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Evaluation of a Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composite for a Thin-Bonded Pavement Overlay

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16. Abstract (Limit: 250 words)

A need arose at the MnROAD research facility to provide a thin beam structural overlay on a moderately deteriorated concrete pavement test cell. This research was done to evaluate a polyvinyl alcohol fiber reinforced engineered cementitious composite (PVA-ECC) and assess the prospects to utilize the material in the bonded pavement overlay. PVA-ECC is a ductile material that can achieve extremely high flexural strength and tensile strain capacity, characteristics which can prevent reflective cracking in pavement. The PVA-ECC mix was tailored by including coarse aggregate to maintain some of the benefits of typical concrete pavements. Workability, flexural and compressive strength, ductility and durability tests were done to assess the performance at varying fiber contents. Results show that fiber at 16 lbs/cy achieved the highest flexural and compressive strength, at 1030 and 6910 psi respectively. The paired student's t-test shows that 16 lbs/cy of fiber can improve flexural strength by between 150 and 300 psi with 95% confidence. This small increase and lack of any noticeable ductile behavior do not make the PVA-ECC beneficial for overlay applications. This research found that the modified PVA-ECC with the low doses of fiber examined in this study are not suitable for the overlay at MnROAD.

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EXECUTIVE SUMMARY

This research project was done to evaluate a tailored polyvinyl alcohol fiber reinforced engineered cementitious composite (PVA-ECC) and assess the prospects to utilize the material in a thin-bonded pavement overlay. ECC consists of a high content of cement and fly ash, water, and fine sand reinforced by short-discontinuous fibers. As a composite, PVA-ECC is a ductile material that can achieve extremely high flexural strength and tensile strain capacity, characteristics which can prevent reflective cracking in pavement overlays. The tailored PVA-ECC investigated in this study included coarse aggregate to maintain some of the benefits of typical concrete pavements that are compromised in true ECC, such as reduced scaling and surface deterioration.

This study investigated rheological and mechanical properties of a PVA-ECC mix at varying fiber contents. Workability and rheological characteristics of the different mixes were used to assess the ease of placing and finishing. Effect of the varying fiber contents was determined by flexural strength, compressive strength, and freeze-thaw durability tests. A linear variable differential transformer (LVDT) was used to gauge the ductility of the material under bending.

Different fiber contents used in the trial batches ranging from 0 to 24 lbs/yd^3 produced highly variable results. Flexural strength and compressive strength was also found to fluctuate within a single mix. Statistical analysis was performed with results from laboratory testing to determine the influence of the PVA fibers at different fiber contents. Results show that fiber content at 16 lbs/cy was able to achieve the highest flexural and compressive strength within the range of fiber contents used in this study. The paired student’s t-test shows that 16 lbs/cy of fiber was able to improve flexural strength by between 150 and 300 psi compared to the control with 95% confidence. Despite this improvement, the modified PVA-ECC was only able to achieve a maximum flexural strength of 1030 psi and was unable to demonstrate any noticeable ductile behavior.

Results from this study conclude that modified PVA-ECC at fiber contents between 0 and 24 lbs/cy does not achieve the necessary properties to be considered beneficial for a thin-bonded overlay. Further investigation should be done to evaluate a wider range of fiber contents. More samples from each mix should be prepared to support more significant statistical analysis.

1 INTRODUCTION

MnROAD is the Minnesota Department of Transportation's cold weather pavement test facility used to research innovative materials and pavement types. The facility consists of more than 50 test cells on both a low volume roadway and interstate highway. Recent observation of one concrete pavement cell showed moderate distress and cracking. This cell consisted of four and five inch overlay over existing PCC with skewed joints at 15 foot spacing. The current overlay was not reinforced with dowels and was surfaced with a traditional pavement grind. This study was intended to develop an overlay with minimal structural thickness and sufficient strength an ductility to bridge over the discontinuities and distress in the pavement. This new overlay was to be a cost effective and efficient means of repair for the deteriorated cell.

Concrete overlays have become a widely used method of rehabilitating deteriorated and cracked pavement. Overlays are considered an appropriate solution when the existing pavement experiences moderate to high distress, causing typical resurfacing techniques to become expensive and unreliable. Bonded concrete overlays are generally very thin and are placed directly on the existing pavement.

This study was intended to investigate the prospects for using a modified engineered cementitious composite (ECC) as a thin (one and a half inch), flexible, bonded overlay. To be considered an effective means of repair, the modified ECC would need to achieve high flexural strength and toughness, and show ductile properties under loading. The material must maintain construction feasibility and be able to reach high strengths at early ages to facilitate short traffic diversion times. Finally, the material must provide these properties at reasonably low costs to be an economical solution to deteriorated pavements.

One identifying component of ECC is short, discontinuous fibers. Polyvinyl alcohol (PVA) fiber, a newly developed high performance fiber, is used in ECC to help achieve high tensile strain capacity, toughness and structural integrity that is vital to pavement overlays. The design of the modified ECC to be studied in this research included PVA fibers; however, other mix components and proportions were altered to more closely follow standard concrete pavement design. This was done in hope of gaining the benefits of PVA-ECC, including tensile ductility and high flexural strength, while still maintaining important performance characteristics of conventional concrete pavement.

This report includes background knowledge on the properties and mechanics of PVA-EC, the design process of the modified PVA-ECC, a description of the laboratory tests performed a summary of the results, statistical analysis of the results and recommendations that were formed from the findings.

2 STATE OF THE ART

Engineered cementitious composites were first developed by researchers at the University of Michigan Advanced Materials Research Laboratory. ECC is comprised of a high content of cement and fly ash along with water, fine sand, and fiber. Polyvinyl alcohol fibers are short discontinuous fibers made from organic material. They are considered structural fibers due to their high modulus of elasticity and tensile strain capacity. The unique microstructure of PVA fiber causes the formation of a strong bond with the cementitious matrix [1]. This requires much consideration throughout the design process to obtain the high ductile behavior of the composite. The unique combination of materials in PVA-ECC forms a composite that has proven to achieve a tensile train capacity of more than 3%, flexural strength greater than 2,000 psi, compressive strength over 10,000 psi, and tensile strength near 750 psi [1]. These high strengths are extremely advantageous in pavement by allowing earlier opening times for traffic.

The ductile behavior of PVA-ECC can be attributed to the ability of ECC to exhibit strain hardening. This phenomenon, typically found in ductile metals, is achieved by the formation of numerous tightly spaced micro-cracks [2]. This microcracking allows ECC to continue carrying load far beyond the first crack formation. The micro cracks are less than 60 micrometers in width, making ECC an ideal candidate for pavement applications. This very small crack width allows the ECC to maintain low permeability, improving pavement durability and reducing the ingress of moisture and other adverse liquids.

ECC has many benefits when considering thin-bonded overlays besides increased strength and reduced water penetration as described above. Overlays that are placed directly on existing substrate form a bond with the old pavement which has already undergone shrinkage. When the new overlay material experiences initial shrinkage it will be restrained by the bond with the substrate and subjected to tensile stresses. Similar compressive and tensile stresses are also caused by temperature changes. These stresses are most extreme around existing joints and cracks. These stresses cause the formation of new cracks in the overlay at the joint location, a behavior known as reflective cracking. Traffic loading over existing joints leads to bending stresses in the overlay and variable deformation between the layers, another cause of reflective cracking. The prevention of reflective cracking is one of the major challenges in bonded overlays. However, study has shown increased load carrying capacity and deformability in flexure in PVA-ECC when used as an overlay [3]. Microcracking and increased strength can eliminate reflective cracking, reduce surface deterioration and extend the pavement service life.

Despite all the advantages of PVA-ECC described above, it can still provide some obstacles for applications where strict specifications limit the extent of deviation from conventional PCC. Most importantly, ECC does not include any coarse aggregate, which provides a challenge when considering pavement applications. Coarse aggregate is crucial to pavement durability, as it reduces the amount of scaling and surface deterioration. However, coarse aggregate is believed to interfere with the complex composite mechanical performance. This concept is based on the assumption that the increase in fracture toughness from the coarse aggregate will reduce the desired ductile behavior of the composite [4]. Also important is the fact that ECC achieves stiffness and consistency similar to conventional concrete from the fibers. Adding coarse aggregate to the mix is expected to reduce workability and make finishing difficult.

In summary, the ductile and high strength properties of PVA-ECC make it an ideal candidate for an overlay material, and even with the addition of coarse aggregate, could be a suitable solution for the deteriorated test cell at MnROAD.

3 MODIFIED PVA-ECC MIX CONSIDERATIONS

This section describes the materials used in the PVA-ECC composite and discusses the mix design process used to develop the modified mix. This research was intended to investigate the performance of a modified PVA-ECC to be used in a bonded pavement overlay. This modified PVA-ECC included small coarse aggregate, unlike typical ECC which is mortar based. Inclusion of the coarse aggregate was intended to preserve important pavement characteristics such as resistance to scaling, abrasion, and deterioration; and to maintain consistency with standard specifications for concrete pavement construction. PVA-ECC utilizes low fiber contents, typically less than 2% by volume. However it was recognized that utilizing small coarse aggregate along with fiber, even at these low contents, could produce an un-workable mix for pavement applications. This study was done to evaluate the performance of PVA-ECC at minimal fiber contents, from 0 to 1%, where mixing, placing and finishing of the concrete is not drastically affected. These low fiber contents will also reduce costs and make the material an economically feasible repair method. The intent was to determine if this modified mix could still obtain some benefit of true ECC, such as ductility and high flexural strength, which would provide an effective overlay for deteriorated pavements.

3.1 Material Properties

The table below summarizes the materials used in this study.

