fiber
Weight: lb/cy (kg/m^3)	974 (578)	778 (462)	1170 (694)	537 (319)	28.5 (17)	43.8 (26)

Table 17: Summary of findings from self-healing of ECC study.

Property	Findings
Self-healing	• Significant factors: temperature, number of cracks • Higher temperatures caused the ECC to recover more tensile strength and recover less tensile strain. • Amount of self-healing increased as the number of cracks increased in the ECC samples. Samples with more cracks experienced more self-healing. • Self-healing process reaches completion within 5 cycles.
Ultimate Tensile Strength Recovery	• Significant factors: temperature, pre-loaded strain • Ultimate tensile strength recovery increased as temperature increased. • Ultimate tensile strength recovery decreased as the pre-loaded strain increased for the ECC samples. Samples with higher pre-loaded strains recovered lower amount of ultimate tensile strengths.
Tensile Strain Capacity Recovery	• Significant factors: temperature, pre-loaded strain • Tensile strain capacity recovery decreased as temperature increased. • Tensile strain capacity recovery decreased as the pre-loaded strain increased for the ECC samples. Samples with higher pre-loaded strains recovered lower amount of tensile strain capacity.

2.9 Water Permeability of Cracked Cementitious Composites

In 2005, Lepech and Li *(8)* evaluated the water permeability of cracked ECC in a laboratory setting. The focus was to determine the permeability of cracked ECC and how it relates to the crack widths of the ECC samples.

Table 18 shows the mix proportions for the ECC and mortar mixes evaluated. Tensile plate specimens measuring 11.8×3×0.5 inch (300×75×12 mm) were constructed using an ECC mix and a mortar mix. The standard mortar mix specimens were reinforced with various levels of wire reinforcement. Table 19 shows the specimen characteristics used in this experiment. Tensile tests were carried out at 28 days where the samples were subjected to a uniaxial deformation of 0.11 inch (2.7 mm), which corresponds to a strain of 1.5% in the ECC samples. At 1.5%, the crack widths have reached their maximum widths and further deformation will only increase the frequency of cracks in the ECC samples. The permeability for the cracked and un-cracked samples was determined using both a falling head and a constant head setup.

Table 18: Mix proportions for ECC and mortar mixes evaluated in water permeability study.

	Cement	Sand	Fly Ash	Water	Superplasticizer	PVA Fiber (% vol)
ECC	1.0	0.8	1.2	0.53	0.03	2
Mortar	1.0	2.5	-	0.35	-	-

Table 19: Specimen characteristics evaluated in water permeability study.

Specimen Series	Reinforcement Ratio	Crack Width, mil	Crack Spacing, inch
R/M-1	0.009	30-100	2
R/M-2	0.019	8-20	0.4-1.2
R/M-3	0.028	5-8	0.2-0.6
ECC	0.000	1.5-3	0.08-0.2

R/M-# means reinforced mortar specimens with # levels of reinforcement.

Table 20 shows the summary of findings from this study. The water permeability coefficient for cracked ECC, 3.28×10^{-10} ft/s (1×10^{-10} m/s), was at least two orders of magnitude smaller than the water permeability coefficients for cracked mortar, 3.28×10^{-8} ft/s (1×10^{-8} m/s). The performance of the cracked ECC showed the water permeability coefficient is on the same order for that of un-cracked mortar. Current US concrete codes allow a maximum crack width of 12 mils (300 μm), which gives a permeability roughly five times bigger than the permeability of cracked ECC. The low permeability of ECC is anticipated to lead to more durable and longer lasting structures.

Table 20: Summary of findings from water permeability study.

Property	Findings
Permeability	• Significant factors: crack width • Permeability of cracked ECC 100 times smaller than of Reinforced Mortar samples. • Permeability of cracked ECC on "per crack" basis is on the same order of magnitude as uncracked Mortar. • Permeability of ECC is not significantly increased when subjected to high levels of deformation.

2.10 Long-term Durability Performance of ECC

Lepech and Li *(9)* evaluated the long-term durability of ECC in terms of freeze-thaw exposure, accelerated weather exposure, fatigue loading, skid resistance, and long-term tensile strain capacity. The objective was to determine how ECC can resist the effects of the environment over a period of multiple years. Table 21 shows a summary of the findings from this study.

Freeze-thaw resistance was determined using ASTM C666A. Both ECC and concrete samples were cast and tested in a side by side comparison. The samples were exposed to 300 cycles. The concrete samples did not survive the test; the ECC samples not only survived the test but also had a tensile strain capacity of 3%.

The accelerated weather exposure was determined by placing samples that were cured for 28 days into hot water for 26 weeks. A single fiber pullout sample showed the interface properties between the fiber and matrix significantly changed. This caused the ECC samples to lose tensile strain capacity, dropping from 4.5% to 2.75% after 26 weeks of soaking. This was characterized as "great performance" because 26 weeks of soaking is equivalent to 70 years of hot and humid exposure.

Fatigue flexural loading was conducted on a concrete/concrete and ECC/concrete overlay test specimens. The results of the test show that the ECC/concrete overlay had twice the load capacity of the concrete/concrete overlay system. The ECC/concrete overlay had a fatigue life several orders of magnitude higher and also had deformations that were significantly higher than the concrete/concrete overlay. It was believed that an ECC overlay will eliminate reflective cracking from the subsequent layer.

Skid resistance was determined with the help of Michigan Department of Transportation (MDOT). Four ECC road surface samples were cast, each one having a different type of surface treatments: (1) tined grooves with a rake, (2) ECC cured under burlap, (3) textured with Astroturf® (a common practice in Michigan to rough up the surface), and (4) coarse sand placed on the surface. Using MDOT Test Method 111, the Aggregate Wear Index (AWI) was determined for all four ECC road samples. The samples were subjected to 4 million tire passes, and the AWI was determined on these samples under wet conditions. The AWI for the four samples ranged from 360 lbs (1.6 kN) to 517 lbs (2.3 kN), well above the 270 lbs (1.2 kN) minimum acceptable value for truck-line roads in Michigan. The recommended surface treatment is to use transverse tined grooves, which achieved an AWI of 517 lbs (2.3 kN).

Long-term tensile strain capacity was determined by a series of tensile tests performed on various aged ECC samples. The tensile strain capacity of the ECC was 5% at 10 days. However, this value dropped significantly to only 3% after 180 days. While 180 days was the oldest sample tests, the tensile strain capacity is expected to remain at 3% for any samples tested after 180 days.

Table 21: Summary of Findings from long-term durability study.

Property	Findings
Freeze-thaw Resistance	• Concrete samples did not survive 300 freeze-thaw cycles. • ECC samples reached tensile strain of 3% after 300 freeze-thaw cycles.
Accelerated Weathering	• Tensile strain of ECC dropped from 4.5% to 2.75% after 26 weeks of accelerated weathering, which corresponds to 70 years of exposure. • Loss of tensile strain capacity attributed to the change in fiber/matrix interface properties over time.
Flexural Fatigue	• ECC overlay displayed supreme performance over concrete overlay. • ECC overlay had double the loading capaicty, significantly higher deformations, and a fatigue life several orders of magniture higher than the concrete overlay tested. • ECC overlay believed to experience no reflective cracking.
Skid Resistance	• Significant factors: surface finishing • Skid Resistance tests show all four finishing methods tested gave ECC roadway samples suffecient AWI skid resistance. • Recommended finishing method is transeverse tined grooves, which gave an AWI value of 2.3 from testing.
Long-term Tensile Strain	• Tensile strain capacity of ECC decreased as age of sample increased. • ECC mix exhibiting 5% strain at 10 days had a 3% strain at 180 days. • Tensile strain capacity is expected to remain at 3% after 180 days.

2.11 High Early Strength ECC

In 2006, Wang and Li *(9)* investigated the durability of high early strength gain ECC. The objective was to see how artificial flaws (beads) can be used to promote the multiple cracking behavior that makes ECC have a large tensile strain capacity.

Table 22: ECC mix proportions for high early strength evaluation.

Mix ID	Cement	Sand	Other aggregate	Water	Fine fly ash	PVA fiber	Addmixture[1]
SC01	1526[2] lb/yd^3 (905 kg/m^3)	1221 lb/yd^3 (724 kg/m^3)	--	590 lb/yd^3 (350 kg/m^3)	153 lb/yd^3 (91 kg/m^3)	43.8 lb/yd^3 (26 kg/m^3)	359 fl oz/yd^3 (10.7 L/m^3) [PT20]
SC19	1455[2] lb/yd^3 (863 kg/m^3)	1163 lb/yd^3 (689 kg/m^3)	41.4[5] lb/yd^3 (25 kg/m^3)	563 lb/yd^3 (334 kg/m^3)	145 lb/yd^3 (86 kg/m^3)	43.8 lb/yd^3 (26 kg/m^3)	343 fl oz/yd^3 (10.2 L/m^3) [ML330]
HP08	1506[3] lb/yd^3 (893 kg/m^3)	1506 lb/yd^3 (893 kg/m^3)	--	492 lb/yd^3 (292 kg/m^3)	--	43.8 lb/yd^3 (26 kg/m^3)	163 fl oz/yd^3 (4.8 L/m^3) [GL3200] 664 fl oz/yd^3 (19.8 L/m^3) [NC534]
HP09	1430[3] lb/yd^3 (848 kg/m^3)	1430 lb/yd^3 (848 kg/m^3)	54.0[6] lb/yd^3 (32 kg/m^3)	469 lb/yd^3 (278 kg/m^3)	--	43.8 lb/yd^3 (26 kg/m^3)	153 fl oz/yd^3 (4.5 L/m^3) [GL3200] 631 fl oz/yd^3 (19 L/m^3) [NC534]
OP08	938[4] lb/yd^3 (556 kg/m^3)	787 lb/yd^3 (466 kg/m^3)	--	502 lb/yd^3 (297 kg/m^3)	1180 lb/yd^3 (700 kg/m^3)	43.8 lb/yd^3 (26 kg/m^3)	388 fl oz/yd^3 (11.5 L/m^3) [ML330]

[1] PT20: accelerator and high-range water-reducing admixture containing ammonium calcium nitrate and napthalene sulfonate salt; ML330: melamine formaldehyde sulfonate-based high-range water-reducing admixture; GL3200: polycarboxylate-based high-range water-reducing admixture; NC534: calcium nitrate-based accelerator.
[2] Rapid-hardening cement (Type S-30 Korea).
[3] Type III cement.
[4] Type I cement.
[5] Polypropylene beads used as artificial flaws.
[6] Polystyrene beads used as artificial flaws.

Five different mixes were tested: two use Type 3 cement (HP08 and HP09), two used a "rapid-hardening blended Portland cement" (SC01 and SC19), and one used a Type 1 cement (OP08). The samples were mixed in a Hobart-type mixer with 2.6 gallon (10 L) capacity. The mixes with the blended Portland cement do not need an accelerator admixture as it had little effect. The mixes with Type 3 cement had the highest early strength when a combination of polycarboxylate-based high-range water-reducing admixture and calcium nitrate-based accelerator was used in the absence of calcium chloride. Table 22 shows the mix proportions for the ECC mixes evaluated. Tests carried out on the samples included: compressive strength, tensile strength, flexural strength, and a single fiber pullout test.

The mixes with Type 3 cement and the blended cement exhibited a compressive strength of 3.6 ksi (25 MPa) after 4 hours, while the Type 1 cement took over 20 hours to reach the same strength. The Type 3 cement did not have much compressive strength in the first 2 hours after placement even when an accelerator was added. The blended cement sets within 1 hour and can reach strengths of 2.9 ksi (20 MPa) within 2 hours after placement.

The tensile strain capacity of mix SC01 was 4% at 3 hours and 7% at 7 hours. However, these values dropped to less than 1% after 24 and 72 hours. This loss of tensile strain capacity is due to the matrix toughness increasing over time (i.e. the concrete keeps curing). This causes the interface properties between the matrix and the fibers to change considerably, resulting in the loss of the strain-hardening capabilities of the ECC.

What makes strain-hardening possbile in ECC is the ratio of complimentary energy, J_b', to the crack tip toughness, J_{tip}. Without having this ratio above 1, strain-hardening will not take place in the ECC. Figure 4 shows these two areas on a stress-strain curve. In this study, this ratio for mix SC01 is 12 after 10 hours, but drops considerably to just 1 after 3 days and remains unchanged after 7 days. This mix did not exhibit multiple cracking behavior, but other mixes in the experiment did.

