Superhydrophobic Engineered Cementitious Composites for Highway Bridge Applications: Technology Transfer and Implementation

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16. Abstract

The strength and durability of highway bridges are two of the key components in maintaining a high level of freight transportation capacity on the nation's highways. Superhydrophobic engineered cementitious composite (SECC) is a new advanced concrete material with polyvinyl alcohol fibers and hydrophobic compounds. The improved mechanical performance and improved durability of the material was demonstrated in CFIRE projects 04-09 and 05-10. SECC is an effective substitute to conventional concrete than can improve the strength and durability demanded in key regions of highway bridges. This report discusses the technology transfer of the material through the use of technical publications, conference presentations, and creation of a web-based platform dedicated to the material. The implementation of the material as a link slab on a ramp leading to a parking structure is also discussed.

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EXECUTIVE SUMMARY

The United States' infrastructure is in desperate need of repair especially in northern regions that are exposed to harsh freezing and thawing. Components of infrastructure in these regions that are especially prone to deterioration are bridge approach slabs. These elements provide a link between heavily reinforced bridge decks and unreinforced pavements which is often flexible asphalt. These link slabs are exposed to harsh conditions such as exterior forces from differential thermal expansion/contraction of the adjacent slabs, impact forces from vehicles hitting the pavement, from differential rutting, and bending from subgrades that are often unstable because of their proximity to embankments or retaining walls. Moreover, joints form between the adjacent pavements which allow water to enter and thus drastically reduce the lifespan of the material. If a ultra-durable cementitious material is used at the key infrastructure elements which are capable of bending without losing their load carrying capacity, having the ability to dissipate large impact loads, forming little to no joint between the adjacent pavements, and having an engineered air void system to withstand over 500 freeze-thaw cycles, the integrity of bridges will be significantly higher, and the lifespan of these critical infrastructure elements will be significantly longer.

Recent CFIRE projects 04-09 and 05-10 demonstrated the improved mechanical performance and improved durability characteristics of superhydrophobic engineered cementitious composites (SECC). These studies demonstrated that engineered cementitious composites can be produced with high strength matrices and still allow for superior flexural performance. This is possible because the small, well distributed air voids which are created by the addition of superhydrophobic emulsions act as artificial flaws in the cementitious matrix and promote multi-cracking and strain hardening behavior. The use of high strength matrices was not explored in the past as the strength of the cementitious matrix in ECC was typically reduced to allow for better flexural behavior. The higher strength matrices produced also allow for a better durability performance. Moreover, the addition of the superhydrophobic emulsions creates an air void system with ideal properties to resist against several thousand equivalent freeze-thaw cycles as well as reduce water absorption and chloride permeability.

Recent CFIRE reports also discuss the measures taken to produce the most efficient material. Mixing procedure, optimal proportions of materials, and the use of supplementary cementitious materials to provide similar if not better performance at a replacement of 50% were analyzed. Compressive strength, flexural behavior, freeze-thaw resistance, chloride permeability, water absorption, rate of absorption, and air void analysis were tested to analyze ECC/SECC samples while contact angle, droplet size distribution, and zeta potential were used to analyze the characteristics of the superhydrophobic emulsions used for SECC.

Based on the laboratory experiments, it is clear that SECC demonstrates properties that would be ideal for critical infrastructure elements. However, determining the best way to make the switch from laboratory experiments to real world applications is essential; the successful implementation of a new, quality material requires much thought and research to accomplish.

This report focuses on the transfer of information about this project through publications, presentations, and workshops and the implementation of the material by producing a link slab made of SECC on a ramp leading to a parking structure. The benefits of the material are even further promoted through the creation of a dedicated web-platform for the latest information and developments on advanced SECC. Informing other researchers and industry of the benefits of the material opens new options and ideas for the best way to implement the material. Moreover, communicating with industry on the benefits of SECC allows to more interest in the material and better possibilities for application of the material in infrastructure project.

From several conference presentations and workshops, interest in SECC from other researchers and members of industry throughout the world has grown tremendously. The successful completion of a link slab using SECC was accomplished; the performance of the slab will be monitored over several years. The implementation of this link slab is a large step into utilizing SECC in larger infrastructure projects.

1. INTRODUCTION

The strength and durability of highway bridges are two key components in maintaining a high level of freight transportation capacity on the nation's highways [1-5]. The superhydrophobic engineered cement composite (SECC) is a new advanced high performance fiber reinforced concrete (HPFRC) material with polyvinyl alcohol fibers and hydrophobic compounds was developed at UW-Milwaukee with support of NSF, RGI, and CFIRE (projects 04-09/05-10) [6,7]. The reported research work demonstrated that SECC is an advanced substitute to conventional concrete that can provide the strength and durability demanded in the key regions of highway bridges.

Conventional cement-based concrete is brittle and inevitably develops cracks, often due to drying shrinkage during curing, which are further extended after loading and weathering. CFIRE projects 04-09/05-10 provided a strong scientific background on a new generation of SECC fiber-reinforced concrete, with enhanced durability and very large ductility, providing a sustainable material with a service life up to 120 years required for critical parts of concrete infrastructure, especially, the components of highway bridges.

The superhydrophobic hybridization approach [8-10] is a highly effective method for improving the durability of concrete with large volumes of (up to 50%) of mineral additives and by-products used as cement replacement. This alleviates the shortcomings of traditional concrete technologies and, due to the reduction of portland cement dosage and improved concrete durability, the proposed concept provides a paradigm shift in cement and concrete technologies that can serve as a backbone for the sustainable development of the concrete pavement and bridge industries. Indeed, the developed SECC meets the highest sustainability benchmarks and can be used as the next technological platform for sustainable concrete infrastructure with high performance and longer service life.

The design of SECC is based on three principles [7,11]:

1. Micromechanical design of the composite with 1 to 4 % (by volume) of fibers (PVA, high modulus polyethylene, shape memory alloys) in order to realize the ductile strain-hardening performance.

2. Application of small quantities (0.01 to 0.1% of cement weight) of siloxane-based hydrophobic admixtures (e.g., based on polyethyl-/polymethyl-hydrosiloxane, PEHSO) modified by super-fine submicro- or nano-sized materials (such as nano-silica, nano-clay additives or SiO_2-rich reactive powders) and use of an effective superplasticizer to form a controlled air-void structure coated by superhydrophobic layers.

3. Inclusion of selected supplementary cementitious materials (SCMs) in combination with SiO_2-rich reactive powders (silica fume, metakaolin, nano-silica) to decrease cement content and boost the performance sustainability of the material.

The average service life of concrete infrastructure in Wisconsin is 40-50 years, with up to 10% of bridge decks reinforced by uncoated rebar needing replacement after 30 years [3, 12]. Highways, bridges, and other critical transportation infrastructure components are deteriorating due to loading and deformation, aging, de-icing, and other detrimental factors in addition to rebar corrosion [1-5]. Furthermore, the direct costs for roadway improvements are escalating because the price of key materials needed for highway and bridge construction has increased rapidly (~46% from 2004) [2,13]. Indirect costs of highway bridge construction, in the form of environmental damage, are being realized in relation to the production and recycling of basic concrete materials.

The time is right for a new paradigm to address the urgent need for highly durable and sustainable materials to meet the challenges that the state Departments of Transportation (DOT's) and Federal Highway Administration (FHWA) face recently to accommodate the future needs for freight transportation. The developed SECC concrete is a new advanced material required for critical parts of highway bridges and other concrete infrastructure components; which can transform the ways in which state DOT's and engineers build and repair highway infrastructure.

2. BACKGROUND

The durability of concrete bridges is primarily limited by the performance of connection regions or joints between bridge components, especially in decks. A recent CFIRE project investigated the use of precast bridge approach slabs that could reduce the early distress noted in service [14]. The connection between an approach slab and bridge deck, or joints in the bridge deck, or the portion of bridge deck bent in negative curvature above mid-span bridge piers are critical bridge locations (Figure 1) where durability problems are apparent and premature deterioration occurs, thereby resulting in regular maintenance demands or early replacement. A material that does not exhibit early-age shrinkage and cracking and can withstand the deformation demands from truck loading, while providing durability, could be used in these particularly susceptible regions. The feasibility of SECC was proven with CFIRE projects 04-09/05-10 [6,7]. These projects developed advanced superhydrophobic fiber-reinforced concrete material based on the engineered cementitious composite (ECC) concept [11] that helps to overcome the deficiencies of regular concrete used in bridges and pavements: the brittleness (thereby requiring reinforcement to allow deformation without failure) and inadequate durability (thereby requiring frequent repair).