Table 1: Material Properties

Coarse Aggregate	
Type	Pea Rock
Source	Meridian Quarry, St. Cloud MN
Gradation	CA-80
Max Size	3/8 in
BSG (SSD)	2.7
Fine Aggregate	
Type	Ottawa Sand
Source	Agg. Industries, Elk River MN
Fineness Modulus	2.63
Absorption Capacity	0.40%
BSG (SSD)	2.65
Cement	
Type	Type I Portland Cement
Source	Lafarge Davenport
SG	3.15
Fly Ash	
Type	ASTM Class F
Source	Coal Creek
SG	2.8

Two different PVA fibers were to be used in the composite. RCS15 fibers are very fine, flexible fibers that are expected to facilitate the formation of the small microcracks and ductile behavior of PVA-ECC. RF400 fibers are much longer and thicker than the RCS15. Because of the stiffness of the RF400, they are considered a structural fiber and contribute to the high flexural and compressive strength of PVA-ECC. The material properties of each fiber are listed in the table below.

Table 2: Fiber Properties

Fiber Name	RCS15	RF4000
Manufacturer	Nycon	Nycon
Material	Polyvinyl Alcohol	Polyvinyl Alcohol
Configuration	Resin-bundled chopped fiber	Chopped fiber
Color	White or yellowish white	Yellowish white
Specific Gravity	1.3	1.3
Length	1/3" (8mm)	1.18" (30mm)
Tensile Strength	203,000 psi (1400 MPa)	130,500 psi (0.9GPa)
Chemical Stability	Stable	Stable
Absorption	Minimal	Minimal

Figure 1: RCS15 (left) and RF400 (right) [5]

Aggregate was chosen to most closely reflect that in true ECC, while still meeting Mn/DOT standard concrete pavement specifications. The coarse aggregate had a maximum size of 3/8 inch and fit into the CA-80 gradation band. The coarse aggregate test report and description is included in appendix A. The fine aggregate in this mix had a fineness modulus of 2.65 with an absorption of 0.4%. The fine aggregate test report showing the gradation and Mn/DOT specified limits is also shown in appendix A.

3.2 Mix Design

The water to cement ratio is crucial in determining the strength of the composite. A low water to cement ratio in PVA-ECC is expected to increase the strength of the mix along with promoting even fiber distribution and mixture consistency [1]. However, bringing this ratio too low could reduce the workability of the concrete, which is already at risk due to the addition of the coarse aggregate. The modified ECC mix was to have a slump between zero and two inches. A water to cement ratio of 0.32 was believed to achieve the best balance between strength and workability. Chemical admixtures were used to obtain rheological properties that are more desirable to pavement overlays. A mid-range superplastizer was used to accommodate the low water to cement ratio. Finally, air entertainer was added to ensure adequate freeze thaw durability. The mix design used a standard Mn/DOT target air content of 6.5%.

ECC is a mortar based composite and typically has around 2 to 3 times more cementitious material than conventional concrete [6]. The modified mix contains a cementitious content much higher than common concrete pavements but is still within the limits Mn/DOT's specifications. Another identifying property of PVA-ECC is an extremely large fraction of pozzolanic material. The range of fly ash content which is considered optimum varies between different experimental results. Some PVA-ECC mixes replace cement with fly ash at a ratio of 2 to 1 (fly ash to cement), while others have found 1.2 to 1 provides the best overall performance [1]. There are many theories on the influence of fly ash in PVA-ECC. Some believe that Fly Ash reduces the bond strength between the fibers and matrix, allowing the fibers to pullout rather than rupture at small crack openings. This ultimately increases the ductility of the composite. The addition of fly ash is also expected to improve the workability of the mix, one of the major challenges imposed by adding coarse aggregate. Because this study was intended to develop a modified mix for a pavement overlay, it was important to consider extended traffic diversion due to delayed strength gain from the addition of fly ash. The original design utilized a 45 percent by weight substitution of fly ash for cement, about 0.8 to 1 fly ash to cement. After this mix tested inadequate strength for the proposed pavement application, the fly ash was reduced to 30 percent by weight (0.4 to 1 fly ash to cement) and used throughout the extent of the project.

The table below shows the mix design derived from the major considerations discussed above.

Table 3: Mix Design

Component	lb / cy	Weight Fraction
Coarse Aggregate (SSD)	1465	0.38
Fine Aggregate (Stock)	1240	0.32
Cement	625	0.16
Fly Ash	265	0.07
Water	270	0.07

The ratio of materials listed above was kept constant upon the addition of fibers. The fiber content was to be varied between 0 to 25 lbs/cy. This range was suggested as a starting point by the fiber manufacturer. A fiber content of 25 lbs/cy corresponds to around 1.1% percent by volume of fiber. Since true PVA-ECC utilizes fiber content around 2%, 1.1% was considered a reasonable limit when including coarse aggregate. This reduction in fiber was intended to maintain workability and allow proper mixing. The total fiber would consist of half RCS15 and half RF4000. Further discussion of the procedure will be included in the next section of this report.

Careful attention was taken to select materials with properties that would benefit the rheological and mechanical properties of the final composite. These materials were combined in a mix design with minimal deviation from true ECC in hope to obtain a ductile, high strength composite.

4 EXPERIMENTAL DESIGN

This section discusses the experimental process used to assess the PVA-ECC at different fiber contents. It describes each laboratory test performed to evaluate the performance of the mixes.

4.1 Experimental Design Description

The scope of this study originally included batching and testing five modified PVA-ECC mix designs at varying fiber contents between 0 and 25 lbs/cy. Beams, cylinders, and prisms were made for each mix to be tested for flexural strength, compressive strength and freeze thaw durability. All trail mixing, preparation and moist curing of samples took place at the Mn/DOT Office of Materials and Road Research laboratory. Each mix was batched and poured on separate days. The first batch was done at the low end of the fiber content range, with the intention of increasing the fiber content until a peak was reached. The fiber content to be used in subsequent mixes was chosen based off the workability and results from strength testing of the previous mix. This process was used in hope of determining the fiber content which achieves optimum performance. The mixing was done using a tilting drum mixer. Samples of fresh concrete from each mix were measured for air content, density, and slump, all of which are important contributors to the potential performance as an overlay material. Specimens were moist cured and tested for strength after 7, 14, 21, 28 and 56 days.

4.2 Summary of Tests Performed

Fresh Concrete

- Workability – slump of fresh concrete
    - ASTM C138
- Air Content – pressure method
    - ASTM C231
- Density (Unit Weight)
    - ASTM C18

Hardened Concrete

- Flexural Strength – four point bending
    - ASTM C78
- Compressive Strength – cylinder specimens
    - ASTM C78
- Freeze Thaw Durability – rapid freeze-thaw cycles
    - ASTM C666
- Bond Strength – slant shear
    - ASTM C886
- Finishing and Surface Characteristics – thin test slab on existing pavement
- Ductility and Toughness – four point bending with LVDT sensor

4.3 Flexural Strength

Flexural strength tests were performed at the Mn/DOT Office of Materials and Road Research Laboratory. Flexural strength was tested in accordance with the ASTM C39 standard test method using four point loading. Two different machines were used, as beams at higher fiber contents were expected to exceed the capacity of the manually loaded machine. The pictures below show both the automatic and manual loading equipment.

Figure 2: Four Point Bending – Automatic

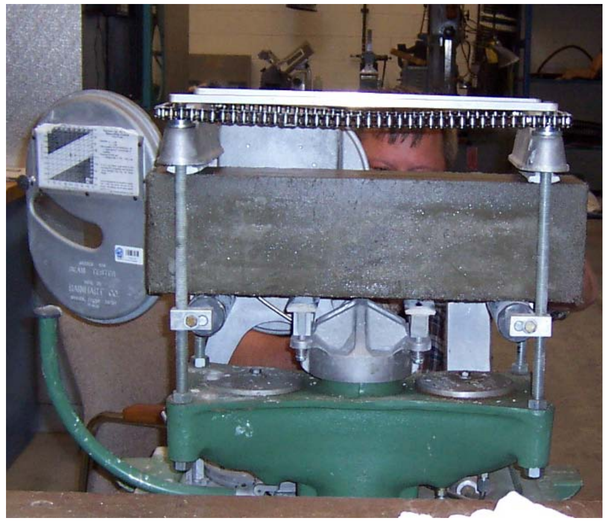

Figure 3: Four Point Bending – Manual

4.4 Compressive Strength

Compressive strength tests were also performed at the Mn/DOT Office of Materials and Road Research Laboratory. Compressive strength was tested according to the ASTM C78 standard test method using molded cylindrical specimens. The picture below shows the equipment used to complete this test.

Figure 4: Compression Test

4.5 Freeze-Thaw Durability

Prisms made for Freeze-Thaw Durability tests were brought to be tested at the American Engineering Testing facility in St. Paul, Minnesota. They were tested in accordance with the ASTM C666 standard test method for measuring freeze-thaw durability. This test method determines the resistance of concrete specimens to continually repeated rapid cycles of freezing and thawing. It simulates the environmentally induced stress the overlay would experience in Minnesota due to the severe seasonal changes.

4.6 Finishing and Surface Characteristics

A test slab was poured on existing pavement and finished with a broom drag, the proposed finish for the overlay. This was done to reveal any difficulties of texturing the surface due to the PVA fibers. The slab then was treated with typical Mn/DOT curing compounds and monitored for any surface cracking or scaling.

4.7 Ductile Behavior

It was presumed that it was difficult to observe any ductile behavior of the material when testing full six by six inch beams for flexural strength because the thickness of the specimens reduces the flexibility of the beam and restrains any noticeable amount of bending. To test this idea, thin beams at about 1.5 inches thick were prepared in the last three batches. A linear variable differential transformer (LVDT) was used to monitor vertical displacement of the beams as they were loaded in four point bending. The test apparatus applied stress to the thin beams at a constant rate. The LVDT was used to test if the resulting vertical displacement, an indicator of tensile strain, would increase with an increase in fiber content. Below are pictures of the equipment used to complete these tests.