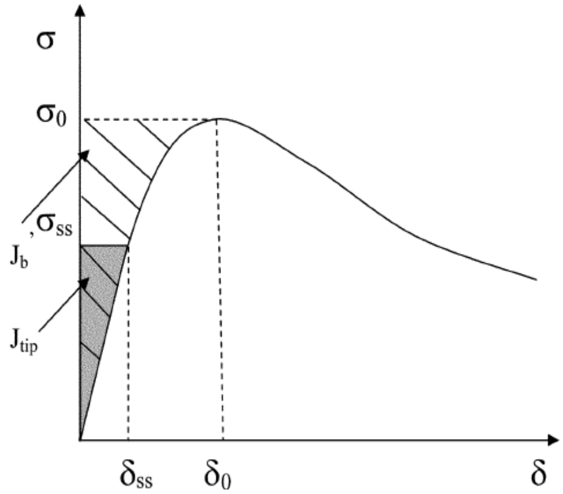

Figure 4: Typical stress-strain curve for ECC: hatched area represents complimentary energy (J_b') and shaded area represents crack tip toughness (J_{tip}). (9)

Mixes SC19, HP08 and HP09 all showed signs of distributed cracking and strain-hardening in the tensile test. SC19 showed a tensile strain capacity of 2.5% after 21 days. This mix showed multiple cracking behavior with the average crack spacing of 0.12-0.16 inches (3-4 mm). HP08 also showed signs of multiple cracking, but it's tensile strain capacity was only 1% after 28 days. Mix HP09 showed the best results. At 5 hours, it had a strain capacity of 4% and a strength of 435 psi (3 MPa). At 50 days, it had a strain capcity of 3.5% and a strength of 725 psi (5 MPa). This mix had multiple cracking with an average crack size of 26 mils (65 μm) at an average spacing of 0.1 inche (2.5 mm). The results showed that flaw size tailoring is an effective way to improve ductility, but is not a replacement for interface tailoring between the fibers and matrix within the mix. Mix OP08 showed a tensile strain capacity of 3% at both 24 hours and 90 days.

For the flexural testing, the strength increased for mixes SC19, HP09, and OP08. The vertical beam displacement for all mixes decreased over time. At 24 hours the vertical beam displacement was about 0.6 inches (15 mm) for all mixes with a bending stress of 1.45 ksi (10 MPa). These values changed to 0.4 (10 mm) displacement and a stress around 1.45 ksi (10 MPa) after 28 days. Table 23 summarizes the findings from this study.

In summary, the rapid-hardening cement is required for high priority applications as it reaches a strength of 3 ksi (21 MPa) within 3 hours. It also will exhibit a tensile strain capacity of 2% in the long-term. An ECC with type 3 cement with a HRWR and accelerator admixures can reach stress of 3 ksi (21 MPa) within 4 hours and will have a tensile strain capacity of 3.5% after 50 days. Another observation was the interface properties between the matrix and fibers change over time, expeically early on. These properties stabilized after 14 days. Lastly, the artificial flaws placed in the mixes were necessary to promote multiple cracking behavior in ECCs with high early strengths. The size of these artificial flaws can be selected so the ECC mix will have a large tensile strain capacity, up to 4%.

Table 23: Summary of findings from high early strength evaluation study.

Property	Findings
High Early Compressive Strength	• Significant Factors: cement type • Rapid hardening cement is desired to achieve high early strengths of 3 ksi (21 MPa) within 3 hours of placement.
Tensile Strain Capacity	• Significant Factors: cement type, artificial flaws, time • Type I cement had the highest 28 day tensile strain capacity of 3%. Type III had tensile strain of 2% and Rapid hardening had strain of 1% (without flaws added to mix) • Mixes with artificial flaws saw an increase in 28 day tensile strain capacity by a factor of 2 (1% to 3% for Rapid hardening and 2% to 4% for Type III) • Tensile strain decreases as time increases. Adding artificial flaws decreases the change in tensile strain with respect to time.
Flexural Strength and Verticle Displacement	• Significant Factors: cement type, time • Rapid hardening cement had smallest displacement 0.28 inches (7 mm) while Type I and Type III cements had displacement above 0.4 inches (10 mm) after 28 days. • All three cement types had ultimate flexural strength of 2.2 ksi (15 MPa). • Verticle displacement decreases as time increases for all three cement types. All cement types have initial displacement of 0.4 inches (10 mm). • Flexural strength decreases as time increases. Rapid hardening cement had smallest initial flexural strength of 1ksi (7 MPa) while Type I and Type III had flexural strength over 1.45 ksi (10 MPa).
Multiple Cracking Behavior	• Significant Factors: artificial flaws • Artificial flaws are needed for early strength ECC mixes. Without these flaws, long-term tensile strain capacity is less than 2% and ECC mixes do not undergo much strain-hardening before failure occurs.

2.12 De-icing Salt Scaling Resistance of Mechanically Loaded ECC

In 2007, Sahmaran and Li *(11)* evaluated the durability of non-air entrained ECC under mechanical loading and freeze-thaw cycles when in the presence of de-icing salt in a laboratory setting. The focus was to determine how an ECC sample will deteriorate when subjected to these conditions, which resemble those of a bridge deck.

There were two ECC mixes and two mortar mixes evaluated. Table 24 shows the mix proportions evaluated while Table 25 shows the properties of the PVA fibers evaluated. ASTM C672 was used to assess the scaling resistance of concrete surfaces. The ECC was formed into test specimens measuring 14×2×3 inches (350x50x75 mm) and were subjected to a four point bending load to various deformations up to 0.08 inch (2.0 mm). The specimens then underwent 50 freeze-thaw cycles of 18 hours at -64±6°F followed by 6 hours at 73±6°F. For the tensile test, cylindrical samples measuring 3×6 inches were pre-cracked to 1.0% and 2.0% tensile strain levels. Samples were then subjected to 50 freeze-thaw cycles as previously described.

Table 26 shows a summary of the findings from this study. The mass of surface scaled-off particles for the mortar samples was above 0.4 lb/ft^2 (2 kg/m^2) whereas all but one of the ECC samples were below the 0.2 lb/ft^2 (1 kg/m^2) limit. In the tension test, pre-crack ECC-1 samples had a tensile strain of 3.2% and an ultimate tensile strength of 600 psi (4.1 MPa) after 50 freeze-thaw cycles. Pre-cracked ECC-2 samples had a tensile strain of 3.4% and an ultimate tensile strength of 550 psi (3.8 MPa) after 50 freeze-thaw cycles.

Table 24: Mix proportions for ECC and mortar mixes evaluated in de-icing salt scaling study.

	ECC-1	**ECC-2**	**Mortar-1**	**Mortar-2**
FA/C	1.2	2.2	-	0.4
W/CM[1]	0.27	0.27	0.35	0.35
Water (W), lb/cy (kg/m^3)	557 (331)	550 (327)	362 (215)	362 (215)
Cement, Type I (C), lb/cy (kg/m^3)	960 (570)	650 (386)	1035 (614)	725 (430)
Fly ash, Class F (FA), lb/cy (kg/m^3)	1152 (684)	1427 (847)	-	311 (185)
Sand (S), lb/cy (kg/m^3)	766 (455)	755 (448)	2586 (1535)	2500 (1486)
PVA Fiber, lb/cy (kg/m^3)	43.8 (26)	43.8 (26)	-	-
High range water reducer, lb/cy (kg/m^3)	8.25 (4.9)	6.2 (3.7)	-	-
Air Content, % (No PVA Fibers)	3.8	4.0	2.9	3.1
Air Content, % (With PVA Fibers)	8.7	9.3	-	-

[1] CM = cementitious material = fly ash + cement

Table 25: Properties of PVA fibers evaluated in de-icing salt scaling resistance study.

Nominal strength	**Apparent strength**	**Diameter**	**Fiber length**	**Young's Modulus**	**Elongation, %**
235 ksi (1,620 MPa)	158 ksi (1,092 MPa)	1.5 mil 39 µm	0.3 inch (8 mm)	6,210 ksi (42.8 GPa)	6.0

Table 26: Summary of findings from de-icing salt scaling resistance study.

Property	**Findings**
Mass of scaled-off particles	• Significant factors: beam deflection • The mass of scaled-off particles increased as the pre-loaded ECC beam deflection was increased. ECC-2 beam with 0.08 inch (2.0 mm) deflection was the only ECC sample to have more than 0.2 lb/ft^2 (1 kg/m^2) mass of scaled-off particles. • Mass of scaled-off particles increased as fly ash content increased.
Tensile strain capacity	• Significant factors: fly ash conent, number of freeze-thaw cycles • Tensile strain capacity increased as fly ash conent increased. • Tensile strain capacity increased as the number of freeze-thaw cylces increased for the pre-cracked ECC samples.
Ultimate tensile strength	• Significant factors: fly ash conent, number of freeze-thaw cycles • Tensile srenght increased as fly ash conent increased. • Tensile strength increased as the number of freeze-thaw cylces increased for the pre-cracked ECC samples. • Pre-cracked ECC samples' tensile strengths after 50 freeze-thaw cycles are 6% lower than uncracked ECC samples air cured for 28 days.
Self-healing	• ECC specimens underwent self-healing in the presence of the sodium chloride solution. Unhydrated cement is exposed to solution and hydrates.
Air entrainment	• ECC samples had significant resistance to freeze-thaw without the addition of air-entraiment into the samples.

2.13 ECC with High-Volume Fly Ash

In 2007, Wang and Li *(12)* investigated the properties of ECC with a high amount of fly ash in laboratory samples. The objective was to create an ECC mix that was economically viable while still retaining the desired tensile strength and tensile strain capacity typically exhibited by standard ECC mixes.

Twelve different ECC mixes were prepared and tested (Table 27 and Table 28). Mixes M41 to M46 were subjected to both a single fiber pullout test, which determined the fiber/matrix interface properties, and a uniaxial tensile test. Mixes ECC R0 and ECC G1 through ECC G4 were subjected to a direct uniaxial tension test to determine the tensile strength and the tensile strain capacities. Lastly, compression tests were carried out on select test specimens to determine the rate of strength gain over time. Specimens M41 to M46 and ECC G0 were tested at an age of 3 months; all other specimens were tested at an age of 28 days.

Table 27: Mix proportions for mixes M41 through M45 (by weight).

Mix ID	Cement[1] (C)	Sand (S/C)	Fly ash[2] (FA/C)	Water (W/C)	W/CM[3]	HRWRA[4]	Fiber (% vol.)
M41	1.0	0.8	0.1	0.27	0.24	0.03	2.0
M42	1.0	0.8	0.2	0.29	0.24	0.03	2.0
M43	1.0	0.8	0.8	0.43	0.24	0.03	2.0
M44	1.0	0.8	1.0	0.48	0.24	0.03	2.0
M45	1.0	0.8	1.2	0.53	0.24	0.03	2.0
M46	1.0	0.8	1.5	0.60	0.24	0.03	2.0

[1] Type I cement
[2] Fly ash Class F
[3] Water-to-cementitious material (fly ash + cement) ratio
[4] Melamine formaldehyde sulfonate-based high-range water-reducing admixture

Table 29 summarizes the finding from this study. Results of the fiber pullout show that the frictional stress and chemical bond between the fibers and matrix dropped with an increase in fly ash content. The slip-hardening coefficient remained unchanged with an increase in fly ash. This caused the matrix fracture energy to drop with an increase in fly ash; a low fracture energy value is desired for improved strain-hardening potential in the ECC. Samples of mixes M41 to M45 showed that an increase in fly ash caused a decrease in the first crack strength from 670 psi (4.64 MPa) to 535 psi (3.69 MPa); ultimate tensile strength dropped from 794 psi (5.48 MPa) to 650 psi (4.47 MPa); the tensile strain capacity greatly increased with an increase in fly ash, from 0.37% to 2.7%. For samples ECC R0 through ECC G4, the most desirable mix was ECC G3 as it had the highest first crack strength of 570 psi (3.92 MPa), the second highest ultimate tensile strength of 700 psi (4.77 MPa), and had the second highest tensile strain capacity of 4.29% out these six mixes. The compression test showed that mixes ECC R0 through ECC G4 all gained compressive strength at a much lower rate than mix M45. Mix M45 had a compressive strength of 8 ksi (55 MPa) at 7 days while the other six mixes had strengths of only 3.3 ksi (23 MPa) at 7 days. At 100 days, mix M45 had a compressive strength of 10.8 ksi (75 MPa) while mix ECC G3 had a strength of 7.25 ksi (50 MPa). Table 30 shows the complete results of the tensile tests for samples ECC R0 to ECC G4.