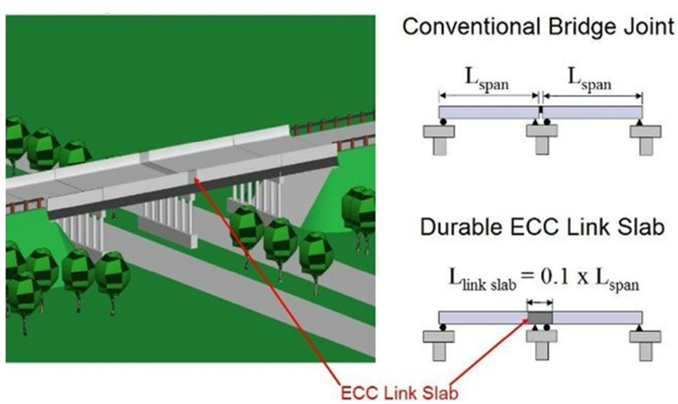

Figure 1: Design for bridge deck link slab retrofit [15]

3. RESULTS OF PHASE I AND II INVESTIGATION

ECC materials, a novel type of HPFRC, may exhibit very ductile performance under tension such as steel [11, 15-19], Figure 2. The strain capacity of ECC can be increased by a factor of

200 (vs. plain concrete) when high-strength reinforcing fibers are three-dimensionally dispersed in the mortar. A variety of fibers, including polymeric, steel and carbon, have been examined [11]. Most recent research has been conducted with high modulus polyethylene (i.e., Spectra 900) or polyvinyl alcohol (PVA Kuralon K-II) fibers. In order to realize multi-cracking fracture and associated strain–hardening response, ECC uses a relatively weak cementitious matrix (optionally, with a large content of fly ash) [11]. This process hinders the application of ECC in severe environmental conditions as a weaker matrix leads to reduced durability properties. Indeed, in addition to improved deformability and crack control, a SECC/HPFRC material providing long-term durability and improved performance at severe environments is highly desired; therefore, combining high-performance cement matrix and bendable ECC is an attractive option.

The CFIRE projects 04-09/05-10 demonstrated the feasibility of a new material based on ECC with superhydrophobic hybridization (SECC). Due to the reduction of portland cement use and improved concrete durability, the proposed concept provides a paradigm shift in cement and concrete that can serve as a backbone for the sustainable development of the concrete industries. Until now, this concept has not been applied to the HPFRC materials. Recent research has demonstrated that superhydrophobic HPFRC effectively controls the initial cracking while providing extreme deformation and strain enhancement, overperforming conventional engineered cementitious composites (ECC) as illustrated in Figure 2 [6]. The superhydrophobic hybridization of concrete engages interdisciplinary work combining biomimetics (lotus effect), chemistry (siloxane polymers such as polyethyl/polymethyl-hydrosiloxane, PESHO/PMHS) and nanotechnology (nano-SiO_2 particles) to resolve the fundamental problems of concrete such as insufficient durability and corrosion resistance [20]. The superhydrophobic action is intended to change the volume, size, and distribution of air voids in the concrete, as well as the bond with PVA fibers to realize the controlled pull-out behavior. Furthermore, the controlled air void structure created by the addition of PESHO admixtures results in preferred strain hardening fracture modes by introducing artificial flaws to initiate multi-cracking behavior, Figure 2.

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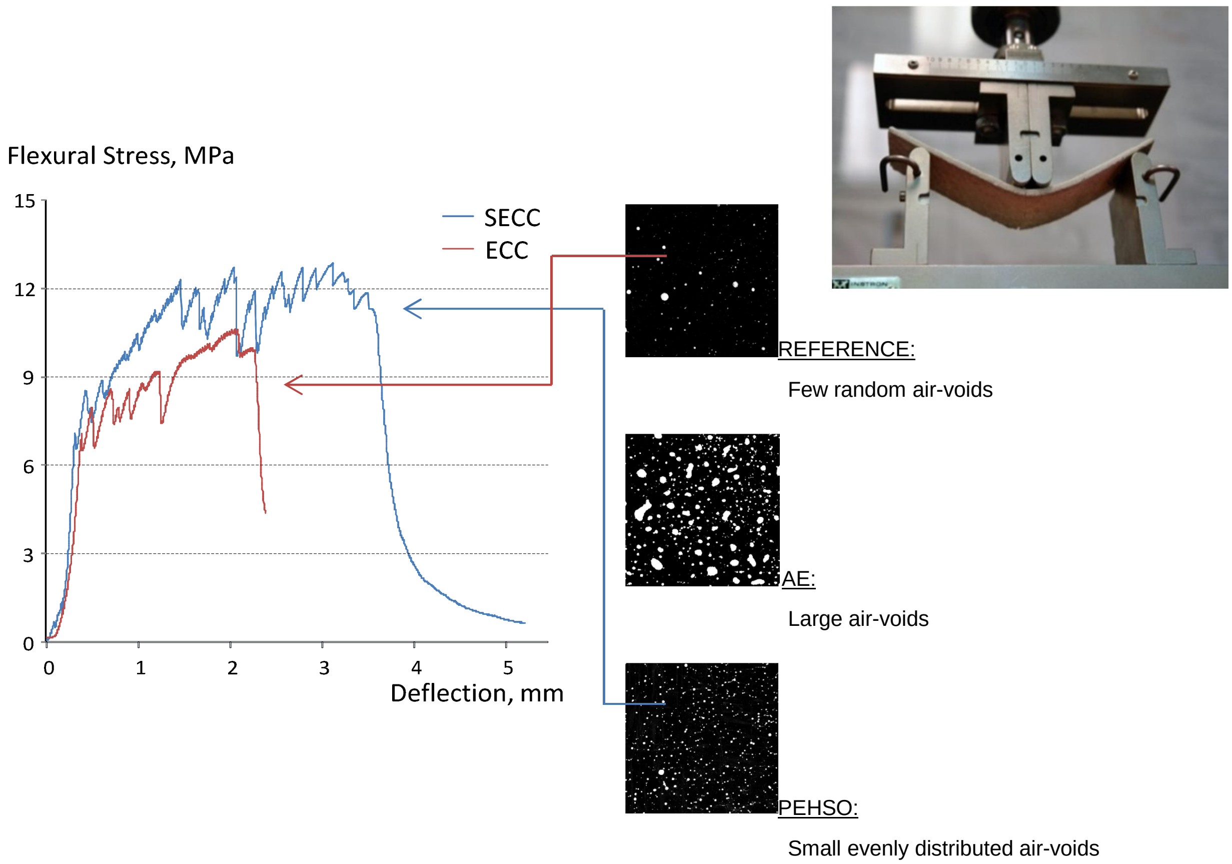


Figure 2: The strain-hardening and improved ductility performance of developed SECC

Superhydrophobic surfaces, or surfaces that have a water contact angle Θ larger than 150°, have generated much interest due to their potential in industrial applications (mainly for self-cleaning), but they have not yet been employed for enhancing concrete durability (Figure 3). In terms of enhancing concrete, this nature-inspired approach can improve the performance of hydrophobic materials that control wettability [9,10]. To manufacture superhydrophobic admixture the hydrogen containing siloxane admixture (e.g., PEHSO) is combined with small quantities of submicro- or nano-sized particles (Figure 3). Here, a modified PEHSO admixture (used at a dosage of 0.01…0.1% of cement weight) releases hydrogen and forms small (10 - 100 μm), uniform air voids evenly distributed within the cement paste (Figure 3). For optimal performance, more than 70% of the PEHSO must be dispersed to the size of less than 1 μm [8]. As a result, the surface of the voids is covered by the hydrophobic particles, providing the effect of superhydrophobic hybridization.