Figure 5: LVDT Data Collector

Figure 6: LVDT Sensor

4.8 Bond Strength

Because the PVA-ECC was to be used in a bonded overlay on existing pavement, it was important to assess the bond strength with conventional concrete. Since it is difficult to apply direct tension to concrete specimens, the Slant Shear Test was used to measure the bond strength. In this test, the PVA-ECC is bonded to conventional concrete at an angled plane in a cylinder.

This two layered specimen is tested in compression. Do to the specific angle of the bonded plane and the resulting stresses at the interface layer, the maximum applied compressive load is then the bond strength.

The laboratory test performed in this research involved investigating both fresh concrete properties and mechanical properties to develop a comprehensive understanding of PVA-ECC.

5 RESULTS

This section includes an in depth description of the results obtained from the tests described in section four. The rheological properties are discussed and hardened failed concrete specimens are shown in pictures. The performance of the different mixes in flexural strength, compressive strength, freeze thaw durability and ductile behavior are discussed.

5.1 Result of 45% Fly Ash Substitution

As mentioned in section three, the first mix contained 45% by weight fly ash substitution. The plot below shows the compressive and flexural strength of this mix. The results showed that this fly ash content was too high for the pavement application due to delayed strength gain. This mix had a fiber content around 8 lbs/cy. At this low fiber content, the composite did not gain much stiffness from the fiber. The slump measured 7.5 inches, much higher that the desired 0 to 2 inches. Finishing specimens from this mix also showed plenty of room for additional fiber.

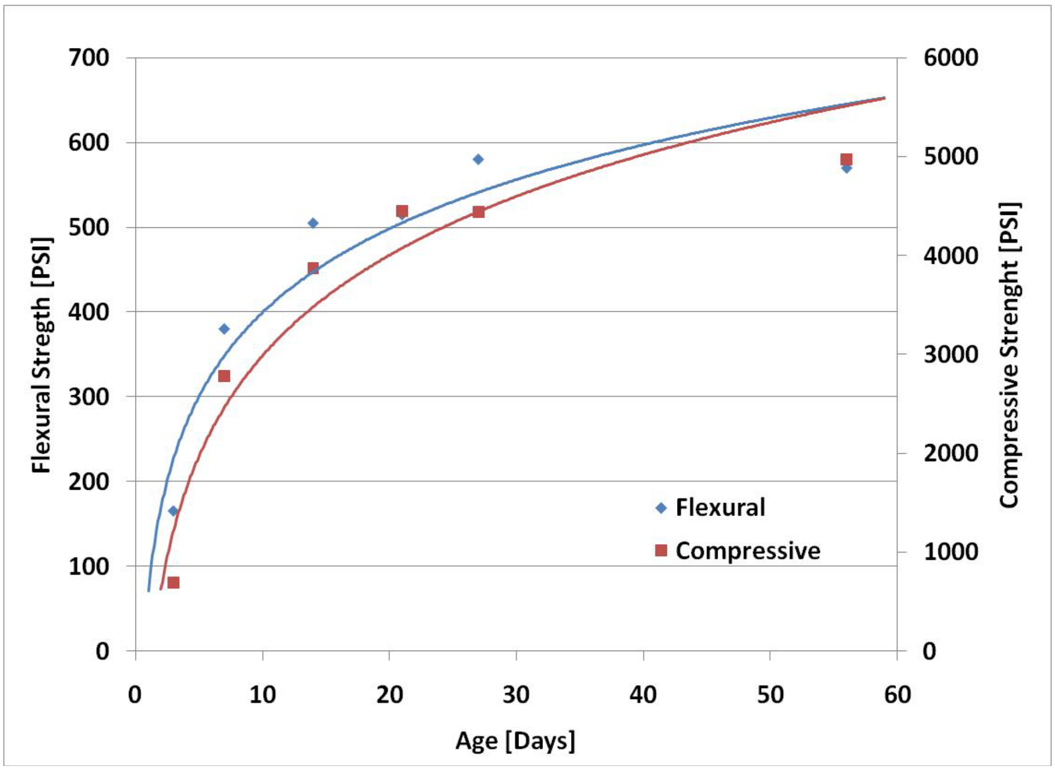

Figure 7: Strength vs. Age at 45% Fly Ash Replacement

5.2 Fiber Content and Rheological Properties

Based off the observations from the first batch, the second batch was to have reduced fly ash, at 30% substitution of cement by weight, along with double the fiber content. Below is a table of the different fiber contents used in the five subsequent batches.

Table 4: Design Fiber Contents

Mix	Fiber Content (lb/yd^3)	Percent Volume
1 (Control)	0	0
2	16	0.77
3	18	0.82
4	22	1.01
5	24	1.09

The table below summarizes some of the rheological properties of the fresh concrete from each batch along with the actual fiber contents that were added adjusted for differences in trim water and air content.

Table 5: Mix Properties

Mix		45% Fly Ash	1	2	3	4	5
Fiber Content	lb/yd^3	8.220	0	16.78	17.95	22.08	23.79
Percent Volume Fiber	%	0.375	0	0.766	0.820	1.008	1.086
Air Content	%	10.0	8.1	4.8	9.7	8.0	3.8
Density	lb/ft^3	134.28	137.84	143.16	134.56	138.60	146.31
Sump	in	7.5	8	0.75	2	1.1	0
w/c		0.32	0.31	0.30	0.32	0.30	0.28

As this table shows, different mixes had extremely variable air content and slump despite the fact that a constant dose of admixture was used and the water to cement ratio was kept close to constant. The water to cement ratio was only slightly variable due to differences in the trim water added to ensure proper mixing. The measured air content did seem to be dependent on fiber content. However, an increase in fiber did generally reduce the slump of the mixture. The control mix, mix number one, had the highest slump of all the mixes despite the fact that mix number 3 had a higher water to cement ratio. The density was also slightly inconsistent across the different mixes but did not show any correlation to the fiber content.

It is important to note some observations made during the batching of the different mixes that may have affected the properties of the mix. In mix three, the mixing drum was very full and made it difficult to ensure the batch had been adequately mixed. The fiber was added after the rest of the materials had been mixed, which leads to the possibility that they were not evenly dispersed. In mix number five, the high fiber content and minimal amount of trim water that was added also made it difficult to mix.

5.3 Failed Specimens

The pictures below show the modified PVA-ECC beams and cylinders after failure. They illustrate the typical failure patterns of the specimens, along with the variation in fiber contents used in the different mixes. Examination of the failed specimens found that the fibers were fairly evenly dispersed and randomly oriented, aligned in both the transverse and longitudinal directions. The beams typically failed within the center third of the beam, indicating failure by flexure versus shear. The prisms most commonly failed in shear, with the exception of a few specimens which showed cone shear or crumbled under loading.