Table 28: Mix proportions for mixes ECC R0 through ECC G4.

Mix ID	Cement[1]	Sand	Ash	Water	HPMC[2]	HWRW[3]	Fiber
ECC R0	1412 lb/cy (838 kg/m^3)	1412 lb/cy (838 kg/m^3)	-	616 lb/cy (366 kg/m^3)	2.2 lb/cy (1.26 kg/m^3)	28 lb/cy (17 kg/m^3)	43.8 lb/cy (26 kg/m^3)
ECC G0	982 lb/cy (583 kg/m^3)	786 lb/cy (467 kg/m^3)	1179 lb/cy (700 kg/m^3) (Bottom ash)	502 lb/cy (289 kg/m^3)	-	32 lb/cy (19 kg/m^3)	43.8 lb/cy (26 kg/m^3)
ECC G1	535 lb/cy (318 kg/m^3)	1180 lb/cy (701 kg/m^3)	857 lb/cy (509 kg/m^3) (Class F) 321 lb/cy (191 kg/m^3) (Fine fly ash)	502 lb/cy (289 kg/m^3)	0.27 lb/cy (0.16 kg/m^3)	32 lb/cy (19 kg/m^3)	43.8 lb/cy (26 kg/m^3)
ECC G2	535 lb/cy (318 kg/m^3)	1180 lb/cy (701 kg/m^3)	1181 lb/cy (701 kg/m^3) (Class F)	502 lb/cy (289 kg/m^3)	0.27 lb/cy (0.16 kg/m^3)	32 lb/cy (19 kg/m^3)	43.8 lb/cy (26 kg/m^3)
ECC G3	535 lb/cy (318 kg/m^3)	1180 lb/cy (701 kg/m^3)	321 lb/cy (191 kg/m^3) (Fine fly ash) 421 lb/cy (250 kg/m^3) (Class F) 421 lb/cy (250 kg/m^3) (Bottom ash)	502 lb/cy (289 kg/m^3)	0.27 lb/cy (0.16 kg/m^3)	32 lb/cy (19 kg/m^3)	43.8 lb/cy (26 kg/m^3)
ECC G4	535 lb/cy (318 kg/m^3)	1180 lb/cy (701 kg/m^3)	1181 lb/cy (701 kg/m^3) (Bottom ash)	502 lb/cy (289 kg/m^3)	0.4 lb/cy (0.16 kg/m^3)	32 lb/cy (19 kg/m^3)	43.8 lb/cy (26 kg/m^3)

[1] Type I cement
[2] Viscosity agent: hydroxypropyl methylcellulose
[3] Melamine formaldehyde sulfonate-based high-range water-reducing admixture

Table 29: Summary of findings from high-volume fly ash evaluation study.

Property	Findings
First Crack Tensile Strength	• Significant Factors: fly ash content, fly ash type • First crack strength decreased as the fly ash content increased. Highest strengths were achieved at a fly ash/cement ratio of 0.1. • Bottom ash had lowest strength while combination of bottom, fine fly ash, and Class F fly ash had highest strength of 570 psi (3.92 MPa).
Ultimate Tensile Strength	• Significant Factors: fly ash content, fly ash type • Ultimate tensile strength decreased as the fly ash content increased. Highest strengths were achieved at a fly ash/cement ratio of 0.2. • Bottom ash had lowest strength while combination of bottom, fine fly ash, and Class F fly ash had highest strength of 700 psi (4.77 MPa).
Ultimate Tensile Strain Capacity	• Significant Factors: fly ash content, fly ash type • Ultimate tensile strain capacity increased as the fly ash content increased. Highest tensile strain capacities were achieved at fly an ash/cement ratio of 1.5. • Bottom ash had lowest tensile strain capacity while combination of bottom, fine fly ash, and Class F fly ash had highest strain of 4.29%.
Compressive Strength	• Significant Factors: fly ash content • Compressive strengths decreased with an increase in fly ash content. Mixes ECC G1 through ECC G4 had 28 day compressive strengths of 5 ksi (35 MPa).

Table 30: Tensile test results for mixes ECC R0 to ECC G4.

Mix ID	Ash	First crack strength	Ultimate tensile strength	Tensile strain capacity (%)
ECC R0	-	423 psi (2.9 MPa)	640 psi (4.4 MPa)	4.88±0.59
ECC G0	1179 lb/cy (700 kg/m^3) (Bottom ash)	478 psi (3.3 MPa)	600 psi (4.1 MPa)	3.41±0.69
ECC G1	857 lb/cy (509 kg/m^3) (Class F) 321 lb/cy (191 kg/m^3) (Fine fly ash)	550 psi (3.8 MPa)	613 psi (4.2 MPa)	1.54±1.33
ECC G2	1181 lb/cy (701 kg/m^3) (Class F)	536 psi (3.7 MPa)	693 psi (4.8 MPa)	3.90±0.61
ECC G3	321 lb/cy (191 kg/m^3) (Fine fly ash) 421 lb/cy (250 kg/m^3) (Class F) 421 lb/cy (250 kg/m^3) (Bottom ash)	570 psi (3.9 MPa)	691 psi (4.8 MPa)	4.29±0.57
ECC G4	1181 lb/cy (701 kg/m^3) (Bottom ash)	450 psi (3.1 MPa)	630 psi (4.4 MPa)	3.95±0.17

2.14 ECC with Characteristic of Low Drying Shrinkage

In 2009, Zhang et al. *(13)* examined the drying shrinkage strain of conventional laboratory ECC. The goal was to develop an ECC mix that had low drying shrinkage strain, but also performed well when subjected to a uniaxial tensile test. In this study, there were three areas of focus:

1. How mix parameters, such as water-to-cement ratio and the type of cement, influence the drying shrinkage strain;
2. How these same parameters influenced the tensile behavior of the ECC mixes;
3. How the drying shrinkage influenced early age cracking of the ECC.

A total of ten ECC mixes were prepared: nine of them used a composite cement specifically designed to reduce the drying shrinkage strain while the tenth used an ordinary Portland cement. Of the nine mixes, there were three different water-to-cement (W/C) ratios, and for each W/C ratio there were three different sand-to-cement (S/C) ratios. Table 31 shows the chemical composition of the composite cement used. Table 32 shows the mix proportions for the ECC mixes evaluated. A drying shrinkage test was performed, where the deformation of the samples was measured for 28 days after de-molding. A uniaxial test was also performed at 3, 7, and 28 days. This test determined the samples' first crack stress and strain as well as the ultimate stress and strain of the ECC. Lastly, a restricted plate test was performed where a square sample was fixed along its four sides and left to dry for 5 days, after which the drying shrinkage crack pattern was observed.

Table 33 summarizes the findings from this study. Results of the drying shrinkage test showed that the maximum strain for the low shrinkage mixes was 242×10^{-6}, while the strain for the traditional ECC was almost $1{,}200\times10^{-6}$. For the tensile test, the low shrinkage ECC mixes had an average first crack stress of 319 psi (2.2 MPa) and a strain of 220×10^{-6}. The traditional ECC had a first crack stress of 381 psi (2.63 MPa) and a strain of 180×10^{-6}. The ultimate stress and strain at 28 days for the low shrinkage ECCs were about 580 psi (4 MPa) and 1.5%, respectively, compared with a stress of 691 psi (4.77 MPa) and a strain of 0.8% for the traditional ECC. For the restricted plate test, the traditional ECC had visible cracks while the low shrinkage ECC did not exhibit any such cracks.

Table 31: Chemical composition (%) of composite cement used in the low shrinkage ECC mixes.

CaO	SiO_2	AL_2O_3	FE_2O_3	MgO	K_2O	NA_2O	TiO_2	LOI
33.75	19.63	18.03	0.47	1.28	0.50	0.28	0.62	6.26

Table 32: Mix properties for the nine low shrinkage ECC and the one traditional ECC mixes.

Mix No.	Composite cement	Portland cement (Type 1)	Fly ash	Water	Sand	Superplasticizer	Fiber (% vol)
1	1.0	--	--	0.45	0.8	0.012	1.7
2	1.0	--	--	0.45	1.1	0.018	1.7
3	1.0	--	--	0.45	1.4	0.022	1.7
4	1.0	--	--	0.50	0.8	0.011	1.7
5	1.0	--	--	0.50	1.1	0.013	1.7
6	1.0	--	--	0.50	1.4	0.020	1.7
7	1.0	--	--	0.55	0.8	0.010	1.7
8	1.0	--	--	0.55	1.1	0.011	1.7
9	1.0	--	--	0.55	1.4	0.016	1.7
10	--	1.0	0.25	0.50	0.8	--	1.7

Table 33: Summary of Findings from the low drying shrinkage study.

Property	Findings
Drying Shrinkage	• Significant factors: cement type, W/C ratio, S/C ratio • Low shrinkage ECC had maximum dry shrinkage strain of $242*10^{-6}$. Tradition ECC had dry shrinkage strain of $1200*10^{-6}$. • Higher W/C ratio will cause higher dry shrinkage strain. • Higher S/C ratio will cause lower dry shrinkage strain.
Tensile strength	• Significant factors: S/C ratio • W/C ratio has little effect on first crack and ultimate tensile strengths. • Higher S/C ratio caused higher first crack strength at same W/C ratio regardless of time. • Lower S/C ratio caused higher ultimate strength at same W/C ratio after 28 days. • Mix 7 had tensile strength of 628 psi (4.3 MPa).
Tensile Strain Capacity	• Significant factors: W/C ratio, S/C ratio • Higher W/C ratio will cause higher first crack strain ultimate strain regardless of time. • Higher S/C ratio will cause lower first crack and ultimate strain at same W/C ratio regardless of time. • Mix 7 had tensile strain of 2.6% at 28 days.
Drying shrinkage crack pattern	• Significant factors: cement type • The ECC with Type 1 cement had visible dry shrinkage cracks. • Composite cement did not show any visible cracking.

2.15 Influence of curing temperature on flexural performance of ECC

Zhu and Yang *(14)* evaluated how different curing temperatures and curing times affected the flexural performance of ECC. Table 34 shows the mix proportions for the ECC mix evaluated. ECC specimens were cured at four temperatures (68°F/20°C, 104°F/40°C, 140°F/60°C, and 176°F/80°C) for 3 days at a relative humidity (RH) of 98%, then cured in the lab room at 68°F

(20°C) with RH of 45%. The samples measuring 12.6×1.6×0.5 inch (320×40×12 mm) were then tested using four-point loading to find flexural performance after curing for 3, 7, 28, and 90 days.

Table 35 summarizes the results from the study. The first crack load increased as temperatures increased after 3 and 7 days of curing, from 15 lbs (73 N) to 40 lbs (180 N) and 36 lbs (160 N) to 45 lbs (201 N), respectively. First crack load increased as the curing time increased at 68°F (20°C) and 104°F (40°C), but did not change as the curing time increased at 140°F and 176°F. The deflection decreased as the temperature increased for all curing times tested, from 0.71 inches (18 mm) at 68°F (20°C) to only 0.4 inches (10.5 mm) at 176°F (80°C). The maximum load increased as temperature increased regardless of curing time. Maximum load at 68°F (20°C) was 56 lbs (248 N) while the maximum load at 176°F (80C) was 76 lbs (340 N). There was no significant difference observed between samples cured at 140°F (60°C) and 176°F in this study.

Table 34: Mix proportions for ECC mix evaluated in influence of curing temperature study.

Cement	**Aggregate**	**Fly ash**	**Water**	**High range water reducer**	**Fiber**
642 lb/cy (381 kg/m^3)	780 lb/cy (462 kg/m^3)	1500 lb/cy (890 kg/m^3)	540 lb/cy (319 kg/m^3)	23 lb/cy (13.7 kg/m^3)	43.8 lb/cy (26 kg/m^3)

Table 35: Summary of findings from influence of curing temperature evaluation study.