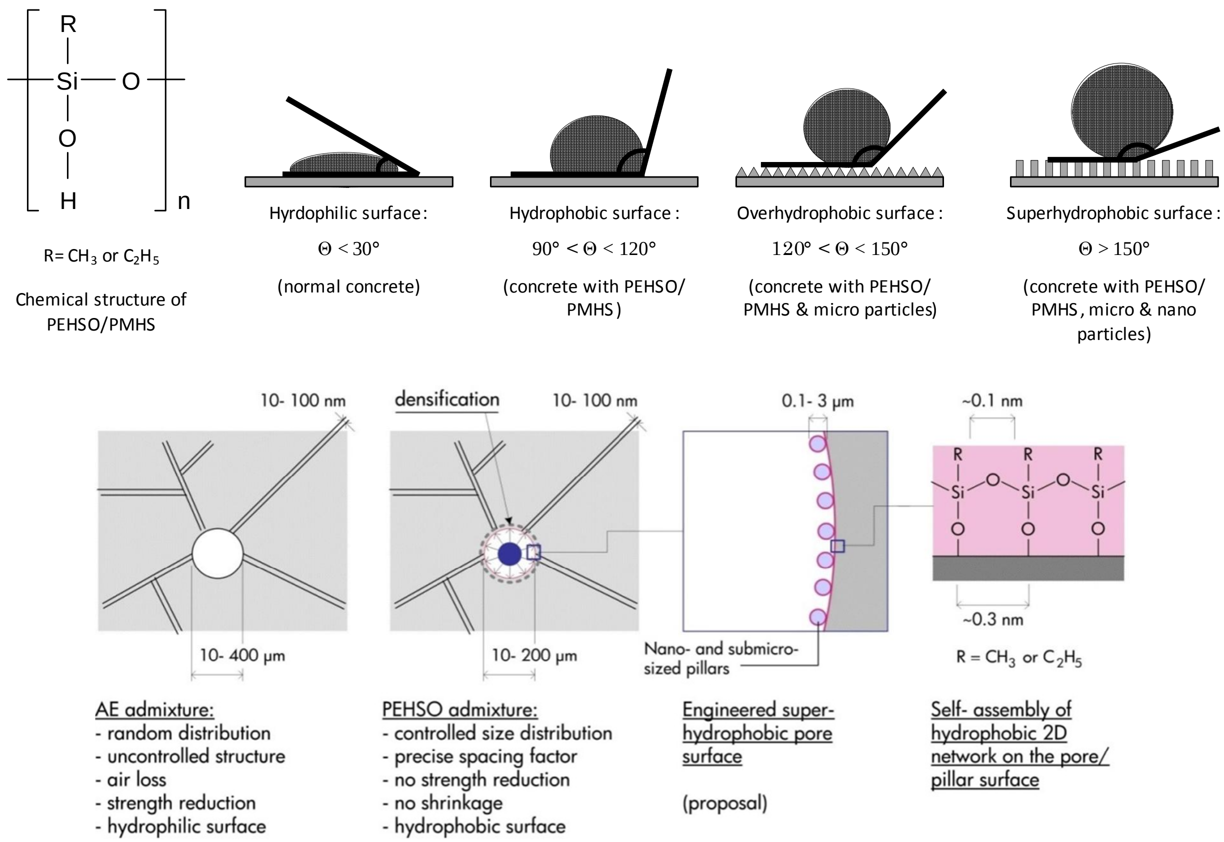


Figure 3: The concept of superhydrophobic hybridization of concrete

The volume, size and distribution of the air voids within the hardened cement phase can be precisely tailored by preparing the water-based PEHSO emulsion with a certain droplet size. Micro- or nano-sized particles provide the micro-roughness within the pore space, which plays an important role in forming superhydrophobic surfaces within the hardened cement phase/paste, tweaks the bond between the cementitious matrix and fibers, and improves the self-healing potential of concrete. The application of the PEHSO admixture in superhydrophobic HPFRC/SECC helps to control the bond of the fibers and realize controlled pull-out behavior rather than fiber rupture. Furthermore, the controlled air void structure is used to design the preferred multi-cracking fracture modes (Figure 2). The synergetic effects of these parameters on SECC durability were verified by recent research project 05-10.

3.1 CFIRE 04-09

Results from CFIRE 04-09 indicate that the use of PVA fibers in ECC/SECC structural materials proved to be an effective innovative solution, resulting in exceptional ductility and durability, which are important for maintaining high levels of freight transportation capacity on the nation's highways. Experimental programs have successfully demonstrated that the use of 2.75% by volume of PVA fibers provides greater strain hardening behavior, as compared to ECC with fewer fibers.

It was determined that a siloxane based emulsion manufactured with higher quantities of polyvinyl alcohol surfactant (PVAS) emulsifiers (4.4% PVAS) mixed at high speed (10.000 rpm) when used at a very small dosage of 0.25 g/l (0.4 lb/yd^3) provided the best hydrophobic hybridization of concrete as demonstrated the contact angle it made with mortar tiles. Additionally, the emulsion provided the best improvement in flexural behavior when added to ECC. Superhydrophobic emulsions based on metakaolin over-performed those with silica fume or portland cement demonstrating the increase in contact angle and resistance to water penetration in addition to impressive compressive strength and flexural behavior. However, it was observed that the use of excessive quantities of hydrophobic/superhydrophobic admixtures (up to 0.5 g/l or 0.8 lb/yd^3) sometimes contribute to excessive gas generation, and expansion of unrestrained specimens during the initial stages of curing.

The addition of selected SCMs to the SECC matrix also results in an improved flexural behavior. Not only does this make the ECC material more environmentally friendly, but it can also improve the durability. Experiments determined that the use of either metakaolin or silica fume can improve the flexural behavior and compressive strength of the PVA-ECC. Moreover, when siloxane based emulsions are added, metakaolin and silica fume samples displayed very little loss in strength and flexural behavior as compared to specimens with other SCMs.

Experimental research demonstrated that the use of superhydrophobic emulsions can be very beneficial for the mechanical behavior of SECC and it is expected that these materials will provide drastic improvements in freeze-thaw resistance as opposed to conventional mortars. Freeze-thaw studies performed on selected PVA-ECC with hydrophobic siloxane based emulsions demonstrated excellent performance through 700 freeze-thaw cycles with temperatures ranging between -50°C and 20°C.

It was successfully demonstrated that the obtained SECC are characterized by strain-hardening performance and multi-cracking. The deflection behavior of larger ECC beams is controlled by interfacial bond and fiber pullout and a very consistent performance was noted for ECC manufactured at low W/C; however, significant scattering of experimental data was observed at higher water-to-cement ratios.

3.2 CFIRE 05-10

Work within CFIRE 5-10 demonstrated the ability of superhydrophobic engineered cementitious composites (SECC) to create a ductile material while still maintaining high strengths and a very dense structure. The addition of hydrophobic/superhydrophobic admixtures not only results in a less permeable material with water resistant structure, but also creates the artificial flaws that lead to multi-cracking behavior and enhanced strain-hardening ability.

Using an experimental matrix considering fibers with three different sizes at varying volumes (2.0, 2.25, 2.5, 2.75, and 3.0%), the optimal performance was demonstrated by larger (RECS 15x12 mm) PVA fibers used at a dosage of 2.75% by volume.

The addition of supplementary cementitious materials (SCM) can lead to environmentally friendly composites by lessening the burden from cement production. This research demonstrated that the use of 5% silica fume and 45% granulated blast furnace slag creates SECC with an extremely durable matrix. These SCMs can, therefore, be used in SECC intended to last 120 or more years.

The addition of hydrophobic emulsion (0.25 g/L, as a single dose) to SECC mixtures resulted in an improved flexural behavior with only the slightest decrease in compressive strength due to the formation of beneficial air-void structure. However, the compressive strength of this material would have dropped even more drastically if conventional air entraining admixtures had been used. The fact that these hydrophobic emulsions are capable of creating a controlled air void structure with smaller, better spaced voids contributes to improved behavior. The addition of hydrophobic emulsions demonstrated the improvement in flexural behavior in all specimens presented within this research. Moreover, the addition of these hydrophobic emulsions demonstrated improved resistance to freezing and thawing.

When micro particles were added to the hydrophobic emulsion, the hydrophobic performance of the material was significantly improved. Even though by definition the treated concrete surfaces cannot reach the superhydrophobicity benchmark (contact angle greater than 150°, Figure 3), the improvement of contact angle when micro- and nano- particles were added to the admixture provided a good development towards superhydrophobicity.

Even though data shows that ECC, especially based on blended systems with SCM (5% silica fume, SF and 45% ground granulated blast furnace slag, BFS), performed extremely well through durability testing without any intentionally added air, it is a safe assumption that over the course of the intended lifespan (120 or more years), SF-BFS specimens that incorporate the hydrophobic/superhydrophobic admixtures would perform better. The addition of 5% silica fume and 45% ground granulated blast furnace slag created an extremely durable matrix, which is the reason for using these in the research; however, their performance was only monitored through 400 accelerated freeze-thaw cycles (at -50°C in 5% NaCl). The main benefit of hydrophobic emulsions that was seen during freezing and thawing cycles was the resistance to surface scaling. Even though this was not numerically evaluated within the research, it is an important durability aspect. If these specimens were to have been tested longer, it is safe to say that the ones showing surface scaling would begin to display drops in performance such as cross sectional area change and dynamic modulus of elasticity. This is due to the fact that when surface scaling occurs, water can more easily penetrate into the specimen and upon freezing create internal stresses leading to the deterioration of the material. The use of a lower w/cm ratio, not only displayed better compressive strength and stiffness before freezing and thawing, but provided a better resistance to freezing and thawing. The ECC/SECC materials with a lower w/cm ratio also provided a denser matrix with lower permeability.