	
Figure 8: Shear Failure	**Figure 9: Cone Shear Failure**

	
Figure 10: Beam Failure Example 1	**Figure 11: Beam Failure Example 2**

5.4 Flexural Strength Results

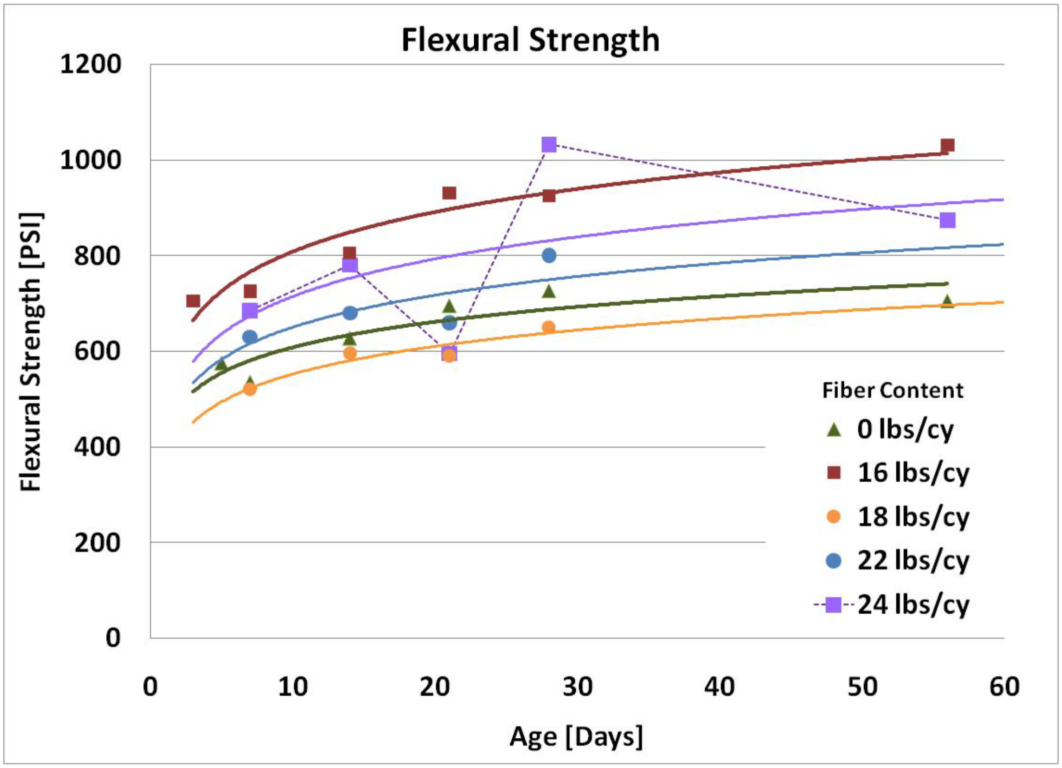

Figure 12: Flexural Strength vs. Age – All Mixes

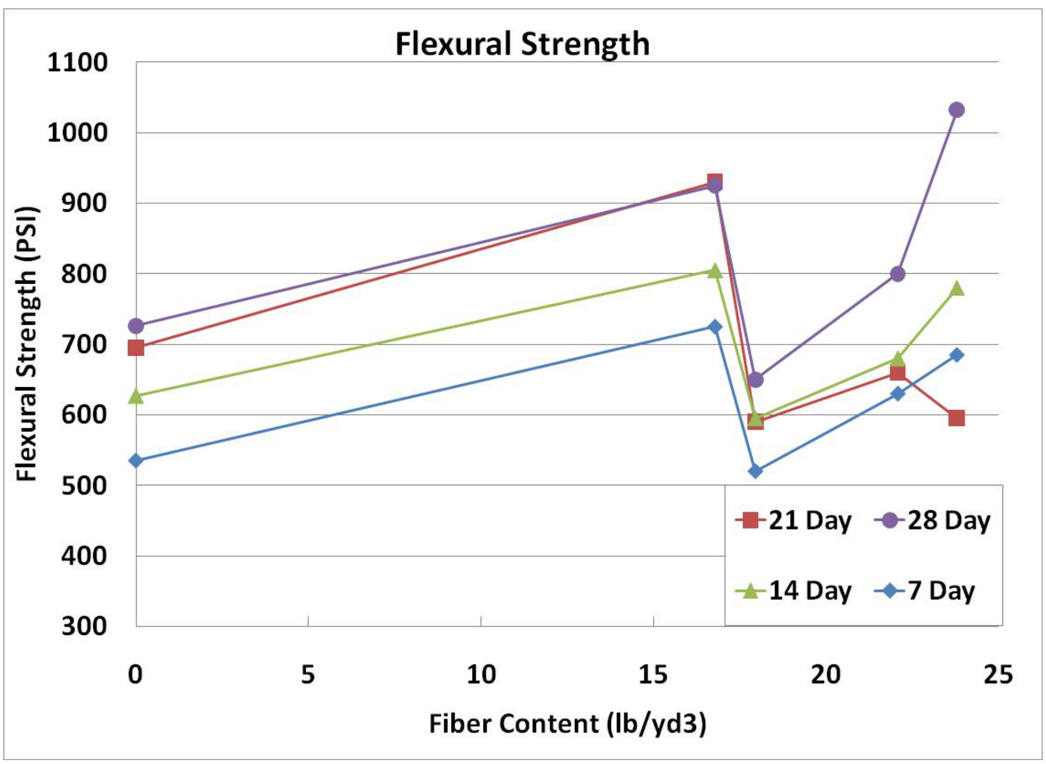

Figure 13: Flexural Strength vs. Fiber Content – All Mixes

5.5 Compressive Strength Results

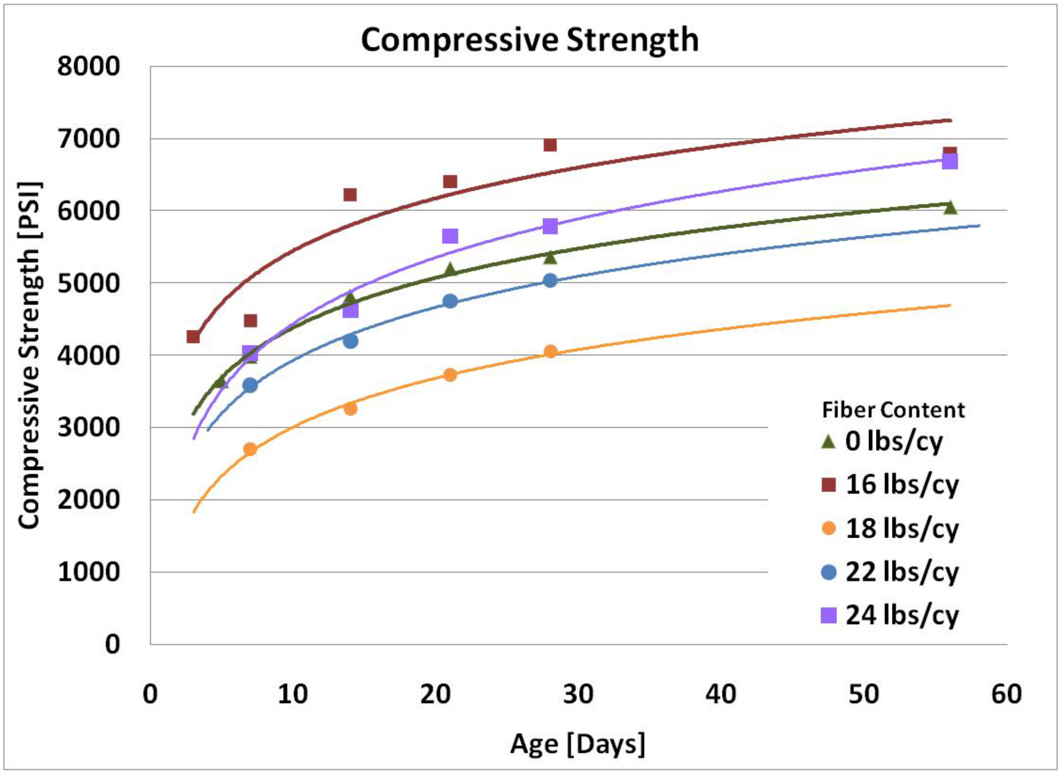

Figure 14: Compressive Strength vs. Age – All Mixes

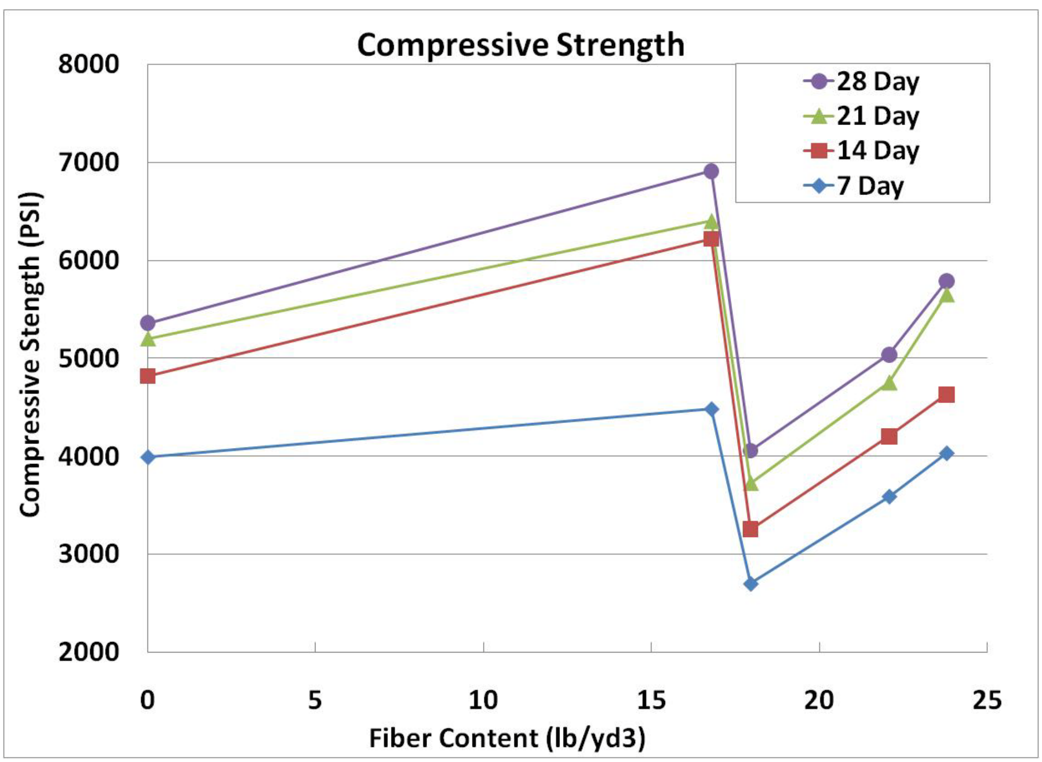

Figure 15: Compressive Strength vs. Fiber Content – All Mixes

5.6 Flexural and Compressive Strength: Comparison and Trends

The plots above illustrate the complex, and unpredictable, behavior of the tailored PVA-ECC material studied in this research. Both flexural and compressive strength increased from the control when fiber was added at 16 lbs/cy in mix two. This increase was visible in all days that the specimens were tested. When fiber was increased to 18 lbs/cy in mix three, there was a drastic decrease in both flexural and compressive. At 18 lbs/cy, the strength was even less than the control, which suggested that addition of fiber past this point was detrimental to performance. This drop in strength led to the belief that the optimum fiber content was around 16 lbs/cy. To test this idea, 22 lbs/cy was added to mix four, which was expected to achieve the lowest strength of the four mixes. In contrast, there was actually a consistent increase in strength from 18 lbs/cy to 22 lbs/cy. Still, at 22 lbs/cy strength was usually always lower than the control. The final mix at 24 lbs/cy showed extremely variable results. At 21 days, this mix achieved the lowest flexural strength of all the mixes, but then jumped to reach the maximum strength at 28 days. Compressive strength, however, was consistently between that at zero and 16 lbs/cy.

Of the five different mixes at varying fiber contents tested in this study, mix two at 16 lbs/cy reached the highest flexural and compressive strength. This mix achieved a maximum flexural strength of 1030 psi at 56 days and a maximum compressive strength of 6910 psi at 28 days. When compared to the control mix with zero fiber, there was an increase in flexural strength of about 300 psi and an increase in compressive strength around 900 psi. Despite this increase, the strength at this optimum fiber content is considerably less than that found in true PVA-ECC.