Property	**Findings**
First crack strength	• Significant factors: temperature, curing time • First crack strength increased as temperatures increased for all cure times. • First crack strength increased as curing times increased for 68°F (20°C) and 104°F (40°C). No such change was observed for 140°F (60°C) and 176°F (80°C).
Ultimate tensile strength	• Significant factors: temperature, curing time • Ultimate strength increased as temperatures increased for all curing times. • Ultimate strength increased as curing time increased for all four curing temperatures.
Beam verticle deflection	• Significant factors: temperature, curing time • Verticle deflection decreased as temperatures increased for all curing times. • Verticle deflection remain relatively constant regardless of curing time for all four curing temperatures. Max deflection occurred at 7 days.

2.16 Fatigue analysis of ECC-Steel composite deck under wheel trucking load

In 2011, Kakuma et al. *(15)* evaluated the fatigue properties of an ECC and steel composite deck subjected to repeated "vehicle wheel" loads in a laboratory setting. The composite deck was subjected to a 33.7 kip (150 kN) load for 1.2 million repetitions. The focus was to determine the service life for the ECC deck.

The composite deck was 9.5 ft × 8 ft (2.9 m × 2.44 m). There were three steel U-ribs used to simulate the bridge girders. No dimensions were given for the depth of the ECC deck, and no mix proportions were given in this experiment. There were seven loading points along the deck; each one was loaded and unloaded in numerical order to simulate a vehicle wheel load in motion across the deck.

The results show the maximum crack width in the ECC layer was only 1.6 mils (0.04 mm), which remained constant over the duration of the 1.2 million load repetitions. Using JSSC

(Japan Society of Steel Construction) Code, it was estimated that fatigue cracks will appear around 10,600,000 load cycles, which corresponds to 2,400 vehicles/day/lane over a 400 year period. Therefore, 1,200,000 cycles would represent a 45 year design life. This was determined using Equations 3 and 4 below.

$$\Delta\sigma_{eq} = \sqrt[3]{\frac{\sum \Delta\sigma_i{}^3 n_i}{\sum n_i}} \qquad \text{(Eq. 3)}$$

where $\Delta\sigma_{eq}$ = equivalent stress range (N/mm^2), $\Delta\sigma_i$ = stress range measured in one cycle (N/mm^2), and n_i = number of cycles with $\Delta\sigma_i$

$$N_{Ti} = ADTT_{SLi} * \gamma_n * 365 * Y \qquad \text{(Eq. 4)}$$

where N_{Ti} = number of repetitions, $ADTT_{SLi}$ = heavy traffic volume (vehicles/day/lane), γ_n = coefficient (0.03), and Y = service period (years)

Table 36 shows the summary of findings from this experiment. ECC is a desirable material to use as a bridge deck. The results showed the ECC deck experienced low crack widths, the largest crack only 1.5 mils (0.04 mm) wide. High fatigue resistance is expected based on the performance of the deck in this study.

Table 36: Summary of findings from composite deck fatigue analysis study.

Property	Findings
Fatigue Resistance	• Fatigue cracks are expected around 10.6 million load repititions. • No fatigue cracks were observed in the ECC overlay during the 1.2 million load repititions. • ECC is expected to have 45 year design life with an ADTT of 2400 veh/day/lane.

2.17 Evaluation of a Polyvinyl Alcohol Fiber Reinforced ECC for a Thin-Bonded Pavement Overlay

Akkari *(16)* evaluated the use of an ECC as a thin-bonded overlay system in Minnesota. The objective was to determine if an ECC mix containing coarse aggregate would exhibit the same mechanical properties as typical ECC mixes that do not contain any coarse aggregate. Tables 37 and 38 show the mix proportions and fiber information for the ECC. The substantial amount of coarse aggregate in this mix design is very unusual for an ECC mix. In this experiment, the amount of fiber added was varied between 0 and 25 lbs/cy (15 kg/m^3). Properties of the fresh ECC were measured: air content, density, and slump. A wide range of tests were conducted on the ECC samples: flexural strength (ASTM C78), compressive strength (ASTM C78), freeze thaw durability (ASTM C666), bond strength (ASTM C886), ductile behavior, and the finishing characteristics. The ductile behavior was determined using 1.5 inch (38 mm) thick ECC beam subjected to a four point bending load. LVDT's were used to measure the vertical displacement of the beams. Finishing characteristics were found by placing a test slab on top of existing pavement and finished using a broom drag. Any surface cracking or scaling that occurred was recorded.

The fresh properties of the ECC, air content and slump, peaked at a fiber content of 18 lbs/cy (10.5 kg/m^3), with values of 9.7% and 2 inches (50 mm) respectively. The density was also lowest at this fiber content at a value of 134.6 pcf (80 kg/m^3). Flexural strengths were highest at a fiber content of 16 lbs/cy, reaching a strength of over 1 ksi (6.9 MPa) at 56 days. Compressive strengths were also highest at this fiber content, reaching a strength of 7 ksi (48.2 MPa) at 28 days. The freeze-thaw durability factor was 89.3 for a fiber content of 16 lbs/cy (9.5 kg/m^3). The results showed that the addition of fibers may slightly reduce the durability for the ECC. The concrete to ECC bond strength was found to be 1.2 ksi (8.3 MPa), which is adequate for an overlay. The ductile behavior found from the thin beam test showed that a displacement of 0.15 inches can be achieved with a fiber content of 22 lbs/cy (13 kg/m^3) at 21 days. The displacement dropped with lower fiber contents. The slab finishing showed that the ECC can be easily finished using a broom drag without any additional steps or effort.

Table 39 shows a summary of finding from this experiment. Statistical analysis was carried out on the results of the experiment. It was found there was a large deviation in the data collected. This meant that a small flexural strength could be confidently achieved with the addition of fibers. Also, only one of the four mixes with fibers experience a significant increase in compressive and flexural strength. The conclusion reached was that the ECC mix used did not experience high enough increases in compressive and flexural strengths for use as an overlay. The ECC mix was not found to be suitable for use as a thin overlay.

Table 37: ECC mix proportions for thin-bonded pavement overlay application.

Mix ID	Coarse Aggr. (SSD)	Fine Aggr.	Cement, Type I	Fly ash, Class F	Water	Fiber	Fiber (% vol.)
1	1,465 lb/cy (870 kg/m^3)	1,240 lb/cy (735 kg/m^3)	625 lb/cy (370 kg/m^3)	265 lb/cy (157 kg/m^3)	270 lb/cy (160 kg/m^3)	0 lb/cy (0 kg/m^3)	0
2	1,465 lb/cy (870 kg/m^3)	1,240 lb/cy (735 kg/m^3)	625 lb/cy (370 kg/m^3)	265 lb/cy (157 kg/m^3)	270 lb/cy (160 kg/m^3)	16 lb/cy (9.5 kg/m^3)	0.77
3	1,465 lb/cy (870 kg/m^3)	1,240 lb/cy (735 kg/m^3)	625 lb/cy (370 kg/m^3)	265 lb/cy (157 kg/m^3)	270 lb/cy (160 kg/m^3)	18 lb/cy (10.5 kg/m^3)	0.82
4	1,465 lb/cy (870 kg/m^3)	1,240 lb/cy (735 kg/m^3)	625 lb/cy (370 kg/m^3)	265 lb/cy (157 kg/m^3)	270 lb/cy (160 kg/m^3)	22 lb/cy (13 kg/m^3)	1.01
5	1,465 lb/cy (870 kg/m^3)	1,240 lb/cy (735 kg/m^3)	625 lb/cy (370 kg/m^3)	265 lb/cy (157 kg/m^3)	270 lb/cy (160 kg/m^3)	24 lb/cy (14 kg/m^3)	1.09

Table 38: Properties of the fibers used in the ECC mix for a thin-bonded pavement overlay.

Property	REC15	RF4000
Material	Polyvinyl Alcohol	Polyvinyl Alcohol
Length	1/3" (8mm)	1.18" (30mm)
Tensile Strength	203,000 psi (1,400 MPa)	130,500 psi (900 MPa)
Specific gravity	1.3	1.3

Note: Fiber portion in ECC consisted of half REC15 fibers and half RF4000 fibers.

Table 39: Summary of Findings from modified ECC for thin-bonded pavement overlay.

Property	Findings
Flexural strength	• Significant Factors: fiber content, age • Flexural strength decreased as the fiber content increased. Highest strengths were achieved at a fiber content of 16 lbs/cy (9.5 kg/m^3) with value of 1 ksi (6.9 MPa) at 5 days. • Flexural strength increases as age of sample increased.
Compressive strength	• Significant Factors: fiber content, age • Compressive strength decreased as the fiber content increased. Highest strengths were achieved at a fiber content of 16 lbs/cy (09.5 kg/m^3) with value of 7 ksi (48.2 MPa) at 28 days. • Compressive strength increases as age of sample increased.
Air content	• Significant Factors: fiber content • Air content increases, then decreases as fiber content increases. Highest air content was achieved at fiber content of 18 lbs/cy (10.5 kg/m^3) with value of 9.7%.
Slump	• Significant Factors: fiber content • Slump increases, then decreases as fiber content increases. Highest slump was achieved at fiber content of 18 lbs/cy (10.5 kg/m^3) with value of 2 inches (50 mm).
Freeze-thaw resistance	• Significant Factors: fiber content • Freeze thaw resistance decreases slightly as fiber content increases. • The freeze thaw durability factor was 89.3 for a fiber content of 16 lbs/cy.
Finishing Characteristics	• Significant Factors: none • Drag broom can be used to sufficiently finish surface of ECC.
Ductile behavior (Beam deflection)	• Significant Factors: fiber content • Beam deflection increases as fiber content increases. Highest beam deflection of 6 mils (0.15 mm) was achieved at fiber content of 22 lbs/yd (13 kg/m^3).
Bond strength	• Significant Factors: none • Concrete/ECC bond strength measured as 1.02 ksi (8.3 MPa).

CHAPTER 3: PRODUCTION OF ECC

3.1 Introduction

Chapter 3 discusses the production of small-scale and large-scale batches of ECC. Different ways of measuring the workability of ECC are presented. Multiple ECC mixes and batching sequences were evaluated to develop consistent and durable ECC in the field using commercially available concrete mixing trucks. Quality control in the field is important, and research shows that the rheological properties of fresh ECC can be measured and used to determine if the ECC will exhibit sufficient hardened mechanical properties.

3.2 Design of ECC for Processing and Workability Requirements

In 2003, Fischer et al. *(4)* evaluated how to design an ECC mix that can be mixed in conventional gravity-based drum mixers. Part of the research project focused on measuring the workability of ECC and if it can be mixed in gravity-based drum mixers.

Table 40 shows the mix proportions for the ECC mixes evaluated in this experiment. The mixing procedure is described in Table 41. Sand, fly ash, and 1/3 of the cement were dry mixed for one minute, followed by 80% of the water. Next, the remaining water, cement, and superplasticizer were added. Lastly, the PVA fibers were added. Samples were mixed in a planetary mixer first, then in a drum mixer.

Table 40: Mix proportions for the five high workability and the traditional (M-ref) ECC mixes

	M-ref	**M-1**	**M-1**	**M-3**	**M-4**	**M-5**
Cement	1.00	1.00	1.00	1.00	1.00	1.00
Sand	0.60	0.80	0.80	0.80	0.80	0.80
Fly Ash (F)	0.00	0.50	0.50	0.50	0.50	0.50
Fly Ash (C)	0.15	0.30	0.30	0.30	0.30	0.30
W/C	0.45	0.36	0.37	0.38	0.40	0.42
W/CM	0.450	0.195	0.202	0.207	0.220	0.230
W/Solids	0.260	0.134	0.138	0.142	0.150	0.158
MFS[1]/C	0.020	0.030	0.030	0.030	0.030	0.030
HPMC[2]/C	0.00150	0	0	0	0	0

[1] MFS = superplasticizer.
[2] Viscosity agent: hydroxypropyl methylcellulose

Table 41: Mixing sequence used in this evaluation study.