The addition of superhydrophobic admixtures to ECC creates a durable material by introducing a controlled air void structure that allows for higher ductility and improved freeze-thaw resistance. This material can provide a lifespan for critical elements of bridges that will be significantly longer than the materials currently being used. Moreover, the use of SECC in highway infrastructure will significantly reduce repair that may be required. Despite an increased cost of production for this material, the cost throughout its lifespan is significantly reduced. With increasing freight on highways, the need for a more durable material is evident, and indeed superhydrophobic engineered cementitious composites can provide this required durability and mechanical response for critical elements of transportation infrastructure.

4. TECHNOLOGY TRANSFER

4.1 UWM-SUSTAINABLE INFRASTRUCTURE WORKSHOPS

The University of Wisconsin-Milwaukee hosted two workshops focused on sustainable infrastructure and were highlighted by the use of fiber reinforced concrete, especially SECC. The first of two workshops was held in November 2012 and was titled “Smart Materials for Sustainable Infrastructure.” The objective of this workshop was not only to promote SECC, but to allow other researchers to present their work on materials for sustainable infrastructure. Still, the main goal of this workshop was to present the research performed at UW-Milwaukee and UW-Madison on ECC and SECC. In addition to this, a world renowned concrete technology researcher, Prof. Surrendra Shah from Northwestern University, gave a presentation on “Controlling the Properties of Concrete through Nanotechnology.” In addition to Dr. Shah, researchers from UW-Madison, UW-Milwaukee, Vladimir State University (Russia), and the National Institutes of Standards and Technology presented their research (please see the program for workshop in Appendix A). Attendees of this workshop included members from local engineering firms, members of the Wisconsin Department of Transportation, members of the American Concrete Institute (ACI), and members of Wisconsin Pavement Association. This workshop was a very successful event; in that researchers and members of industry were able to gather together to hear about current research on sustainable materials. Additionally, there was much interest from industry members on SECC.

The second workshop on “Advanced and Sustainable Materials for Infrastructure Renewal” at the University of Wisconsin-Milwaukee was held in May 2013. Attendees of this workshop included members of industry, members of the Department of Transportation, and researchers from other universities. One presentation during this workshop focused on the use of superhydrophobic engineered cementitious composites for highway applications, and allowed attendees to see the benefits of the material. The keynote speaker for this workshop was Prof. Victor Li from the University of Michigan (Figure 4). Professor Li is known as the pioneer of engineered cementitious composites and his presentation and expertise on the subject was truly beneficial for everyone attending. It also allowed for exchange of ideas among researchers and future collaborations. Other presentations during this workshop included discussions on nano-technology in concrete, superhydrophobicity and icephobicity, the use of fly ash in concrete, and fracture testing of carbon fiber and nanotube reinforced mortars (please see the program for workshop in Appendix A).

Figure 4: Prof. Victor Li presenting ECC at the workshop on "Advanced and Sustainable Materials for Infrastructure Renewal” at UW-Milwaukee

4.2 INTERNATIONAL CONFERENCE PRESENTATIONS

Presentations on the mechanical behavior and durability properties of SECC were given at several different international conferences. These presentations provided other researches and members of industry a chance to see the benefits and features of SECC that make it an attractive alternative to conventional concrete. These included oral presentations and poster presentations at the following conferences (the abstracts or posters for each presentation can be found in Appendix B):

- ACI Fall 2012 Conference (ACI committee 236D: Nanotechnology of Concrete), Toronto, Canada, October 2012
- ACI Fall 2012 Conference (ACI committee 544F: Durability of Fiber Reinforced Concrete),Toronto, Canada, October 2012
- Workshop on “Smart Materials for Sustainable Infrastructure,” Milwaukee, WI, November 2012
- Transportation Research Board Annual Meeting, Washington, DC, January 2013
- CFIRE Student Freight Symposium, Memphis, TN, February 2013
- ACI Spring 2013 (ACI committee 236D: Nanotechnology of Concrete), Minneapolis, MN, April 2013
- Workshop on “Advanced and Sustainable Materials for Infrastructure Renewal,” Milwaukee, WI, May 2013
- ACI Wisconsin Chapter May Meeting, Milwaukee, WI, May 2013
- ACerS Cement Division 4th Advances in Cement-based Materials: Characterization, Processing, Modeling and Sensing, Champaign, IL, July 2013 (Winning Poster)

A presentation regarding the freeze-thaw durability of SECC will also be presented during ASCE Concreep9 @MIT (Cambridge, MA) in September, 2013. The work will also be published in the conference proceedings.

4.3 SECC DEDICATED WEB-PLATFORM

A web-platform dedicated to SECC was created and can be found at super-beton.com [21]. In this website, the research performed on SECC is presented in a non-technical format. Links to technical reports, including CFIRE 04-09 and CFIRE 05-10 are listed for those interested in a better detailed explanation of the material. Within the website discussions of durability, mechanical behavior, superhydrophobicity, and fiber reinforced concrete are discussed. Screen shots of these pages can be seen in Appendix C. Links to similar research are also provided. Future additions to the website will include videos of mixing procedures, student competitions for engineered cementitious composites performed at UW-Milwaukee, and a video of the work performed to cast a slab using superhydrophobic engineered cementitious composites on a ramp leading to a parking structure at UW-Milwaukee. Links to scientific publications of similar work and work performed by the team at UW-Milwaukee will also be present. The web-platform may also serve as a database for research results from UW-Milwaukee, collaborating universities, and other researchers so that there can be a global understanding of the properties of the material so that little to no repetition of research is needed.

4.4 SCIENTIFIC PUBLICATIONS

Several journal articles related to the topic of SECC have been submitted or will soon be submitted for potential publication in high quality journals. The first paper was entitled “Hydrophobic Engineered Cementitious Composites for Highway Applications” and was submitted to Cement and Concrete Composites. Another paper entitled “Freeze-Thaw Resistance of Fiber Reinforced Composites with Superhydrophobic Admixtures” will be published in the proceedings of Concreep9. Additional papers are in the process of being created and will be sent to good quality journals for publication. The abstracts of the already submitted papers can be found in Appendix D.

4.5 PROFESSIONAL VIDEO ON SECC

A professionally produced video is in the process of being created focusing on the benefits and uses of SECC. In this video, interviews with researchers at UW-Milwaukee will be provided which will discuss the benefits and potential uses of the material in infrastructure. The video will also feature the production of the pilot slab created on UW-Milwaukee’s campus composed of SECC. This video will be place on the SECC dedicated web-platform and will serve as a promotional tool for the material.

5. IMPLEMENTATION OF SECC

5.1 PRELIMINARY TESTS AT UW-MADISON

The first phase of the research consisted of casting and testing of small scale beams of size 15 x 3 x 1 inches. The main purpose of these mixes was to arrive at a mix that is capable of providing good workability without loss in strength. A solution to the problems faced by previous preliminary studies in cracking pattern (Griffith cracking) and failure pattern (brittle failure) was also attempted. The factors affecting the results are workability so that a fluid mixture can be achieved for ease of placement on a large scale.

5.1.1 Materials

The ingredients for the chosen PVA mix at UW - Madison are as follows:

- Type I Ordinary Portland cement (Lafarge),
- ASTM Class F Fly Ash (Headwaters Shufer Station, Illinois),
- A fine grained sand with an average grain size of 177 μm (US Silica F-80),
- PVA fiber RECS 15x8 mm (Nycon), and
- Superplasticizer (MEGAPOL 40 DF).

5.1.2 Testing Procedures

Four-point flexural tests are used to determine the flexural strength and mid-span deflection of the beam. The test setup for four point flexure test is shown in Figure 5.

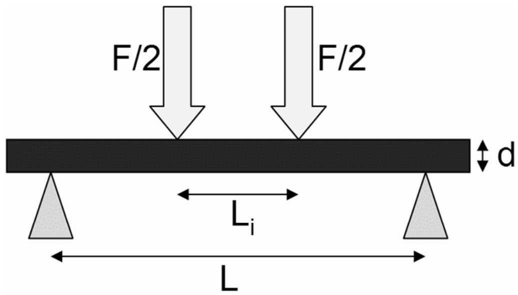


Figure 5: Four-point flexural test

This test is specified by ASTM for fiber reinforced plastic materials. The rubber pads are used for loading to provide uniform load and to prevent load concentrations due to surface defects. In this test, strength is determined by the peak load on the beam and the maximum deflection is at failure of beam. The beam is considered to have failed when the load on the beam drops to 25% of peak load (ductile and plastic failure). Figure 6 shows the test setup for the 15-inch beams.