5.7 Freeze-Thaw Durability Results

The table below provides the freeze thaw results from laboratory testing at American Engineering Testing. Freeze thaw tests were done on the first batch with high fly ash replacement, the control batch, and 16 lbs/cy of fiber.

Table 6: Freeze Thaw Results

Mix	High Fly Ash	1	2
Percent Fly Ash Replacement (%)	45	30	30
Fiber Content (lb/cy)	8	0	13
Durability Factor	92.3	91.3	89.3

AET found all three mixes to have good freeze-thaw durability. The results do not suggest that fibers may influence or improve freeze thaw durability. However, results show that the PVA-ECC tested in this study will provide adequate freeze-thaw durability for Minnesota roads. The full test reports are provided in appendix B, where mix name PVA-1 refers to the high fly ash batch, PVA-2 corresponds to the 16 lbs/cy batch, and PVA-3 is the control batch.

5.8 Finishing and Surface Characteristic Results

The test slab did not showed a moderate amount of difficulty for finishing using a broom drag. The broom did tend to get clogged with small clumps of fibers and had to be cleaned intermittently. Curing using typical Mn/DOT curing compounds did seem effective for the PVA-ECC mix.

5.9 LVDT Results for Ductile Behavior

Below are the displacement plots of the data collected from the LVDT sensors used on the thin slabs. The displacement at failure can be taken as the point where displacement reaches a plateau followed by a significant increase in the displacement rate. The thin beams did not display any significant bending under loading. One beam was tested at 3 days to gauge if the material could achieve any ductility or tensile capacity at an early age which is crucial to pavement applications. The beam failed almost instantly, only reaching a vertical displacement of 0.005 before cracking. Both 18 lbs/cy and 24 lbs/cy showed a vertical displacement at the center point around 0.03 inches at 28, 14, and 21 days. The slabs with 22 lbs/cy tested at 21 days showed a vertical displacement of 0.15 inches. At this displacement the beam would have experienced a moderate degree of bending, although it is possible that it failed much sooner than the visible kink in the displacement.