Mixing Procedure	**Mixing Time (min)**
Sand + Fly Ash + 1/3 Cement: Dry Mixed	1
80% of Total Water added	---
Remaining Cement, Remaining Water, Superplasticizer added alternately and slowly	---
PVA Fibers added slowly	---
Total Mixing Time:	8-10

Table 42 summarizes the results from this study. Mix M-5 was successfully mixed in a gravity-based drum mixer. M-5 did not undergo segregation during mixing and remained homogeneous throughout mixing. M-5 had an air content of 4.3% and a flowability index of 19.25. M-5 was also successfully mixed in a 66 gallon (250 L) drum mixer on a construction site.

Table 42: Summary of findings from processing and workability study.

Property	Findings
Workability	• Significant factors: w/c ratio • Higher w/c ratios caused higher workability of ECC mixes. • Fresh sample of mix M-5 had spread of 35 inches (90 cm) after slump cone was removed. • Fresh sample of mix M-5 had flowability index of 19.25
Air Content	• Significant factors: w/c ratio • Higher w/c ratios caused lower air content. • Mix M-5 had air content of 4.3% after being mixed in drum mixer.

3.3 Field Demonstration of Durable Link Slabs for Jointless Bridge: Decks Based on Strain-Hardening Cementitious Composites

Li and Lepech *(17)* described the process of designing and constructing a durable link slab made from ECC in Michigan. The focus was to perform a field test of an ECC link slab to determine its constructability, making note of any difficulties, and documenting the entire process.

Part of the report focused on the production of ECC. ECC Mix M45 was chosen for evaluation of large-scale production. Table 43 shows the mix proportions for M45. Prior to mixing the ECC in a concrete mixing truck, a site visit was conducted at the ready-mix concrete plant. The ready-mix plant staff helped modify sequence no. 6 from Lepech and Li *(18)*. A new mixing sequence was formed and tested. The mixing sequence evaluated is shown in Table 44.

Three large-scale mixing tests were performed: a 1, 2, and 4 yd^3 (0.76, 1.53, 3.06 m^3) ECC sample batches were mixed in a concrete mixing truck. Every 15 minutes, fresh properties of the ECC were measured and ECC samples were formed and used to determine the mechanical properties. In the 1 yd^3 (0.76 m^3) test, cement balls were formed. After eight gallons of water was added to the mix, the mix became much more fluid. The additional water was needed because the concrete mixing drum was completely dry, which robbed the ECC of mixing water. Further tests were conducted by pre-wetting the concrete mixing drum prior to mixing the ECC. The 4 yd^3 (3.06 m^3)test was performed without any problems (No additional water or admixtures were needed). The 2 yd^3 (1.53 m^3) test was performed with a modified mixing procedure. The water was added first into the truck, followed by the sand. There were no negative effects of this switch; this showed that ECC could be mixed as long as both the water and sand are the first two materials charged into the truck.

Table 45 summarizes the results of the production phase of this study. Compression tests showed that compressive strengths were above 4.5 ksi (31 MPa) after 4 days for the 1 yd^3 and 2 yd^3 (0.76 and 1.53 m^3) tests. Compressive strengths at 28 days ranged from 9 ksi (62 MPa) to 10 ksi (69 MPa). The compressive strengths were not affected by how long the ECC was within the mixing truck. The ECC samples exhibited consistent compressive strengths throughout the 1 hour mixing time. If the ECC is placed with 1 hour after batching it will retain its compressive strength. Tensile tests showed the ultimate tensile strength increases the longer the ECC is held within the concrete truck. Additionally, the tensile strain capacity remained unchanged regardless of how long the ECC is within the mixing truck. Test results showed the average ultimate tensile strength was 855 psi (5.9 MPa) after 28 days and the average tensile strain capacity was 2.2% for the ECC.

Table 43: Mix proportions for the ECC mix used to construct link slab.

Mix ID	Cement, Type I	Fly Ash, Type F	Sand	Water	Superplasticizer	Fiber[1] (% vol.)
M45	1.0	1.2	0.8	0.59	0.014	2.0

[1]PVA fibers: 0.33” (8 mm) long, 1.5 mils (39 µm) diameter

Table 44: Mixing sequence used for large-scale production.

Activity	Time (min)
1. Charge all sand	2
2. Charge portion of mixing water (80-90%), all HRWR, and all hydration stabilizer	2
3. Charge all fly ash	2
4. Charge all cement	2
5. Charge remaining mixing water to wash drum fins (10%-20%)	4
6. Mix at high speed RPM until material is homogeneous throughout.	5-10
7. Bring flowable ECC material to top of mixing drum.	2
8. Charge fibers and mix at high RPM until material is homogeneous.	5-10
Total mixing time:	24-34

Table 45: Summary of findings from ECC link slab field demonstration.

Property	Findings
Mixing	• Significant factors: mixing sequence • Mixing sequence tested was found to deliver ECC with sufficient workability and strengths. • Mixing drum should be wetting prior to mixing ECC to ensure no loss of water take place from the mixture. • 10-20% of mixing water should be withheld until all components are charged into truck. Larger ECC mix sizes should withhold lower % of mixing water.
Compressive strength	• No significant factors. • Compressive strength was above 4.5 ksi (31 MPa) at 4 days for 1 yd^3 and 2 yd^3 (0.76 and 1.53 m^3) tests. • Compressive strength gain dependent on dosage of retarder admixture. High dosages reduce short term strength gain. • Compressive strength remained constant regardless of amount of time ECC was held within the mixing drum up to 1 hour retention time.
Ultimate tensile strength	• No significant factors. • Tensile strength slightly increased the longer the ECC was left in the mixing drum.
Tensile strain capacity	• No significant factors. • Tensile strain capacity remains unchanged regardless of how long the ECC is left in the mixing drum.

3.4 Large-scale processing of ECC

Lepech and Li *(18)* evaluate the design, production, and evaluation of large scale batches (up to 4 yd^3) of ECC. The focus was to design a mix and test multiple mixing sequences to obtain the most workable ECC. Once found, the ECC was mixed in a concrete mixing truck in the field.

There are two criteria that must be met for large productions of ECC: (1) the material exhibits pseudo-tensile strain-hardening characteristics and (2) the material can be mixed thoroughly using commonly available mixing equipment. For the ECC to be mixed in common mixing equipment, it should require minimal mixing energy. The mixes were designed using the Alfred grain size distribution curve, shown in Equation 5. Using this grain distribution curve, the mixes will have optimal particle packing which will make the ECC mix easy to mix in a gravity based drum mixer. Table 46 shows the mix proportions for the ECC mixes evaluated. Figure 5 shows the gradation of the ECC mixes compared to the ideal gradation calculated.

$$CPFT = 100 * \frac{D^q - D_s^q}{D_L^q - D_s^q} \qquad \text{(Eq. 5)}$$

where CPFT is the cumulative percent of particles finer than a particle with a diameter D; D_s is the diameter of the smallest particle in the distribution; D_L is the diameter of the largest particle in the distribution; and q is the distribution modulus which was 0.37

The workability and the tensile strain of the ECC were determined. To measure the workability of the fresh ECC, a slump cone test was used and the flow factor of the material was measured. Equation 6 describes how the flow factor is calculated using a slump cone (D_1 is the diameter of the ECC after slump cone is removed, D_0 is the diameter of the slump cone used).

Table 46: Mix proportions (by dry weight) for ECC mixes in large-scale processing study.

Mix No.	Cement	Fly ash	Sand[1]	Water	High range water reducer	Fiber, % volume[2]
M45	1.0	1.2	0.8	0.56	0.012	0.02
M46	1.0	1.2	1.2	0.58	0.012	0.02
M47	1.0	1.2	1.4	0.59	0.012	0.02
M48	1.0	1.2	1.6	0.60	0.012	0.02

[1] Sand is “F110 foundry sand”
[2] Fiber length is 0.33” (8 mm)

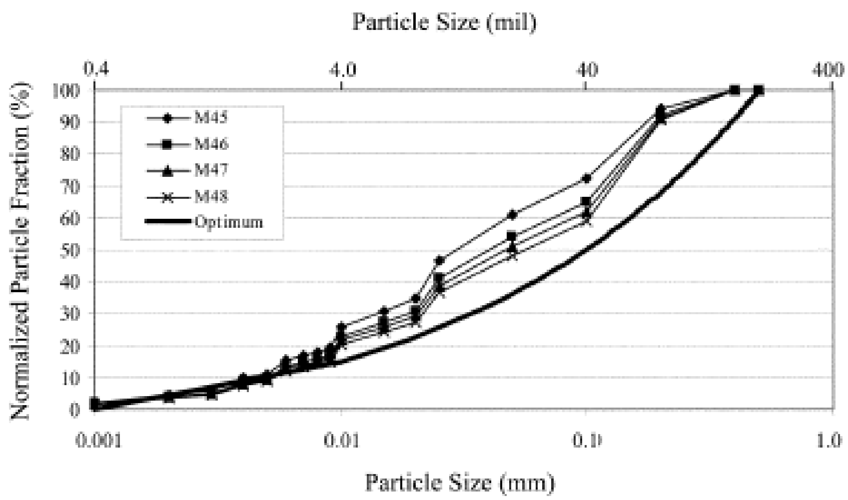

Figure 5: Gradation of ECC mixtures evaluated (sand, fly ash, cement particles). *(18)*

$$\Gamma = \frac{D1 - D0}{D0} \quad \text{(Eq. 6)}$$

The tensile strain was determined using a uniaxial tension test. Both mixes M45 and M46 exhibited strain-hardening behavior with tensile strains of 3.0% and 3.1%, respectively. Mix M46 had a higher flow factor than M45, 3.6 compared to 3.4. Mix M45 was used for large scale mixing because the samples had a smaller standard deviation than mix M46.

In large scale mixing, three objectives were identified: (1) keep the mixture as fluid as possible, (2) ensure the cement is nearly homogeneous before adding fibers, and (3) keep mixing times to a minimum. There were seven different mixing sequences evaluated by preparing 1 ft^3 and 7 ft^3 (0.76 and 5.35 m^3) sample sizes (See Table 47). All three of the objectives had to meet in the 1ft^3 (0.76 m^3) mixer before the sequence was evaluated for the 7 ft^3 (5.35 m^3) mixer. Mix sequences 1, 2, 3, and 7 had severe clumping of the material in the 1 ft^3 (0.76 m^3) mixer, while the other three produced a highly workable, homogeneous mixture. In the 7 ft^3 (5.35 m^3), sequence 5 produced clumping within the mixer, sequence 4 took 25 minutes to complete, and sequence 6 produced a workable and homogeneous mixture. Mixing sequence 6 was found to be the optimal mixing sequence as it was the only mixing sequence to pass both of the mixing tests in a timely manner.

Table 47: Mixing sequences evaluated for large-scale processing.

Trial no.	Sequence	Mixer size		Mixing time, minutes
		1 ft^3 (0.76 m^3)	7 ft^3 (5.35 m^3)	
1	C+S+FA; W(95%); HRWR; W(5%); Fiber	Clumping	-	-
2	C; W(50%); S+FA; W(50%); HRWR; Fiber	Clumping	-	-
3	C(50%); W+HRWR; S+FA; C(50%); Fiber	Clumping	-	-
4	W; C+FA+S; HRWR; Fiber	Passed	Excessive mixing time	25
5	W+HRWR(50%); C+S+FA; W+HRWR(50%); Fiber	Passed	Minor Clumping	14
6	S; W+HRWR; C+FA; Fiber	Passed	Passed	12
7	FA; W+HRWR; C+S; Fiber	Clumping	-	-

Notes: C = cement; S = sand; FA = fly ash; W = water; HRWR = high range water reducer; Fiber = polyvinyl alcohol fiber;

The final step was to mix 1 yd^3, 2 yd^3 and 4 yd^3 (0.76, 1.53, 3.06 m^3) trial batches in concrete mixing trucks. The flow factor of the fresh ECC was over 3.0 after 60 minutes of mixing when a hydration stabilizer was used at a dosage rate of 6 fl oz/100 lb cement (0.06 L/100 kg cement). Samples were cast and tested to determine the mechanical properties of the ECC. Table 48 shows the summary of findings from this study. The 28 day testing results showed the ECC had a compressive strength of 1.35 ksi (9.31 MPa), first crack tensile strength of 700 psi (4.79 MPa), ultimate tensile strength of 860 psi (5.94 MPa), and a tensile strain capacity of 2.2%. This showed ECC could be mixed in a commercially available concrete mixing truck and ECC was able to retain its mechanical properties after 60 minutes of mixing.