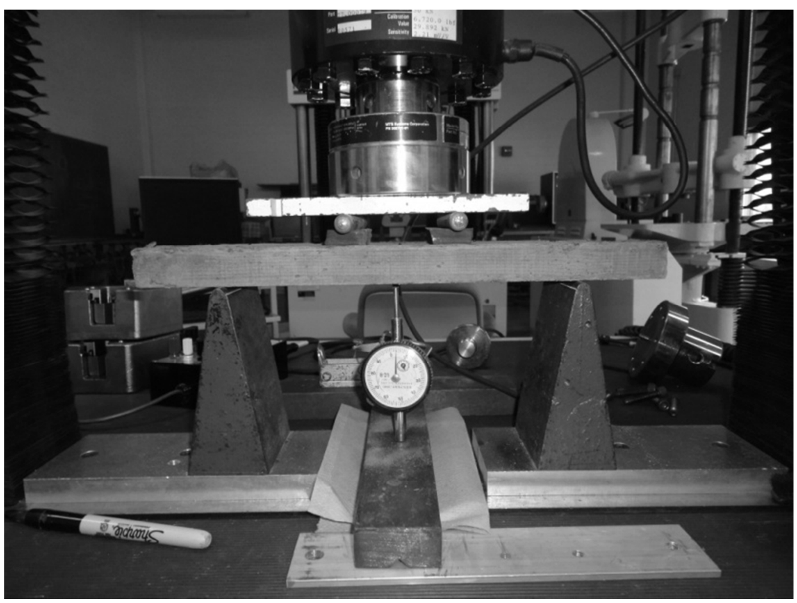


Figure 6: Test setup for 15-inch samples

The spacing between the cracks determines the crack pattern. It may be of 2 types:
a Griffith crack or steady state flat crack. The Griffith cracks occur when the crack spacing in the beam is high. For the 15-inch beams, the lower spacing limit for Griffith cracks is one-inch. Figure 7 shows an example of a Griffith crack.

Figure 7: Griffith crack

Steady state flat cracks occur when the cracks in the beam are closely spaced. If the beams have a crack spacing less than one-inch they are considered to have this crack pattern. Figure 8 shows an example of a steady state flat cracking.

Figure 8: Steady-state flat crack

5.1.3 Trial Mixes

A preliminary mixing procedure based on previous CFIRE studies (CFIRE 05-10) was used as a base to compare future results.

The materials were mixed in a bucket by adding sand and fly ash and mixed using a paint mixer. Next, water and superplasticer were added and mixed and finally, the PVA fibers were added and mixed manually. The material was then transferred to a planetary mixer where the cement was added.

The results of this mixture are as follows. Three beams were cast using the mix and tested using the setup shown in Figure 6. The results of the testing are shown in Table 1. Figure 9 shows the load vs deflection curves for the beams. The flow of the material was 8.5 inches.

Table 1: Test results of Mix 1

	Beam 1-a	Beam 1-b	Beam 1-c
Peak Load (lbs)	220	220	185
Max Deflection (in)	0.2	0.3	0.1

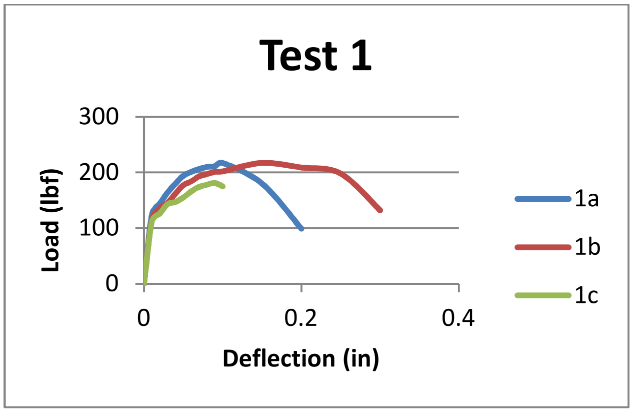


Figure 9: Load vs. deflection curves of Mix 1

The beams had flexural load around 175 to 220 lbs which is lower than the expected load (300 to 400 lbs). The mid-span deflections were between 0.1-0.3 inches which was lower than the expected deflections (0.25-0.35 inches). Two beams 1a and 1c failed by Griffith cracking while beam 1b had a crack spacing of 0.5 inches. It was also observed that the beams' failure was brittle in nature.

For the second trial mix the mixing order was changed. Instead of adding the fly ash before the addition of fibers, 50% of the cementitious materials (fly ash and cement) were added before the fibers and the remaining 50% after the addition of fibers.

The test results of this mixture are as follows. Again, three beams were cast using the mix and the results of the testing are shown in Table 2. Figure 10 shows the load vs. deflection curves for the beams.

Table 2: Test results of Mix 2

	Beam 2-a	Beam 2-b	Beam 2-c
Peak Load (lbs)	230	240	190
Max Deflection (in)	0.25	0.15	0.15

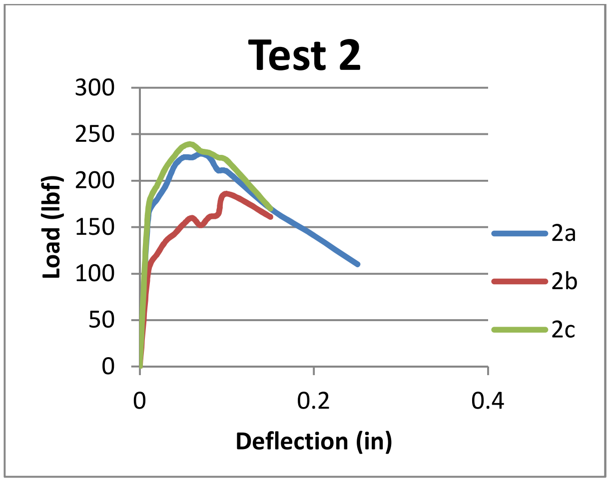


Figure 10: Load vs. deflection curves of Mix 2

The beams had a slightly increased flexural load compared to the base mix (190 – 240 lbs). The mid-span deflections were the same as in the case of the base mix (0.15-0.25 in). All the beams had failed by steady state cracks with crack spacing ranging from 0.5-1 inches. The failure was brittle for all the beams.

The order of the mixing was changed as Trial Mix 2 did not give the expected results either. Therefore a third mix was attempted. In this mix the cementitious materials (fly ash and cement) were added before the addition of the fibers.

Again, three beams were cast using the mix and the results of the testing are shown in Table 3. Figure 11 shows the load vs. deflection curves for the beams.

Table 3: Test results of Mix 3

	Beam 3-a	**Beam 3-b**	**Beam 3-c**
Peak Load (lbs)	370	240	425
Max Deflection (in)	0.35	0.25	0.35

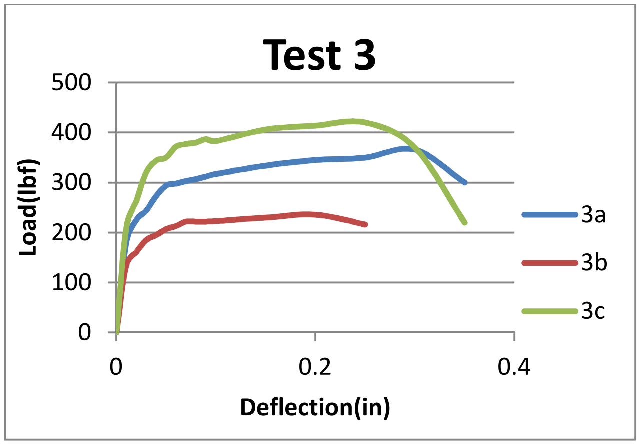


Figure 11: Load vs. deflection curves of Mix 3

The Mix 3 beams had a significant increase in flexural load (240 – 420 lbs) compared to the base mix. The beams also demonstrated higher mid-span deflections (0.25 - 0.35 in). The beams failed by steady state flat cracks with crack spacing less than 0.5 inches. The failure was brittle for all the beams.

The major conclusions derived from the test results are follows:

- From the results, it is inferred that adding fibers at the end of mixing gives the best performance for the beams in terms of flexural strength, mid-span deflection and crack pattern.
- It can also be observed that there is variation in the results of the tests; this can be attributed to the fibers lumping together and becoming unevenly distributed within the mix.
-
- The cracked beams were examined along the cracked surfaces to identify the mode of failure of the fibers. Figure 12 shows the pattern of fiber failure along the cracked surface of the beam.
- The beams had multiple air voids along the surface or in the interior of the beams. These air voids cause stress concentrations on the beams due to the small size of the beams and causes cracks to start from the voids. Figure 13 shows the air voids on the beams.