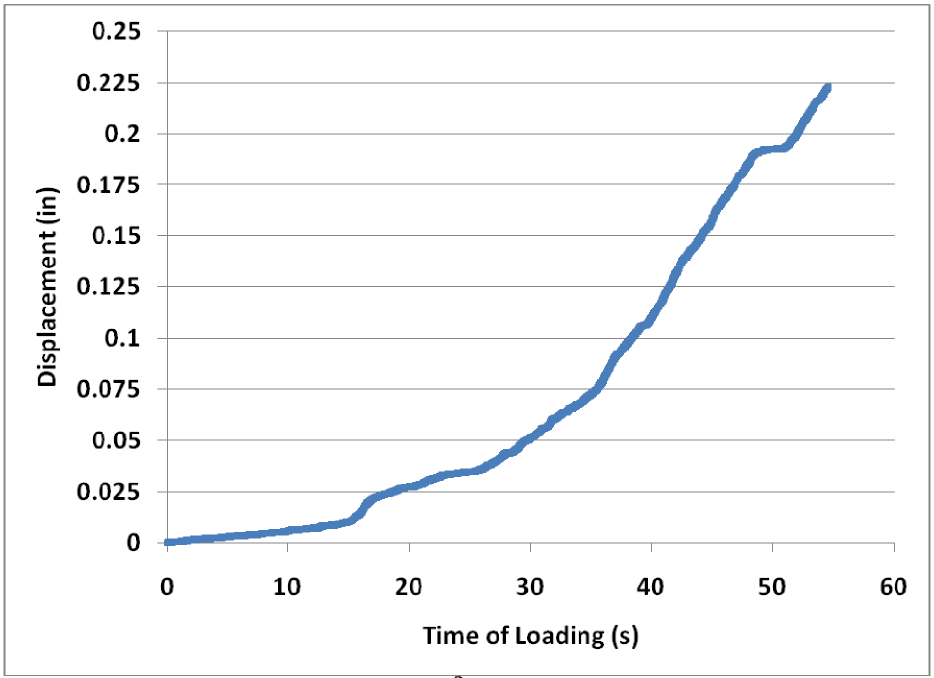

Figure 16: 24 lb/yd^3 – 28 Day Thin Slab

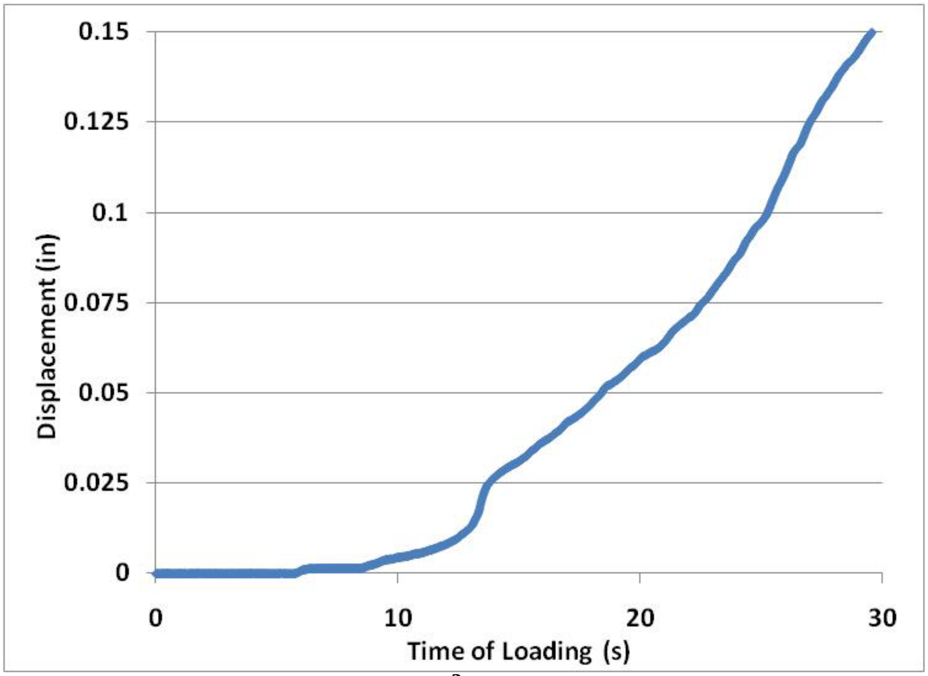

Figure 17: 24 lb/yd^3 – 14 Day Thin Slab

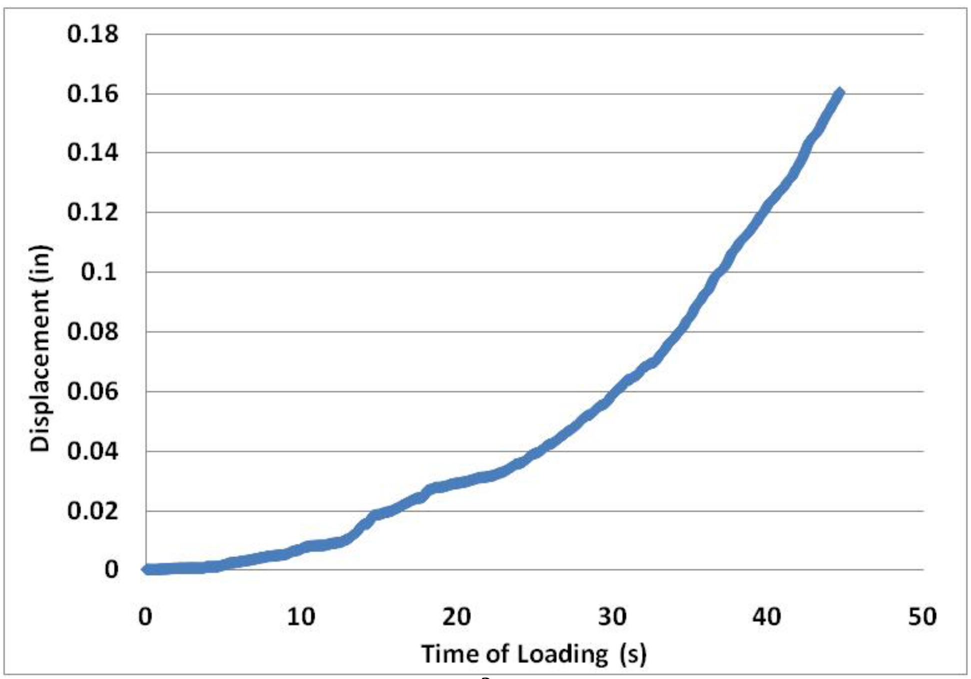

Figure 18: 18 lb/yd^3 – 7 Day Thin Slab

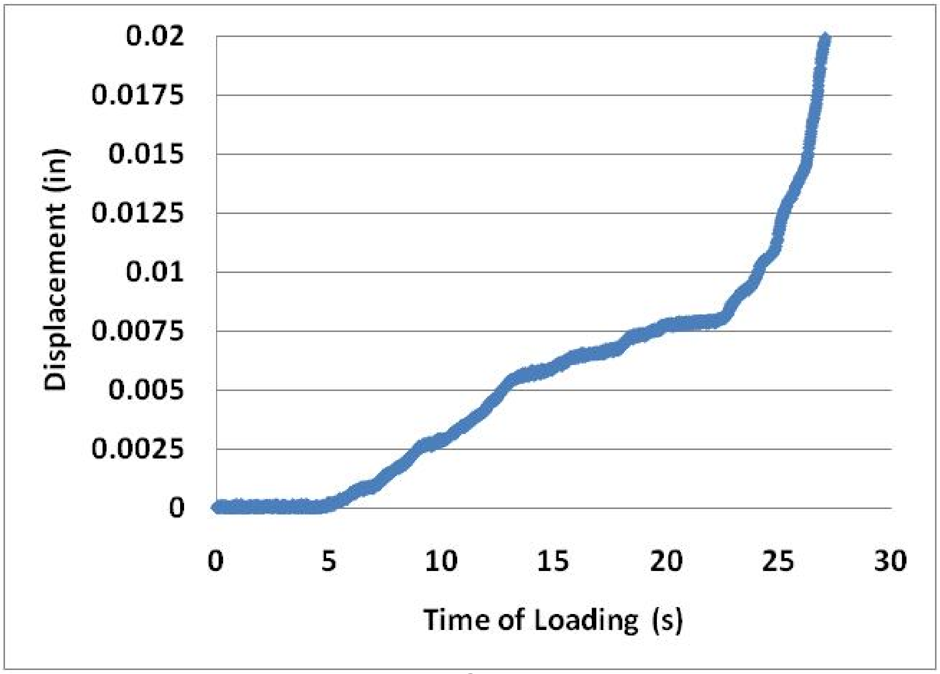

Figure 19: 18 lb/yd^3 – 3 Day Thin Slab

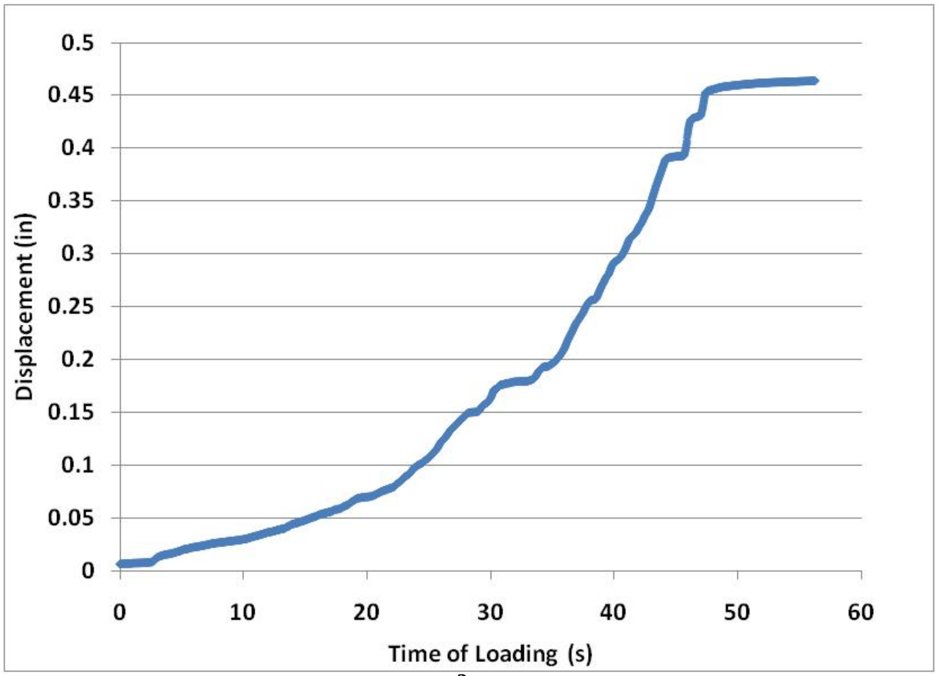

Figure 20: 22 lb/yd^3 – 21 Day Thin Slab

Although the LVDT data did not provide any significant insight on the flexibility of the material, examining the failed thin beams did show some benefit from the fibers. The pictures below illustrate how the fibers did not rupture at the crack location. Instead they were able to hold the crack together and maintain the structural integrity of the beam. This suggests that although the fibers may not prevent large cracks from forming as they do in true ECC, they may help keep the cracks tighter.

Figure 21: Thin Beam Failure 1

Figure 22: Thin Beam Failure 2

5.10 Bond Strength Results

The bond strength from the slant shear test was 1200 psi. This is considered a reasonably high strength for a concrete to concrete bond. The slant shear specimen in shown in figure 15 experienced some crumbling around the base of the plain concrete. The failed plain concrete portion of the cylinder is shown on the right. This could have lead to premature failure, in which case the bond strength would actually be higher than the measured 1200 psi. Regardless, this bond strength is adequate for a bonded overlay application.

Figure 23: Failed Slant Shear Specimen

The results described above obtained from the laboratory testing in this study provided much insight on the performance and unpredictable behavior of the modified PVA-ECC mix.

6 INTERPRETATION AND ANALYSIS OF RESULTS

This section summarizes any meaningful findings inferred from the results in section five. It includes a discussion of possible sources of experimental error that may have influenced the results. Non-Linear regression is used to derive the relationship between flexural and compressive strength of PVA-ECC. Finally, a statistical analysis is done to further investigate the effect of fiber content on the flexural and compressive strength of the composite.

6.1 Interpretation of Fluctuation in Results

As the plots in the previous section show, the relationship between fiber content and strength did not follow any clear trend for either flexural or compressive strength. Although the strength did peak at 16 lbs/cy of fiber, the subsequent drop followed by an increase at higher fiber contents make it difficult determine if this is the true optimum. Besides the fluctuating trend at increasing fiber contents, the fluctuation within a mix also makes it difficult to evaluate the influence of fiber. For example, flexural strength showed more fluctuation within a mix than compressive strength; a drop in flexural strength was not always mirrored with drop in compressive strength; and a significant increase in flexural strength was not always reflected in compressive strength. These major inconsistencies in the data collected from flexural and compressive strength testing could be the result of many different sources of error throughout the experiment.

6.2 Possible Sources of Error

One suspicion for the observed fluctuation in results is large material variability from one mix to another. Although each component came from a single source throughout all the batches, there may have been variation in the preparation of the material. In particular, the moisture content of the coarse aggregate could have varied across mixes. To achieve a saturated surface dry condition, the stockpile coarse aggregate was soaked in buckets and then allowed to drain. This was not an exact procedure, as the time the aggregate was left to drain varied from batch to batch. Differences in the amount of moisture left in the aggregate could influence the workability and strength of the mix.

Another factor affecting the performance of the different specimens was material variability throughout the mix itself. To produce the volume of concrete needed for each batch, the drum mixer was almost filled to capacity. This proved difficult to ensure that all the components had been evenly incorporated. A large amount of variability within the mix could account for the drop in strength some mixes experienced as they aged. For example, one specimen with less aggregate and more fiber could be stronger at 21 days than a specimen with more aggregate and less fiber at 28 days, despite being from the same batch.

Although material and mix variability could account for these discrepancies, error from the testing equipment may have also contributed. The equipment used for the automatic-loading of the four point bending is very sensitive. Improper alignment of the base can introduce a large amount of error. Because a slight bump could skew the base and misalign the equipment, it is not unlikely that this occurred throughout the extent of testing. The variation in results may also be a consequence of different operators running the equipment.

6.3 Relationship between Flexural and Compressive Strength in PVA-ECC

Figure 15 show the relationship between flexural and compressive strength of the five different mixes tested in this study. It helps illustrate how fiber content affects the two properties differently. The first important observation of this plot is that all points from fiber reinforced mixes fall above the control mix except one. This suggests that a mix with fiber at a certain compressive strength will achieve a higher flexural strength than a mix without fiber at the same compressive strength. Because the PVA fibers are primarily used in ECC to increase tensile and flexural strength, the plot shows that the fibers behave similarly even with the use of coarse aggregates. Least-squares regression analysis was used to determine the best fit curve for each fiber content using the common empirical relationship between the flexural strength and compressive strength shown in equation (1).

$$MR = k \times \sqrt{f_c{}'} \qquad (1)$$

$$S_{reg} = \sum_i (y_i - f_i)^2 \qquad (2)$$

$$S_{tot} = \sum_i (y_i - \bar{y})^2 \qquad (3)$$

$$R^2 = 1 - \frac{S_{reg}}{S_{tot}} \qquad (4)$$

In equation (1), $f_c{}'$ is the measured compressive strength and MR is the predicted flexural strength. Extensive research has been done to determine an appropriate value of k for regular Portland Cement concrete, however a range of 9 to 11 (in psi) is usually considered reasonable. [7]

In equations (2) through (4) taken from [8], y_i is the measured value for flexural strength, f_i is the predicted value from equation (1), and $\bar{y}$ is the mean of the measured data. By using the SOLVER function on excel, a k value was determined for each mix that minimizes the sum of the squared differences between the measured and predicted values for flexural strength, or S_{reg} in equation (2). The resulting equations are shown in figure 15. Next, the coefficient of determination, R^2, was calculated for each curve. R^2 values are a measure of goodness of fit, where values closer to one suggest a more accurate model. For all but one mix, R^2 values were at 0.8 or above, implying that the k values are reasonable predictions. The low R^2 for 24 lbs/cy is caused by the large decrease in flexural strength. The k value for the control mix is within the expected range of 9 to 11. Mixes containing fiber have higher k values than the control, with the highest seen at 16 lbs/cy of fiber. This helps support the theory that PVA fibers do contribute to the flexural strength of the concrete and that the observed increase in strength was not only a result of other mix properties such as water content, material properties and mix consistency.