Table 48: Summary of findings from large-scale processing study.

Property	Findings
Flow factor	• Significant factors: mixing sequence, particle gradation, mixing time, hydration stabilizer • The mixing sequence used can cause the material to clump inside the mixer. • Flow factor decreases as the ECC gradation approaches the optimal gradation. • Addition of hydration stabilizer increased flow factor from 2.3 to 3. • Flow factor decreases as mixing times increase. Flow factor of 3 can be obtained after 60 minutes of mixing.
Mixing	• Significant factors: mixing sequence • Sequence 6 was found to be most desirable mixing sequence. ECC material did not clump up in mixer and mixing time was 12 minutes.
Mechanical Properties after mixing	• ECC mixed in comercial concrete mixing trucks exhibited sufficient mechanical properties. • Tests show ECC samples at 28 days had compressive strength of 9.3 ksi (64.2 MPa), first crack strength of 700 psi (4.8 MPa), ultimate tensile strength of 860 psi (5.9 MPa), and tensile strain capacity of 2.2%

3.5 Rheological Control in Production of Engineered Cementitious Composites

In 2009, Yang et al. *(19)* evaluated the rheological properties of laboratory produced ECC and how to control these properties. The focus was to conduct a statistical analysis by means of ANOVA to determine any correlations between the fresh ECC rheological properties and the hardened ECC mechanical properties. Four different factors were investigated:

1. Ratio (by mass) of Class C fly ash to Class F fly ash (C/F).
2. Ratio (by mass) of water to cementitious material (W/CM).
3. Ratio (by mass) of high range water reducer to cementitious material (HRWR/CM).
4. Ratio (by mass) of viscosity-modifying admixture to cementitious material (VMA/CM).

Nine different ECC mixes were developed and evaluated. Table 49 shows the mix proportions for the ECC mixes evaluated while Table 50 shows the properties of the PVA fibers used. ECC mixtures were mixed in a paddle mixer. Table 51 shows the mixing sequence used in this experiment. The fresh properties of the ECC mortar (without PVA fibers) were measured. The rheological properties are described by the Bingham model: plastic viscosity and relative yield stress. A low relative yield stress is desired for high workability. The rheological properties were measured using a rotational viscometer; the workability was measured using a mini-slump cone and Marshal cone test. Mechanical properties were found by subjecting ECC specimens (with PVA fibers) to a uniaxial tensile test at 28 days.

Table 49: Mix proportions (dry weights) for ECC mixes evaluated in rheological control study.

Mixture No.	**Cement, Type I**	**Sand**	**Class F Fly ash**	**Class C Fly ash**	**Water**	**HRWR**	**VMA**	**PVA**
	Lb/cy (kg/m^3)							
1	544 (323)	770 (456)	1526 (906)	0 (0)	441 (262)	15.5 (9.3)	0.03 (0.2)	43.8 (26)
2	544 (323)	770 (456)	1526 (906)	0 (0)	475 (282)	10.5 (6.3)	0.02 (0.1)	43.8 (26)
3	544 (323)	770 (456)	1526 (906)	0 (0)	510 (302)	5.5 (3.3)	0 (0)	43.8 (26)
4	544 (323)	770 (456)	1145 (680)	380 (226)	441 (262)	10.5 (6.3)	0 (0)	43.8 (26)
5	544 (323)	770 (456)	1145 (680)	380 (226)	475 (282)	5.5 (3.3)	0.03 (0.2)	43.8 (26)
6	544 (323)	770 (456)	1145 (680)	380 (226)	510 (302)	15.5 (9.3)	0.02 (0.1)	43.8 (26)
7	544 (323)	770 (456)	763 (453)	763 (453)	441 (262)	5.5 (3.3)	0.02 (0.1)	43.8 (26)
8	544 (323)	770 (456)	763 (453)	763 (453)	475 (282)	15.5 (9.3)	0 (0)	43.8 (26)
9	544 (323)	770 (456)	763 (453)	763 (453)	510 (302)	10.5 (6.3)	0.03 (0.2)	43.8 (26)

Table 52 summarizes the findings from this study. The yield stress decreased as HRWR/CM and W/CM ratios decreased, and yield stress increased as the ratio of C/F and VMA/CM increased. The viscosity decreased as HRWR/CM and W/CM ratios increase, and viscosity increased as VMA/CM and C/F ratios increased. Statistical analysis found a strong correlation between the yield stress and mini-slump flow. Higher mini-slump flow diameters correlated to lower the yield stress values. A correlation between plastic viscosity and Marshal cone flow time was also observed. As the flow time increased, the plastic viscosity also increased. The tensile strain capacity increased with higher C/F, HRWR/CM, and VMA/CM ratios, and decreased with higher W/CM ratios. The ultimate tensile strength increased with higher C/F ratios, but decreased with higher W/CM, HRWR/CM, and VMA/CM ratios. Statistical analysis shows that ultimate tensile strengths and tensile strain capacity both increased with higher plastic viscosity/Marshal cone flow time values.

The conclusion was reached that rheological properties of ECC can be found with Marshal cone flow times and mini-slump flow diameters. A W/CM ratio of 0.25±0.05 is recommended based on the findings from this study. A high plastic viscosity, high Marshal cone flow time, high mini-slump flow diameter, and low yield stress are desirable for any ECC mixture. These values can be adjusted using different amounts of HRWR. Controlling and monitoring these properties can be used as a quality control method for ensuring that ECC with high strengths and strain capacities is being produced and placed.

Table 50: Properties of PVA fibers evaluated in rheological control study.

Fiber Type	**Nominal Strength**	**Fiber Diameter**	**Fiber length**	**Density**	**Fiber content, % vol.**
PVA	235 ksi (1,600 MPa)	1.5 mil (39 µm)	0.33 inch (8 mm)	2190 lb/cy (1,300 kg/m3)	2.0

Table 51: Mixing sequence evaluated in rheological control study.

Mixing Procedure	**Mixing Speed/Time**
Cement + Fly ash + Sand dry mixed	100 rpm for 1 minute
Water + HRWR + VMA added	150 rpm for 1 minute, 300 rpm for 2 minutes
PVA Fibers added	150 rpm for 3 minutes
Total mixing time:	7 minutes

Table 52: Summary of findings from rheological control study.

Property	**Findings**
Yield stress	• Significant factors: HRWR/CM, VMA/CM ratios • Yield stress is primarily controlled by ratio of HRWR/CM and WMA/CM. • Yield stress decreased as HRWR/CM ratio increased. • Yield stress increased as VMA/CM ratio increased. • Yield stress has strong correlation with mini-slump flow diameter. Higher mini-slump flow diameters correlate to lower yield stresses.
Plastic viscosity	• Significant factors: W/CM ratio • Plastic viscosity is primarily controlled by W/CM ratio. • Plastic viscosity decreased as W/CM ratio increased. • Plastic viscosity has strong correlation with Marshal cone flow time. Higher Marshal cone flow times correlate to higher plastic viscosity values.
Tensile strain capacity	• Significant factors: C/F, W/CM ratios, plastic viscosity/Marshal flow time • Tensile strain capacity controlled by ratio of C/F and W/CM. • Tensile strain capacity increased as C/F ratio increased. • Tensile strain capacity decreased as W/CM ratio increased. • Tensile strain capacity increased as plastic viscosity values and Marshal flow times increased.
Ultimate tensile strength	• Significant factors: C/F, W/CM ratios • Ultimate tensile strength controlled by ratio of W/CM and C/F. • Ultimate tensile strength increased as C/F ratio increased. • Ultimate tensile strength decreases as W/CM ratio increased. • Ultimate tensile strength increased as plastic viscosity values and Marshal flow times increased.

CHAPTER 4: APPLICATION OF ECC

4.1 Introduction

Chapter 4 discusses the application and use of ECC in field demonstrations. An ECC link slab was constructed in Michigan. This demonstration validated laboratory test results and showed ECC can be used as a construction material. The entire process from the design of the ECC to the construction of the link slab was documented. ECC has also been evaluated for use as bridge columns in several studies conducted at the University of Nevada, Reno.

4.2 Field Demonstration of Durable Link Slabs for Jointless Bridge: Decks Based on Strain-Hardening Cementitious Composites

In 2005, Li and Lepech *(17)* and *(20)* described the process of designing and constructing a durable link slab made from ECC in Michigan. As mentioned before, the focus was to perform a field test of an ECC link slab to determine the constructability of such a slab, making note of any difficulties that arise, and documenting the entire process.

The process started by designing the link slab. The design of the link slab followed the American Association of State and Highway Transportation Officials LRFD Bridge Design Manual *(28)*. The stresses and strains in the link slab were calculated. Some parameters, such as maximum end rotation angle, were calculated to verify they met the AASHTO design code. The ECC mix was then designed. Table 53 below shows the mix proportions for the original ECC mix. Samples of the ECC mix had a yield strain of 0.02% and yield stress of 500 psi (3.45 MPa). These values were obtained from 40 ECC samples. These were the design values for the ECC; the structure would not rely on the strain-hardening properties of ECC to provide strength, as a factor of safety. Using the ECC's yield strain and stress, a reinforcement ratio was determined to resist the calculated maximum end rotation. Three trial batches were mixed to determine the best mixing sequence to use for production of the ECC in concrete mixing trucks. It was at this time, the contractor was shown how ECC looks during placement and how to apply the necessary surface finishing techniques.

Construction took place between July 25 and October 25, 2005. In total, there were six batches of 7 yd^3 (5.4 m^3) of ECC delivered to the project site. The first link slab exhibited a fair amount of shrinkage cracks after eight days of curing. Laboratory tests were conducted to determine how to reduce the potential for shrinkage cracks by slightly changing the ECC mix proportions. Test results showed that a reduction in water-to-cement ratio from 0.59 to 0.57 caused a huge reduction in shrinkage cracks. Table 54 below shows the updated ECC mix proportions used on the second link slab. The number of shrinkage cracks greatly reduced with the use of this modified ECC mix. Once completed, slabs were covered with plastic and burlap to cure.

Table 53: Mix proportions for the ECC mix used to construct link slab #1.

Mix ID	Cement, Type I	Fly Ash, Type F	Sand	Water	Superplasticizer	Fiber[1] (% vol.)
M45	1.0	1.2	0.8	0.59	0.014	2.0

[1]PVA fibers: 0.33" (8 mm) long, 1.5 mils (39 µm) diameter

Table 54: Modified mix proportions for the ECC mix used to construct link slab #2.

Mix ID	Cement, Type I	Fly Ash, Type F	Sand	Water	Superplasticizer	Fiber[1] (% vol.)
M45	1.0	1.2	0.8	0.57	0.015	2.0

[1]PVA fibers: 0.33" (8 mm) long, 1.5 mils (39 µm) diameter

Table 55 summarizes the findings from this study. Specimens made from the ECC delivered to the construction site showed consistent properties for all six ECC batches. The ECC exhibited compressive strengths of 4.6 ksi (31.7 MPa) and 7.5 ksi (51.7 MPa) at 7 days and 28 days, respectively. Tensile strengths were 480 psi (3.3 MPa) at 7 days and 623 psi (4.3 MPa) at 28 days. Tensile strain capacity was 2.4% at 7 days and 2.2% at 28 days. Proof loadings were conducted once slabs had sufficiently cured. The results showed that some design parameters, such as maximum end rotation, were much lower than the values used in the ECC link slab design calculations.

Table 55: Summary of findings from field demonstration of ECC link slab.

Property	Findings
Compressive strength	• No significant factors. • Compressive strength of ECC was 4.6 ksi (31 MPa) at 7 days and 7.5 ksi (51.7 MPa) at 28 days. No change in compressive strength between the two ECC mixes used.
Ultimate tensile strength	• No significant factors. • Ultimate tensile strength of ECC was 480 psi (3.3 MPa) at 7 days and 623 psi (4.3 MPa) at 28 days. No change in tensile strength between two ECC mixes used.
Tensile strain capacity	• No significant factors. • Tensile strain capacity of ECC was 2.7% at 7 days and 2.2% at 28 days. No changes in tensile strain capacity between two ECC mixes used.
Shrinkage cracks	• Significant factors: water-to-cement ratio • The number of shrinkage cracks decreased as the water-to-cement raio decreased. This was observed both in laboratory experiments and in the completed link slabs.
Workability	• No significant factors. • ECC mix was mixed and delivered in concrete mixing trucks without any complications. ECC was workable and exhibited suffecient mechanical properties.