Figure 12: The region along the cracked section of the beam with fibers failed by breakage

Figure 13: Cracks developed along the air voids in the interior of the beam

Proposed solutions for the problems encountered:

- Lumping of fibers can be reduced by reducing the fiber loading rate and distributing over the entire period of the wet mixing in the planetary mixer. This should reduce the variation of results in a single mix.
- The brittle failure of the beams can be attributed to the failure mode of the fibers as fiber breakage means the strong bond between the matrix and the fibers. The fibers used for the trial mixes had little oiling agent cover. This is the main reason for fiber breakage and brittle failure of the beams. This can be solved by using oiled fibers.
- Irregular air voids in the beams can be reduced by using a table vibrator to compact the ECC mix.

With the major problems faced with the trial mixing solved the mix design and procedure for the final testing was finalized.

5.1.4 Final Mix Design and Procedure

The finalized mix procedure is listed as follows: cement, sand and fly ash were mixed with a paint mixer. Next, water was added and mixed following by the material being transferred to a planetary mixer where the fibers were added as the wet mixing took place. The FRC beams were compacted on a vibrating table. The final mixing design to be used for the test mixes is shown in Table 4.

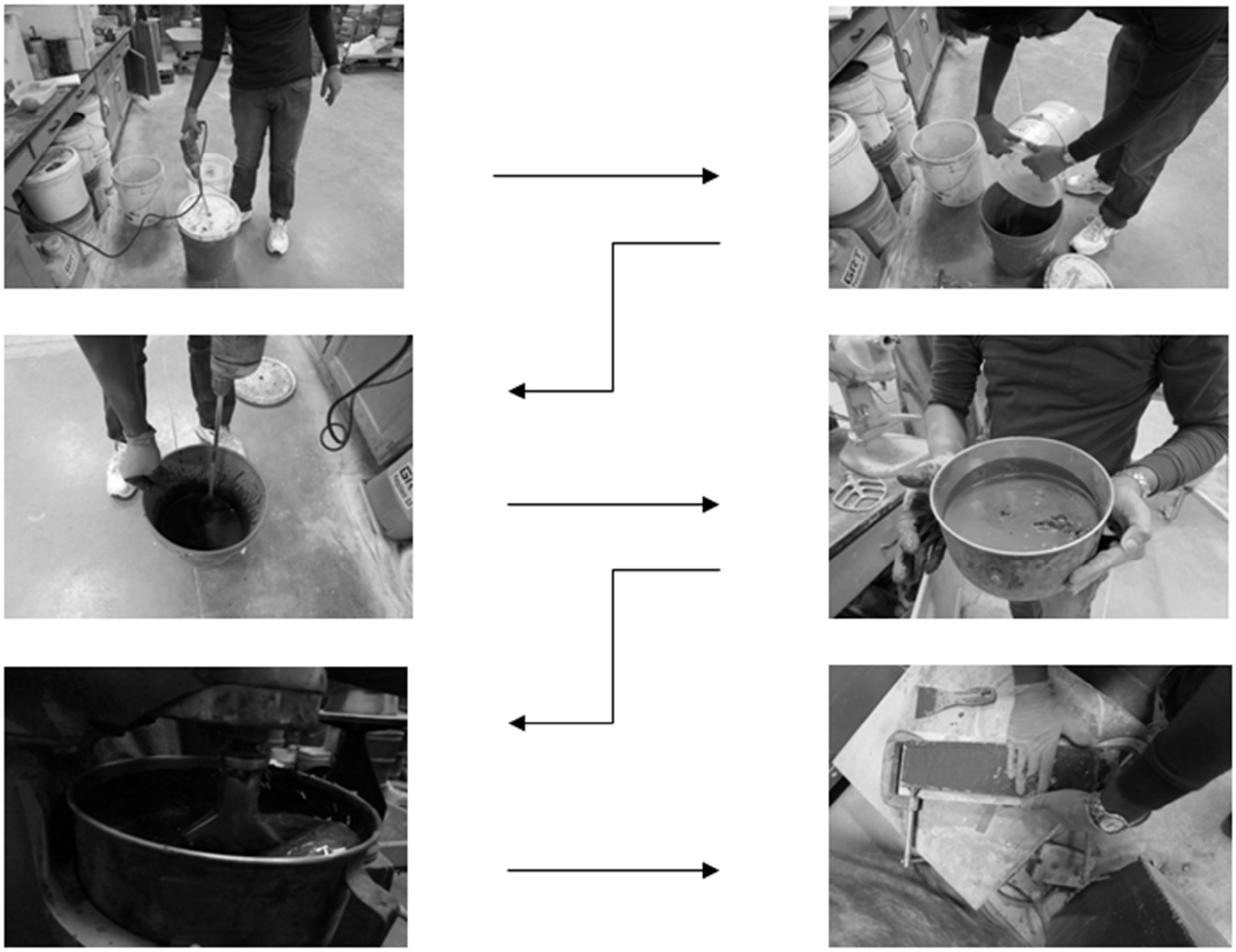


Figure 14: The final mixing procedure

Table 4: Finalized mix design for 15-inch beams

Material	**Cement**	**Fly Ash**	**Sand**	**Water**	**PVA Fiber**	**W/(C+FA)**	**SP**
Fraction by Weight of Cement	1.0	1.2	0.8	0.53	2.2%	0.26	0.9%

Five sets of beams with each set comprising of three beams were tested to get a consistent result for the 15-inch beams. The mix design and mix procedure finalized by the trial mixes were used to cast the beams. Freshly oiled RECS 15x8 mm fibers were purchased for these mixes to avoid the fiber breakage observed in trial mixes. All the beams were tested at three days strength. The beams were cast and covered with plastic sheets for 1 day and then the sheets were removed and the beams were cured in the lab for 2 days. The mixes are numbered from 4 to 8. Results of these mixes are summarized in Table 5 and Figure 15 - Figure 17:

Table 5: Peak load, deflection, and flow of Mixes 4-8

Mix ID	4	5	6	7	8
Average Peak Load (lbs)	360.0	236.7	223.3	273.3	263.3
Maximum Deflection (in)	0.45	0.28	0.28	0.20	0.33
Flow (in)	7.75	7.75	7.75	7.75	7.75

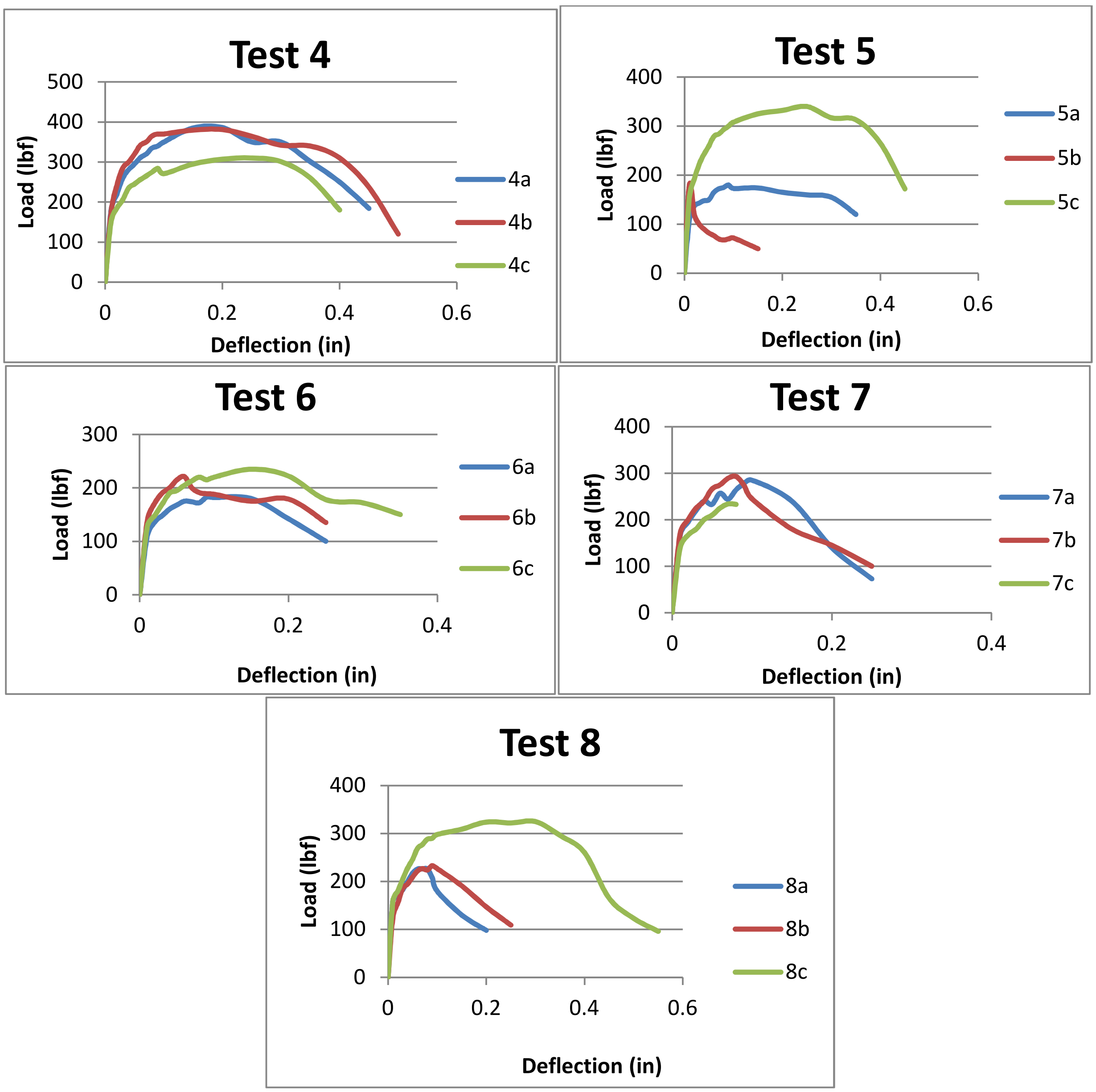
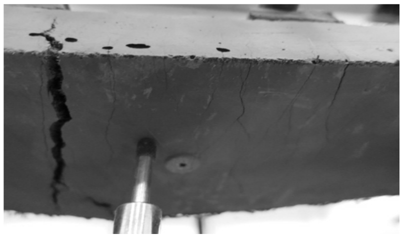