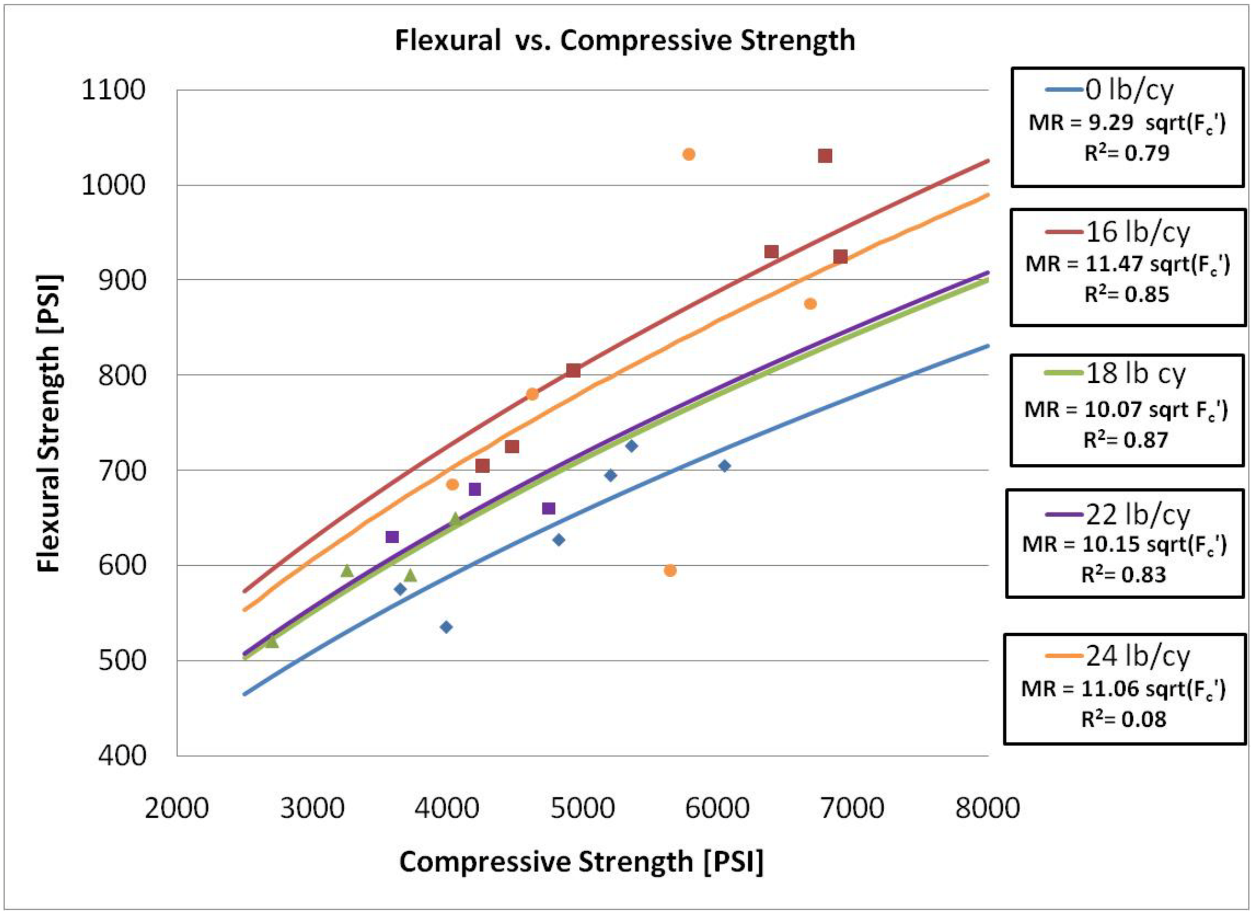

Figure 24: Flexural Strength vs. Compressive Strength – All Mixes

6.4 Statistical Analysis of the Influence of Fiber

Mix number two at 16 lb/cy of fiber achieved optimal compressive and flexural performance and showed the largest benefit in the relationship between flexural and compressive strength. It also did not experience any issues with mixing or display major inconsistencies in results. A statistical analysis compared flexural and compressive strengths from mix two to the control to evaluate the influence of the fibers. The Paired Student's T-Test was used to determine the mean difference in strength between zero and 16 lbs/cy of fiber at 7, 14, 21, 28 and 56 days.

The Student's Paired T-Test was used to test the null hypothesis that concrete with zero fiber will achieve the same strength as concrete with 16 lbs/cy of fiber. The test concluded that the probability that the addition of fiber at 16 lbs/cy will have no impact on flexural strength is 0.05%. A probability of less than 2.5% is considered significant enough to reject the null hypothesis, in which case the test concludes the fibers will have a positive impact on flexural strength.

The test found that flexural strength can be increased by150 psi and 300 psi with 95% confidence with the addition of fibers at 16 lbs/cy. The results for compressive strength are not as promising due to one outlying point at 7 days. The probability that the fibers will have no impact on the compressive strength is 1.6%, which supports that fibers also increase compressive strength. The test found that compressive strength can be increased by 110 to 1500 psi with 95% confidence with the addition of fibers at 16 lbs/cy. The results are summarized in tables 7 and 8.

Table 7: Paired Student's T-Test for Flexural Strength

Flexural Strength difference between 0 and 0.77% Fiber	
Mean Difference	226
95% Confidence Upper Limit	300
95% Confidence Lower Limit	151
Paired T-test One-Tailed Probability for Null Hypothesis (PCC = PVA-ECC)	0.000548
Significance (Smaller than 0.025 for one-tailed is considered significant)	Highly probable that fibers at 16 lbs/cy will increase flexural strength

Table 8: Paired Student's T-Test for Compressive Strength

Compressive Strength difference between 0 and 16 lbs/cy Fiber	
Mean Difference	818
95% Confidence Upper Limit	1524
95% Confidence Lower Limit	112
Paired T-test One-Tailed Probability for Null Hypothesis (PCC = PVA-ECC)	0.0162
Significance (Smaller than 0.025 for one-tailed is considered significant)	Probable that Fibers at 16 lbs/cy will increase compressive strength

Table 9 summarizes the Paired Student's T-Test for all four fiber contents. It tests both possible alternative hypothesis: that fibers increase strength (PVA > PCC) and that fibers decrease strength (PVA < PCC). Although none of the mixes besides 16 lbs/cy show significant results, it is important to note the differences in upper and lower confidence limits.

Table 9: Paired Student's T-Test – All Mixes

Fiber (lb/cy)	16	18	22	24
Alternative Hypothesis	Probability that PVA = PC			
PVA > PCC	0.00055	0.9655	0.1001	0.1136
PVA < PCC	0.99945	0.0345	0.899	0.8864
Mean Difference (PVA - PCC)	225	-57.0	46.8	127.3
Upper 95% Confidence Limit	300	8.28	137	398
Lower 95% Confidence Limit	150	-122	-44.2	-140
Standard Error	26.8	20.5	28.6	84.1

Although analysis performed in this section found that the relationship between flexural and compressive strength was influenced by fiber, statistics show that the increase in strength from fiber is not high enough to be found suitable for the overlay application.

7 CONCLUSIONS

This study consisted of trial batching and performance testing of five different modified PVA-ECC mixes which included coarse aggregate. Listed below are the major findings from this study.

- Within the range of low fiber doses tested in this study, the optimum mix only achieved a minimal increase in flexural strength to the 95% confidence level.
- Statistical Analysis using the paired student's t-test shows there was a significant change in compressive and flexural strength with the addition of fiber in only one out of four mixes.
- Non-linear regression analysis shows the relationship between compressive and flexural strength of PVA-ECC is influenced by the fibers, contributing more to the flexural strength than compressive strength (similar to true ECC).
- Thin beams loaded in flexure did not display any noticeable bending or ductility.
- Fibers in flexural beams did not rupture at failure; instead the pull-out mechanism allowed them to maintain a tight crack width and structural integrity at continued loading.
- The PVA-ECC demonstrated sufficient freeze-thaw durability and bond strength.

Based off the discussion of possible sources of error in the previous section, it is probable that the large fluctuation in strength between the mixes, and within a mix itself, is due to a combination of errors rather than just an adverse interaction between the fiber and aggregate. It is possible that the optimum fiber content for our modified PVA-ECC mix design is not within the range tested in this experiment. Future studies investigating the properties and performance of tailored PVA-ECC like those in this experiment should involve preparing larger batches to allow more meaningful statistical analysis.

In summary, this study was successful in assessing the performance of a tailored PVA-ECC which includes coarse aggregate, and at evaluating the possibility to utilize the material in a thin-bonded overlay. The intent was to determine if this material would demonstrate high flexural strength and ductile behavior which is required to resist reflective cracking. Results and analysis show that the mix design and fiber contents used in this research did not provide such performance. Therefore, the modified PVA-ECC examined in this study is not found suitable for the thin overlay at MnROAD.

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[2] Mo Li and Victor Li. *Behavior of ECC/Concrete Layer Repair System under Drying Shrinkage Conditions.* Advanced Civil Engineering Materials Research Laboratory, Department of Civil and Environmental Engineering. University of Michigan, Ann Arbor, MI. August 2005.

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[4] Jia Huan Yu[1] and Tsung Chan Hou [2]. *Strain and Cracking Surveillance in Engineered Cementitious Composites by Piezoresistive Properties.* [1]School of Civil Engineering, ShenYang Jianzhu University, LiaoNing, China. [2]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI. June 2010.