4.3 Bridge Columns Constructed with ECC

Multiple studies at the University of Nevada, Reno [*(23)*, *(24)*, *(25)*] have been carried out involving the use of ECC in bridge columns subjected to earthquake loads. The focus was to determine how ECC would perform under the earthquake loadings and if the material was suitable for use in bridge columns.

The steel reinforcement was first designed for the columns. The columns were then formed and constructed with the ECC material which was supplied by a local contractor. Columns were placed on the earthquake shake tables and tested. A multitude of sensors were placed on the columns to measure many different properties of the column: displacement, stresses, and strains. The results of all three studies showed that ECC was successfully implemented in bridge columns. ECC was determined to be a suitable material for use in bridge columns because of its superior performance when subjected to earthquake loads. The ECC columns outperformed the concrete columns commonly used around the world. These studies showed that ECC can be produced in Nevada.

CHAPTER 5: COST BENEFITS OF ECC

5.1 Introduction

Chapter 5 discusses the sustainability of using ECC by evaluating the associated cost benefits. A life cycle cost model for ECC was developed and used to evaluate the lifetime performance and total cost of using ECC as a construction material. A life cycle analysis using a finite-element analysis was conducted to determine the service life of ECC. The cost benefits of using ECC in an overlay system compared to concrete and asphalt were evaluated.

5.2 Life Cycle Cost Model For Evaluating the Sustainability of Bridge Decks

In 2001, Keoleian et. al. *(21)* developed a life cycle cost model for ECC link slabs. An economic analysis over the life of the project was performed and results were compared to the costs associated with present day steel expansion joints.

The life cycle being developed have two parts: (1) one focusing on the costs of the materials, construction, repair, and demolition; (2) the other focusing on the costs associated with user delay, vehicle operation, and traffic congestion. The initial bridge construction cost was neglected in this study as the authors estimated that cost would be roughly the same for ECC link slab and steel expansion joint. The expansion joints had a service life of 30 years while the ECC link slab had a service life of 60 years. The 60 year service life was not verified but was determined to be an accurate estimate. Construction and material costs were calculated using historical data. Traffic congestion costs due to construction were determined using a traffic model based on an approach from the Federal Highway Administration (FHWA). The cost of the air pollution associated with the bridge deck construction was calculated and found using data from several sources.

Table 56 shows the results of the economic analysis. Table 57 summarizes the findings from this study. The total cost for the ECC bridge deck was 37% less than the concrete bridge deck over the lifetime of the product. The construction and materials cost (i.e., agency cost) for the ECC was 35% less than the concrete bridge deck. The social costs (traffic congestion, fuel consumption) were found to be 98% of the total life cycle costs of the bridge decks. Lastly, the environmental cost for ECC was $23,300 while for concrete it was $43,100. The emissions of CO_2 from the production of materials, construction of the project, and from the traffic congestion were calculated and tabulated. The results show the ECC deck accounted for 3,500 metric tonnes of CO_2 while the concrete deck accounted for over 5,000 metric tons, a decrease of 30%. In summary, the results showed that the use of ECC link slab is a more desirable alternative to modern steel expansion joints.

Table 56: Results of the economic analysis from the life cycle cost model study.

	Steel expansion joint	**ECC link slab**	**ECC link slab cost advantage over steel expansion joints (%)**
Agency cost	$751,000	$489,000	39
User Cost	$34.9 million	$22.1 million	37
Environmental cost	$43,100	$23,300	46
Total cost	$35.7 million	$22.6 million	37

Table 57: Summary of findings from the life cycle cost model study.

Property	Findings
Overall cost benefit	• Significant factors: overlay material • ECC link slab cost 37% less than a steel expansion joint.
Green-house gas emissions	• Significant factors: overlay material • ECC link slab construction will reduce the CO_2 emissions by 30% compared to that of a steel expansion joint.

5.3 Life cycle analysis of pavement overlays made with ECC

In 2013, Qian et. Al. *(22)* evaluated the long-term properties of laboratory produced ECC related to a pavement overlay. The ECC was subjected to multiple tests to find the long-term durability properties of the material. The focus was to determine if an ECC overlay could perform at a high level over a long service period and determine the associated cost benefits.

In this study, one ECC mix and one concrete mix were evaluated. Table 58 shows the ECC mix proportions. The tensile strain capacity of the ECC was 2.5%, compared to only 0.01% for the concrete. The ultimate tensile strength of the ECC was 770 psi (5.3 MPa). The compressive strength of the ECC was 6.7 ksi (46 MPa) compared to 3.9 ksi (27 MPa) for the concrete. Lastly, the modulus of rupture for the ECC was 1.58 ksi (10.9 MPa) while only 0.7 ksi (4.6 MPa) for the concrete.

A fatigue test and a finite element (FE) analysis of the ECC and concrete materials were conducted. The fatigue test involved subjecting samples to a sinusoidal waveform, four point bending load. The results of the fatigue test showed that ECC has twice the fatigue stress as concrete over the same fatigue life. The JSLAB2004 finite element software *(29)* was used to find the critical stresses of the overlay layer. The location of the maximum tensile stress was located at the bottom of the overlay layer, directly above the crack in the underlying layer, when subjected to an equivalent single axle load (ESAL) of 18 kips (80 kN). Accordingly, it was estimated that a 6.9 inch (175 mm) thick concrete overlay has a service life of 20 years. A 2.5 inch (65 mm) thick ECC overlay has a predicted service life of 40 years. The service life model predicted that both asphalt and unbounded concrete overlays would need to be replaced after 20 years and would each need at least two major repairs to reach a performance period of 40 years. Conversely, ECC would require only one major repair to reach a performance period of 40 years.

An economic analysis was conducted to find the total costs associated with an ECC, hot mix asphalt (HMA), and concrete overlay. The findings showed that the total cost of an ECC overlay is $44.3 million, 40% less than the $72.9 million for a concrete overlay, and 56% less than the $100 million for an HMA overlay. Table 59 shows the results of this analysis. The ECC overlay was found cost effective because of the large reduction in user costs, which resulted from the minimal amount of maintenance work required. Table 60 also shows the summary of findings from this study. The conclusions reached in the report are that ECC is a suitable and desirable material for a rigid pavement overlay.

Table 58: Mix proportions (by weight) for ECC mix evaluated in life cycle analysis study.

Cement	Sand	Fly Ash	Water	Superplasticizer	PVA Fiber[1] (% vol)
1.0	0.8	1.2	0.59	0.012	2.0

[1]PVA Fiber: Kuralon K-II REC15

Table 59: Results of the economic analysis from life cycle analysis study (millions of dollars).

	Concrete overlay	**ECC overlay**	**HMA overlay**	**ECC overlay cost advantage over concrete overlay (%)**	**ECC overlay cost advantage over HMA overlay (%)**
Agency cost[1]	$10.1	$6.22	$14.8	38.4	58.0
User Cost[2]	$61.9	$37.4	$84.2	39.6	55.6
Environmental cost[3]	$0.9	$0.7	$1.11	22.2	36.9
Total cost	$72.9	$44.3	$100	39.2	55.7

[1] Agency costs are responsible by government agencies (i.e. department of transportation) for the construction costs
[2] User costs include vehicle operating costs, user delay costs, etc.
[3] Environmental costs include vehicle emissions.

Table 60: Summary of findings from life cycle analysis study.

Property	**Findings**
Overall cost benefit	• Significant factors: maintenance work, overlay thickness, service life • ECC overlays requires 1 major repair while concrete and HMA overlays require at least 2 major repairs. • Over 40 year analysis period, only 1 ECC overlay is required while both concrete and HMA overlays will need to be replaced after 20 years. • ECC overlays have estimated cost of $44 million. This is 40% less than the concrete overlay ($73 million) and 56% less than the HMA overlay ($100 million) over 40 year analysis period.
Service life	• Significant factors: overlay thickness • ECC overlay of 2.5 inches has estimated service life of 40 years. Concrete overlay of 6.9 inches (175 mm) has service life of only 20 years. • Over 40 year analysis period, only 1 ECC overlay is required while both concrete and HMA overlays will need to be replaced after 20 years.
Maintenance work required	• Significant factors: overlay material • ECC overlays require only 1 major repair for 40 year analysis period. Concrete and HMA overlays require at least 2 major repairs for 40 year analysis period.

CHAPTER 6: PROFESSIONAL CONTACTS

During the literature review, the research team identified two researchers who have made significant contributions to the advancement of ECC: Dr. Victor C. Li and Dr. Michael Lepech. Dr. Li is a Professor of Civil and Environmental Engineering at the University of Michigan. He invented ECC in 1986 and has been working to improve the material since. His work has been critical to the application and development of ECC around the world. Dr. Lepech is an Assistant Professor of Civil and Environmental Engineering at Stanford University. He worked with Dr. Li on multiple ECC studies while obtaining his PhD from the University of Michigan. Like Dr. Li, Dr. Lepech has a lot of experience working with ECC. The research team determined that contacting Dr. Li and Dr. Lepech should be a priority because of their experience with ECC. A telephone interview with these researchers will be helpful in getting additional information about the design, production, and application of ECC as bridge deck overlays. Multiple attempts to contact both researchers have not been successful, but the research team will keep attempting to establish communications with Dr. Li and Dr. Lepech in the coming months.

CHAPTER 7: OVERALL SUMMARY OF LITERATURE REVIEW

7.1 Introduction

This chapter summarizes the overall findings from the comprehensive literature review that was conducted. The summary focuses on the information relevant to the development of an effective laboratory and field experimental program for the NDOT study.

7.2 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 61. The critical variable was found to be the water-to-cementitous 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. Type II, 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 0.020 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 62. 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 result in the ECC losing its desired tensile properties.

Table 61: 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 62: 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)

7.3 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 61 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*(9)*.

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%.

7.4 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 ECC 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.

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.

CHAPTER 8: PROPOSED LABORATORY EXPERIMENTAL PLAN

8.1 Introduction

This chapter focuses on the experimental plan to be implemented in Task 2 of NDOT Project 13-39. The original proposed experimental plan was revised with input from the studies summarized in this comprehensive literature review on ECC. Ranges for the ECC mix proportions were developed such that the material will exhibit sufficient mechanical properties and durability that are desired for bridge deck overlays application. Based on the literature review, the average mechanical properties of ECC measured at 28 days consisted of a tensile strength of 725 psi (5 MPa), a tensile strain capacity of 2.85%, and a compressive strength of 8 ksi (55 MPa). As a starting point, these typical values for ECC mixes are proposed as target values for the mixtures to be designed as part of this study. This will be achieved by first using the typical mix proportions identified in the literature. If the ECC mixes do not meet the set minimum values for tensile strength, tensile strain capacity, and compressive strength, the mix proportions will then be adjusted accordingly. Once the ECC meet these target values, the mixes will undergo testing to evaluate the durability and performance of the material with special consideration due to mixture's resistance to freeze-thaw damage and reflective cracking. The proposed tests from the original proposal and test methods were revised based on the findings from this comprehensive literature review. A wide range of tests for fresh and hardened properties are proposed so the research team can validate the conclusions of previous test results on ECC. Having a large amount of tests will ensure that the ECC mix chosen for field testing will have the most success under Nevada's conditions.

8.2 Evaluation Materials

ECC mixes have a wide range of mix proportions that can be varied. Achieving high mechanical properties and durability of ECC depends on selecting the correct proportions values for ECC evaluation. The type of materials used is also critical to the ECC mixes. Different cement types and fly ash types will have a huge influence on the properties of hardened ECC. Careful consideration was taken during the selection of these ECC mix proportions and materials. Table 63 shows the proposed mix proportion ranges while Table 64 shows the type of materials to be considered.

The four aggregate sources from Nevada will be determined with input from NDOT personnel. Chemical admixtures will also be determined at a later date. The fiber will be provided by a local supplier as will the oiling agent.

Table 63: 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

Table 64: Proposed material types for ECC mixes.