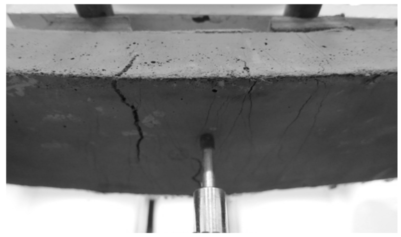
Figure 15: Load vs. deflection curves for Mixes 4 - 8

Beam 4a



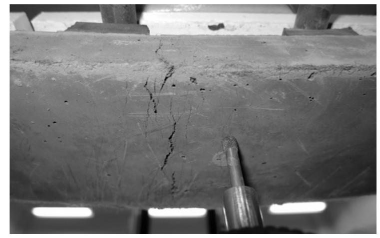
Crack Spacing: 0.5 in

Beam 4b



Crack Spacing: < 0.5 in

Beam 4c



Crack Spacing: < 0.5 in

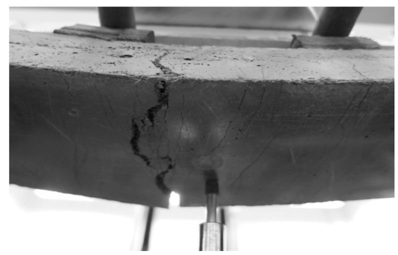
Beam 5a

Crack Spacing: 0.75 in

Beam 5b

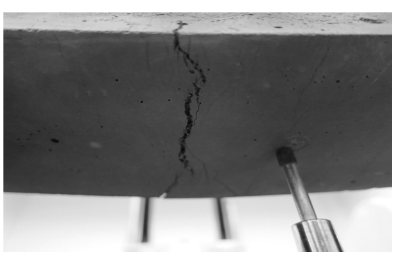
Crack Spacing: single crack

Beam 5c



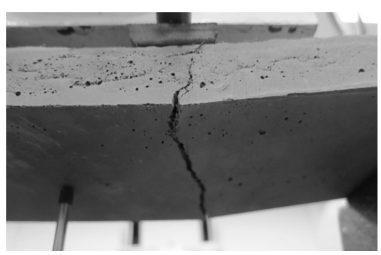
Crack Spacing: < 0.5 in

Beam 6a



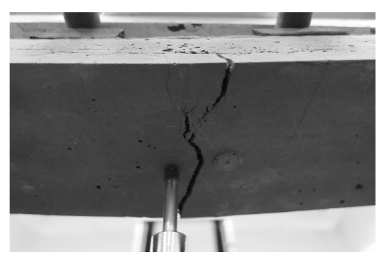
Crack Spacing: single crack

Beam 6b



Crack Spacing: 1-inch

Beam 6c



Crack Spacing: 0.75-inch

Figure 16: Cracking patterns for mixes 4-6

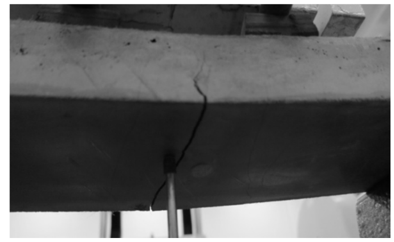
Beam 7a

Crack Spacing: 0.75 in

Beam 7b

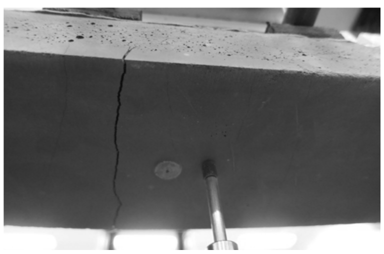
Crack Spacing: 1.25 in

Beam 7c



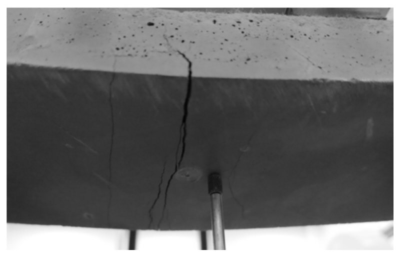
Crack Spacing: 1.5 in

Beam 8a



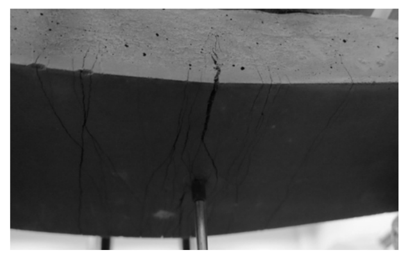
Crack Spacing: 2.4 in

Beam 8b



Crack Spacing: 1.0 in

Beam 8c



Crack Spacing: < 0.5 in

Figure 17: Cracking patterns for mixes 7-8

Results from these sets of testing are as follows:

- Out of the 15 beams tested 10 beams failed by steady state flat cracking.
- Out of the 10 beams
    - All beams had max mid-span deflection values greater than 0.35 in.
    - 9 beams had peak loads greater than 230 lbs.

The strength and deflection were determined based on the criteria mentioned in previous sections. The results of the beams which did not fail by steady state flat cracks are not included in the calculations for the prediction of the performance of medium scale beams. The reason for the omission is that even the smallest defects like air voids and fiber distribution can affect the performance of the small scale beams. It was assumed that these factors would not affect the medium scale beams to the same extent.

Among the 10 beams

The average peak load of the beams	=	291 lbs
The average max mid span deflections	=	0.375 inches

5.2 36-INCH BEAM CREATED AT UW-MADISON

The second phase of the research consisted of casting and testing of medium scale beams with sizes of 36 x 5 x 3 inches. The main purpose of these mixes was to verify whether the results of small scale beams can be replicated on a bigger scale. A solution to the problems from previous work in workability using a drum mixer and cracking pattern was also attempted.

The main difference in mixing the 36-inch beams was the use of a drum mixer instead of a planetary mixer to mix the ECC. The planetary mixer could not be used for this mix because of the quantity of ECC required to cast the beams as it would take several batches of mix to produce the necessary amount of ECC. Secondly if the material is to be used in the field then drum mixer would be used. Therefore the use of drum mixer was selected as a practical measure. Since the way the mixers work are different, changes were expected in workability.

Figure 18: Flexural setup for 36-inch beams

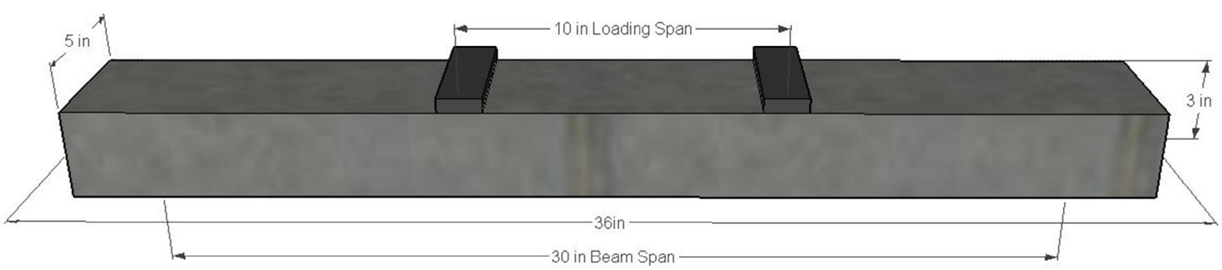


Figure 19: The dimensions of the beam test setup

Two beams were cast from each batch produced at a time in the mixer and they were cured covered with polythene sheet for 3 days and then the sheets were removed and the beams were cured in the lab for 4 days. All the 36-inch beams were tested at 7 days strength.