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APPENDIX A. AGGREGATE GRADATION REPORTS

Coarse Aggregate Gradation Report

State of Minnesota Department of Transportation
Aggregates Test Report
Office of Materials and Road Research
1400 Gervais Avenue
Maplewood, MN 55109

Sample ID Number: CO-CA10-0799 | **Project Number: Research**

Field ID:	FRC 1	Billing Agency:	
Date Sampled:		Project Engineer:	BERNARD
Date Received	08/13/2010	Submitter:	BERNARD
Approved:	8/18/2010 15:49	IAS Name:	
TH Number:		Pit #:	73006
Bridge #:		Pit Name:	Saint Cloud Quarry
Grade Spec:	3137	Pit Owner:	Martin Marietta
Spec Class:		Sampled From:	MN/ROAD STOCKPILE
Quality Spec:	3137.2D2_A	Usage:	PEA ROCK FOR FRC
Plant Name:			
Comment:			

Test Procedures: AASHTO T-19, T-21, T-27(M), T-30(M), T-84(M), T-85(M), T-96(M), T-104(M), T-113(M), T-176(M), T-248(M), T-304 Method A, ASTM C123, ASTM C535, ASTM D3042, ASTM D4791(M), Micro Deval(MP), Percent Crushing(MP) M = MN/DOT Modified MP = MN/DOT Procedures

% Passing Sieve:	Lab Test	Field Test	Spec. Limits Low	Spec. Limits High
9.5mm (3/8")	100			
6.3mm (1/4")	68			
4.75mm (#4)	31			
2.36mm (#8)	5			
2.00mm (#10)	4			
1.18mm (#16)	3			
600um (#30)	2			
425um (#40)	1			
300um (#50)	1			
150um (#100)	1			
75um (#200)	0.6			
%Class A	100.00			

* Value does not meet Spec
~ Value out of Field Lab Tolerance
*** Trace (0.00 - 0.05) Detected
% Shale in Sand N.C. = Trace

☐ Meets Requirements
☐ Does Not Meet Requirements
☒ For Info Only
☐ Incentive/Disincentive

☐ Unable to Verify
☐ Unable to Verify, Not Enough Material Supplied
☐ Within Lab-Field Tolerance
☐ Out of Lab-Field Tolerance

Comments:

Copies To
Project Engineer: BERNARD

Charge: 1 - 1011
1 - 1014

Report Approved By: [signature]

CO-CA10-0799 Ver. 1 | Page 1 of 1 | 8/18/2010 15:49

Fine Aggregate Gradation Report

State of Minnesota Department of Transportation
Aggregates Test Report
Office of Materials and Road Research
1400 Gervais Avenue
Maplewood, MN 55109

Sample ID Number: CO-CA10-0800 **Project Number: Research**

Field ID:	FRC 2	Billing Agency:	
Date Sampled:		Project Engineer:	BERNARD
Date Received	08/13/2010	Submitter:	BERNARD
Approved:	8/20/2010 14:03	IAS Name:	
TH Number:		Pit #:	71041
Bridge #:		Pit Name:	Agg Ind - Elk River
Grade Spec:	3126	Pit Owner:	Aggregate Industries - Elk River
Spec Class:		Sampled From:	MN/ROAD STOCKPILE
Quality Spec:	3126.2C3	Usage:	SAND FOR FRC
Plant Name:			
Comment:			

Test Procedures: AASHTO T-19, T-21, T-27(M), T-30(M), T-84(M), T-85(M), T-96(M), T-104(M), T-113(M), T-176(M), T-248(M), T-304 Method A, ASTM C123, ASTM C535, ASTM D3042, ASTM D4791(M), Micro Deval(MP), Percent Crushing(MP) M = MN/DOT Modified MP = MN/DOT Procedures

% Passing Sieve:	Lab Test	Field Test	Spec. Limits Low	Spec. Limits High
9.5mm (3/8")	100		100	
4.75mm (#4)	100		95	100
2.36mm (#8)	90		80	100
2.00mm (#10)	87			
1.18mm (#16)	76		55	85
600um (#30)	52		30	60
425um (#40)	33			
300um (#50)	17		5	30
150um (#100)	2		0	10
75um (#200)	0.5		0	2.5
Fineness Modulus	2.63		2.45	2.85
% Shale in Sand	0.0		0	2.5

* Value does not meet Spec
~ Value out of Field Lab Tolerance
*** Trace (0.00 - 0.05) Detected
% Shale in Sand N.C. = Trace

- [X] Meets Requirements
- [ ] Does Not Meet Requirements
- [ ] For Info Only
- [ ] Incentive/Disincentive
- [ ] Unable to Verify
- [ ] Unable to Verify, Not Enough Material Supplied
- [ ] Within Lab-Field Tolerance
- [ ] Out of Lab-Field Tolerance

Comments:

Copies To
Concrete Engineer
Project Engineer: BERNARD

Charge: 1 - 1013
1 - 1029

Report Approved By:
David B. Bar[signature]

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APPENDIX B. FREEZE THAW TEST REPORTS

AMERICAN ENGINEERING TESTING, INC.

CONSULTANTS
· ENVIRONMENTAL
· GEOTECHNICAL
· MATERIALS
· FORENSICS

REPORT OF RAPID FREEZING AND THAWING OF CONCRETE

PROJECT:

FREEZE-THAW TESTING
PVA-1

REPORTED TO:

MINNESOTA DEPARTMENT
OF TRANSPORTATION
1400 GERVAIS AVENUE
MAPLEWOOD, MN 55109

ATTN: ALLY AKKARI

AET PROJECT NO: 29-00576

DATE: JANUARY 12, 2011

INTRODUCTION

This report presents the results of recent freeze-thaw testing. Our work was requested and authorized by Ally Akkari of the Minnesota Department of Transportation. The scope of our work was limited to performing freeze-thaw testing on three concrete prisms and reporting the results.

SAMPLE PROCUREMENT

The concrete prisms were received on October 22, 2010. The samples were cast on October 14, 2010 by Minnesota Department of transportation personnel.

TEST PROCEDURES

The samples were placed in our 100% humidity curing room until the samples reached 28 days old. Testing was performed from November 11, 2010 through December 30, 2010. The three prisms were tested in accordance with Procedure A of ASTM:C666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," with the exception of length change. Readings were not possible because the prisms were cast without comparator pins in the ends.

TEST RESULTS

Cycles Completed		Sample ID		
		A	B	C
33	Weight, loss %	.01	.01	.02
	RDME, %	100	100	100
67	Weight, loss %	.04	.05	.06
	RDME, %	100	100	100
99	Weight, loss %	.05	.07	.08
	RDME, %	99	100	99
132	Weight, loss %	.11	.12	.13
	RDME, %	98	99	97

Cycles Completed		Sample ID		
		A	B	C
168	Weight, loss % RDME, %	.17 97	.15 97	.16 96
202	Weight, loss % RDME, %	.19 95	.17 96	.20 96
238	Weight, loss % RDME, %	.21 94	.22 95	.24 94
271	Weight, loss % RDME, %	.24 93	.26 94	.27 93
300	Weight, loss % RDME, %	.26 92	.28 93	.29 92
Durability Factor		92	93	92

REMARKS

The samples were tested to 300 cycles and found to be freeze-thaw durable. Photos after 300 cycles are attached. Should you have any questions regarding this report or if we can be of further assistance, please contact me.

Report Prepared By:
American Engineering Testing, Inc.

Joseph T. Johnson
Engineering Technician III
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Report Reviewed By:
American Engineering Testing, Inc.

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Phone: 651-659-1334
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PHOTOGRAPHS
AET PROJECT NO. 29-00576

Photo 1: After 300 cycles

Photo 2: After 300 cycles

AMERICAN ENGINEERING TESTING, INC.

CONSULTANTS
· ENVIRONMENTAL
· GEOTECHNICAL
· MATERIALS
· FORENSICS

REPORT OF RAPID FREEZING AND THAWING OF CONCRETE

PROJECT:

FREEZE-THAW TESTING
PVA-2 & PVA-3

REPORTED TO:

MINNESOTA DEPARTMENT
OF TRANSPORTATION
1400 GERVAIS AVENUE
MAPLEWOOD, MN 55109

ATTN: ALLY AKKARI

AET PROJECT NO: 29-00576

DATE: FEBRUARY 10, 2011

INTRODUCTION

This report presents the results of recent freeze-thaw testing. Our work was requested and authorized by Ally Akkari of the Minnesota Department of Transportation. The scope of our work was limited to performing freeze-thaw testing on six concrete prisms and reporting the results.

SAMPLE PROCUREMENT

The concrete prisms were received on November 5, 2010. The samples were cast on October 25th (set 2) and 27th (set three), 2010 by Minnesota Department of transportation personnel.

TEST PROCEDURES

The samples were placed in our 100% humidity curing room until the samples reached 28 days old. Testing on set two was performed from November 23, 2010 through February 8, 2011, and set three from November 25 through February 10, 2011. The six prisms were tested in accordance with Procedure A of ASTM:C666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," with the exception of length change. Length change readings were not possible because the prisms were cast without comparator pins in the ends.

TEST RESULTS

Cycles Completed		Sample ID					
		2-A	2-B	2-C	3-A	3-B	3-C
32	Weight, loss %	.03	.01	.02	.01	.00	.01
	RDME, %	100	100	100	100	100	100
66	Weight, loss %	.06	.07	.05	.05	.03	.06
	RDME, %	99	100	99	100	99	100
97	Weight, loss %	.11	.12	.10	.09	.07	.09
	RDME, %	98	99	98	98	97	99

Cycles Completed		Sample ID					
		2-A	2-B	2-C	3-A	3-B	3-C
128	Weight, loss %	.14	.16	.15	.11	.09	.11
	RDME, %	97	97	97	98	97	98
161	Weight, loss %	.19	.21	.18	.14	.11	.13
	RDME, %	95	95	95	96	96	96
194	Weight, loss %	.21	.24	.22	.17	.14	.16
	RDME, %	93	94	93	95	94	95
228	Weight, loss %	.26	.28	.25	.21	.18	.22
	RDME, %	92	93	92	94	93	94
266	Weight, loss %	.36	.33	.31	.25	.22	.26
	RDME, %	90	91	91	92	93	92
300	Weight, loss %	.39	.37	.35	.30	.28	.31
	RDME, %	89	90	89	91	92	91
Durability Factor		89	90	89	91	92	91

REMARKS

The samples were tested to 300 cycles and found to be freeze-thaw durable. Should you have any questions regarding this report or if we can be of further assistance, please contact me.

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