Cement	Sand	Fly Ash	Chemical Admixture	Fiber	Oiling agent
Type I	TBD[1]	Class C and Class F	TBD[2]	Length of 0.5" (12 mm) –TBD[2]	TBD[2]

[1] To be determined in coordination with NDOT
[2] Manufacturer to be determined

8.3 Production of ECC

For ECC to be successfully implemented as a bridge deck overlay material, it must be workable enough to be mixed in a commercially available concrete mixing truck. The mixing sequence to be evaluated is shown below in Table 65. This sequence will be evaluated in laboratory mixing tests. If problems arise, the sequence will be modified to fix any deficiencies. The same sequence evaluated in laboratory testing will also be used and modified as needed at the batching plant when large-scale mixing tests are performed.

Table 65: Proposed mixing sequence for ECC evaluation.

Activity	Add Sand	Add Water + Admixtures	Add Cement and Fly ash	Add Fiber	Total mixing time
Time (min)	2	6	5	6	21

8.4 Test Methods for Evaluation

To evaluate if the ECC mixes properties are suitable for bridge deck overlays, a large amount of tests are being proposed. Table 66 shows a list of tests and test methods to be performed on the ECC samples. The following summarizes the test methods considered in the experimental plan and do not have an established standard procedure (i.e. uniaxial tensile test, LISST, four-point loading thin beam, four-point loading simulated overlay, and the TTI Overlay tester).

The uniaxial tensile test was developed and used to characterize the tensile properties of ECC. It consists of an ECC specimen being subjected to a uniaxial tensile load that measures the maximum tensile strain and tensile strength of the specimen during the test. In 2001, Li et al. *(1)* used the test for an evaluation study to assess the tensile properties of ECC samples with different mix proportions. The test was effective in determining the performance of various ECC mixes in the study. The research team proposes this test method to evaluate the tensile strength and tensile strain capacity of the ECC mixes. Minimum tensile strength and strain capacity values will be set that the ECC mixes must meet before the material's durability will be evaluated in the laboratory.

The Louisiana Interlayer Shear Strength Tester (LISST) is being implemented in place of the simple shear at constant height (SS-CH) test that was originally proposed. The LISST test is a draft AASHTO test method that was developed as part of the NCHRP project 9-40 *(26)* to measure the interface bond strength of asphalt pavement layers in the laboratory. It consists of a cylindrical specimen that is fixed at one end and a shear load is applied to the other end. The University of Nevada, Reno has recently acquired the testing apparatus and the research team believes the LISST test can be used to evaluate the bond strength of ECC for bridge deck overlay applications. The LISST test is easier to perform than the SS-CH. If successful, the LISST test can be potentially implemented as part of the ECC mix design specifications.

The four-point loading thin beam test was developed to characterize the flexural properties of a thin ECC beam. It consists of a four-point bending load that measures the vertical deflection of a 1.5 inch (38 mm) thick beam specimen. In 2011, Akkari *(16)* used the test for a Minnesota DOT evaluation study to determine if ECC was a suitable construction material as a thin-bonded pavement overlay. The test was effective in determining the vertical displacement of ECC beam samples. The research team proposes this test method to evaluate the flexural performance of ECC specimens that would mimic bridge deck overlays.

The four-point loading simulating overlay test was developed and used to characterize the mixture resistance to reflective cracking by subjecting specimens to a repeated four-point bending load. It consists of a composite beam that has an ECC overlay layer placed on top of a concrete bridge deck. In 2001, Zhang and Li *(2)* used the test to determine how an ECC overlay will resist reflective cracking from the subsequent layer. The test was effective in determining an ECC overlay's resistance to forming reflective cracks. The research team proposes this test method to be considered for evaluating the ECC's ability to resist forming reflective cracking when used as a bridge deck overlay.

The Texas Transportation Institute Overlay Tester (TTI OT) is currently being used to characterize the asphalt mixture's resistance to reflective cracking by subjecting a sample to repeated opening and closing movements. The TTI OT was designed to simulate the horizontal opening and closing of joints and cracks in concrete pavements under new asphalt overlays. In 2011, Hajj et al. *(27)* used the test for a NDOT evaluation study to design highly flexible stress relief layers to be placed between an existing cracked asphalt layer and a new asphalt overlay to resist reflective cracking. The research team is proposing to evaluate the test for ECC material given its proven effectiveness in asphalt overlay designs. If found effective, the TTI overlay tester may be implemented as part of the ECC mix design specification or quality assurance.

Table 66: Revised laboratory tests for evaluating ECC mixes

Concrete	Property	Method
Fresh	Workability	Slump of fresh concrete (Nev. T438B)
		Slump flow and stability (Nev. T4147A)
	Air content	Pressure method (Nev. T432D)
	Density	Unit weight (Nev. T435C)
	Set time	Penetration Resistance (ASTM C403)
Hardened (Durability)	Freeze-thaw durability	Rapid repeated cycles (ASTM C666)
	Resistance to chloride ion penetration	Rapid chloride permeability (ASTM C1202)
	Scaling resistance	Scaling resistance (ASTM C672)
	Abrasion resistance	Surface abrasion (ASTM C944)
Hardened (Mechanical Properties)	Compressive strength	Cylindrical specimens (ASTM C39/C78)
	Tensile strength	Uniaxial Tensile Test *(1)*
	Tensile strain capacity	
	Flexural strength	Simple beam with third-point loading (NEV. T442E)
	Bond strength	Slant shear (ASTM C882)
		LISST *(26)*
	Ductility	Four-point loading thin beam *(16)*
	Reflective cracking	Four-point loading simulated overlay *(2)*
		TTI overlay tester *(27)*

CHAPTER 9: REFERENCES

(1) Li, V. C., Wang, S., and Wu, C. (2001). "Tensile Strain-Hardening Behavior of Polyvinyl Alcohol Engineered Cementitious Composites," ACI Materials Journal, Vol. 98, Issue 6, pp. 483-492.

(2) Zhang, J., Li, V. C. (2001). "Monotonic and Fatigue Performance in Bending of Fiber-Reinforced Engineered Cementitious Composite in Overlay System," Cement and Concrete Research 32, pp. 415-423.

(3) Li, V. C., Wu, C., Wang, S., Ogawa, A., and Saito, T. (2002). "Interface Tailoring for Strain-Hardening Polyvinyl Alcohol Engineered Cementitious Composite," ACI Materials Journal, Vol. 99, Issue 5, pp. 463-472.

(4) Fischer, G., Want, S., Li, V. C. (2003). "Design of Engineered Cementitious Composites (ECC) for Processing and Workability Requirements," Proc. Int. Symposium, Warsaw, Poland.

(5) Torigoe, S., Horikoshi, T., Ogawa, A., Saito, T., Hamada, T. (2003). "Study on Evaluation Method for PVA Fiber Distribution in Engineered Cementitious Composite," Journal of Advanced Concrete Technology, Vol. 1, No. 3, Tokyo, Japan, pp. 265-268.

(6) Li, V. C., Horikoshi, T., Ogawa, A., Torigoe, S., Saito, T. (2004). "Micromechanics-Based Durability Study of Polyvinyl Alcohol-Engineered Cementitious Composite," ACI Materials Journal, Vol. 101, No. 3, pp. 242-248.

(7) Ying-zi, Y., Lepech, M. D., and Li, V. C. (2005). "Self-Healing of Engineered Cementitious Composites Under Cyclic Wetting and Drying," Proc. Int. Workshop on Durability of reinforced concrete under combined mechanical and climatic loads", Qingdao, China, pp. 231-242.

(8) Lepech, M. D., and Li, V. C. (2005). "Water Permeability of Cracked Cementitious Composites," University of Michigan, Ann Harbor, Michigan.

(9) Lepech, M. D., and Li, V. C. (2006). "Long-term Durability Performance of Engineered Cementitious Composites," Restoration of Buildings and Monuments, Vol. 12, No. 2, pp. 119-132.

(10) Wang, S., Li, V. C. (2006). "High Early Strength Engineered Cementitious Composites," ACI Materials Journal, Vol. 103, Issue 2, pp. 97-105.

(11) Sahmaran, M., Li, V. C. (2007). "De-icing Salt Scaling Resistance of Mechanically Loaded Engineered Cementitious Composites," Cement and Concrete Research 37, pp. 1035-1046

(12) Wang, S., and Li, V. C. (2007). "Engineered Cementitious Composites with High-Volume Fly Ash," ACI Materials Journal, Vol. 104, No. 3, pp. 233-241.

(13) Zhang, J., Gong, C., Guo, Z., Zhang, M. (2009). "Engineered Cementitious Composite with Characteristic of Low Drying Shrinkage," Cement and Concrete Research, Vol. 39, Beijing, China, pp. 303-312.

(14) Zhu, Y., Yang, Y., (2010). "Influence of Curing Temperature on Flexural Performance of Engineered Cementitious Composites," International Conference on Mechanic Automation and Control Engineering 2010, Wuhan, China.

(15) Kakamura, K.; Matsumoto, T.; Hayashikawa, T.; He, X. (2011). "Fatigue Analysis of ECC-Steel Composite Deck Under Wheel Trucking Load," The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, Hong Kong.

(16) Akkari, A. (2011). "Evaluation of a Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composite for a Thin-Bonded Pavement Overlay," Report MN/RC 2011-11, Minnesota Department of Transportation, Mapplewood, MN.

(17) Li, V. C., Lepech, M. (2005). "Field Demonstration of Durable Link Slabs for Jointless Bridge: Decks Based on Strain-Hardening Cementitious Composites," Michigan Department of Transportation, Research Report Rc-1471, Ann Arbor, Michigan.

(18) Lepech, M. Li, V. (2008). "Large-Scale Processing of Engineered Cementitious Composites," ACI Materials Journal, Vol. 105 No. 5, pp. 358-366.

(19) Yang, E. Sahmaran, M. Yang, Y. Li, V. (2009). "Rheological Control in Production of Engineered Cementitious Composites," ACI Materials Journal, Vol. 106, No. 4, pp. 357-366.

(20) Lepech, M. Li, V. (2009). "Application of ECC for Bridge Deck Link Slabs," Materials and Structures 42, pp. 1185-1195.

(21) Keoleian, G.A.; Kendall, A.; Chandler, R.; Helfand, C.E.; Lepech, M.; Li, V.C. (2001). "Life Cycle Cost Model for Evaluating the Sustainability of Bridge Decks," Life-Cycle Cost Analysis and Design of Civil Infrastructure Systems, pp. 143-150.

(22) Qian, S.Z.; Li, V.C.; Zhang, H.; Keoleian, G.A. (2013). "Life Cycle Analysis of Pavement Overlays Made With Engineered Cementitious Composites," Cement and Concrete Composites 35, pp. 78-88.

(23) Saiidi, M. Wang, H. (2006). "Exploratory Study of Seismic Response of Concrete Columns with Shape Memory Alloys Reinforcement," ACI Structural Journal, Vol. 103, No. 3, pp. 436-443.

(24) Saiidi, M. O'Brien, M. Sadrossadat-Zadeh, M. (2009). "Exploratory Study of Seismic Response of Concrete Columns with Shape Memory Alloys Reinforcement," ACI Structural Journal, Vol. 106, No. 1, pp. 69-77.

(25) Noguez, C. Saiidi, M. (2012). "Shake-Table Studies of a Four-Span Bridge Model with Advanced Materials," Journal of Structural Engineering, Vol. 138, No. 2, pp. 183-192.

(26) Mohammad, L. N., Elseifi, M. A., Bae, A., Patel, N., Button, J., Scherocman, J. A. (2012). "Optimization of Tack Coat for HMA Placement," NCHRP Report No. 712, Transportation Research Board, Washington, D.C.

(27) Hajj, E. Y., Sebaaly, P. E., Porras, J. D., Azofeifa, J. P. C. (2011). "Reflective Cracking of Flexible Pavements, Phase III: Laboratory Evaluation," Research Report No. 13KJ-2, Nevada DOT, Research Division, Carson City, NV.

(28) American Assoication of State Highways Transportation Officials (AASHTO), 1998, LRFD Bridge Design Specifications, Washington D.C.

(29) FHWA. JSLAB-2004 user's manual (upgrade supplement). Prepared by Galaxy Scientific Co. for Federal Highway Administration; 2004. 49p.