5.2.1 Trial Mixes

The same mix design and mix procedure used for the 15-inch beams were attempted for the first mix. The following procedure was used for preparation of FRC in a drum mixer:

- Sand + Cement + Fly-ash added and mixed → Dry mix
- Water + Superplasticizer added and mixed → Wet mix
- PVA fibers added and mixed.

The beams failed by single Griffith cracks. It was observed that the fibers didn't bond well with the matrix. The peak loads were almost half of the predicted peak loads and maximum deflection was well below the expected values. Figure 20 shows the load vs. deflection curves of the beams. Figure 21 shows the cracked surface with fibers sticking out. Table 6 gives shows the values of loads and deflections of the beams.

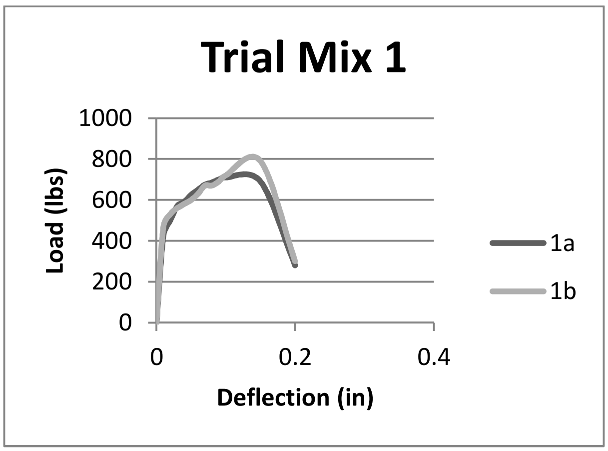


Figure 20: Load vs. deflection of trial Mix 1 for 36-inch beams

Figure 21: Cracked section of Trial Mix 1

Table 6: Results of Trial Mix 1 for 36-inch beams

	Beam 1-A	Beam 1-B
Peak Load (lbs)	765	790
Deflection @ Peak Load (in)	0.15	0.15
Max Deflection (in)	0.2	0.2

Based on these results, it is clear from the results of Trial Mix 1 that the mix procedure used in the planetary mixer cannot be used for the drum mixer.

For Trial Mix 2, the same mix design as in the case of 15-inch beams were used but the order of mixing was changed to account for the fibers not bonding with the ECC matrix as in Trial Mix 1. It was observed during Mix 1 that adding all the cement and fly ash in the beginning made the mix denser. In the planetary mixer the mixing blade distributes the fibers within this dense ECC matrix. In the drum mixer the mixing is done by the rotation of the drum therefore it is not possible to get the required distribution with such a dense mix. To account for this a portion of fly ash was added after the addition of the fibers. This enables the mix to be less dense when the fibers are being added thereby facilitating easier distribution by the drum mixer.

The modified mix procedure in a drum mixer involved:

- Sand + Cement + 70% of Fly-ash added and mixed → Dry mix;
- Water + Super Plasticizer added and mixed → Wet mix;
- PVA fibers added and mixed;
- Remaining 30% of Fly ash added and mixed.

Trial Mix 2 had a flow of 7.5 inches; other results of testing are summarized in Table 7 and Figure 22 - Figure 24.

Table 7: Results of Trial Mix 2 for 36-inch beams

	Beam 2-A	Beam 2-B
Peak Load (lbs)	1720	1480
Deflection @ Peak Load (in)	0.28	0.25
Max Deflection (in)	0.4	0.45

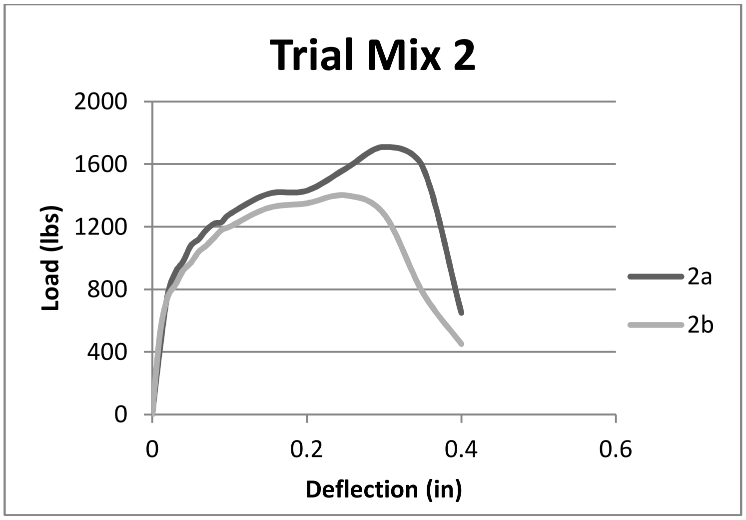


Figure 22: Trail Mix 2 load vs. deflection curves for 36-inch beams

Beam 2a

Crack Spacing: 1 – 1.5 inches

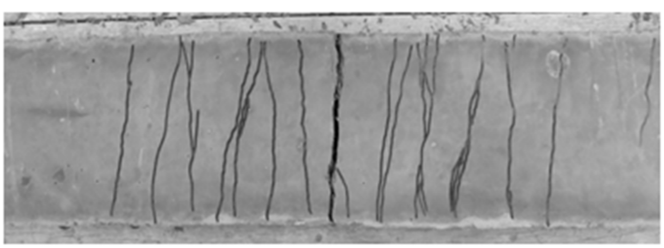


Figure 23: Beam 2a crack spacing and cracked section

Crack Spacing: 1.5 – 2 inches

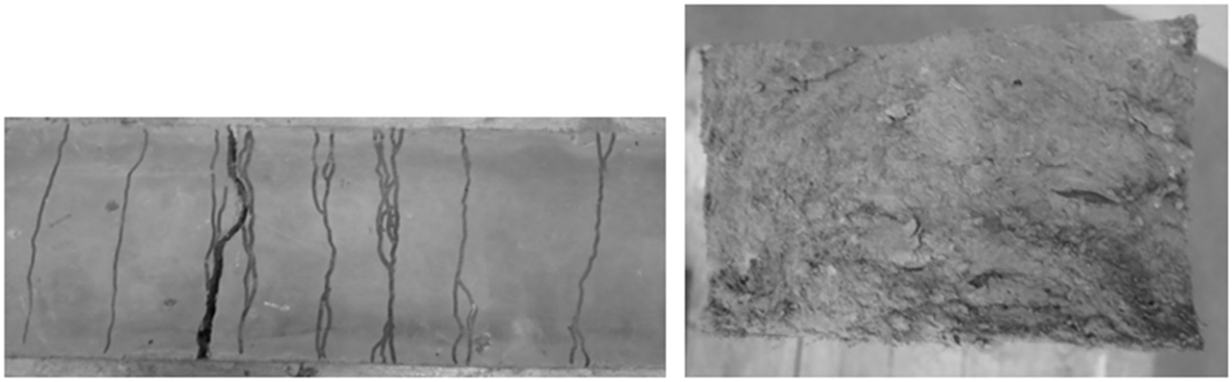


Figure 24: Beam 2b crack spacing and cracked section

The results were satisfactory as far as strength and deflection were concerned but the beams showed crack spacing of around 1 -1.5 inches which was considered as a borderline for Griffith cracks in 15-inch beams so an attempt was made to reduce the crack spacing in the next trial mix.

Trial Mix 3 attempted to reduce the crack spacing of the beams. This was primarily determined by the flexural strength of the beam and the bond strength of the fibers with the ECC matrix. If the bond strength is comparatively less the beam would fail before multiple cracking occurs on the other hand if the bond strength is very high, the brittle failure occurs. Therefore, the mix attempted to reduce the flexural strength and to maintain the same bond strength. This could be done by decreasing the cement content in the mix or by increasing the water content. Since no previous work had been done on these relations, the flexural strength was attempted to be reduced by increasing the water content to get an idea on its impact on the bond strength of the fibers and the flexural strength of the beams.

Water to binder (cement + fly ash) ratio was slightly increased from 0.26 to 0.30. The resulting mix design is listed in Table 8. The procedure used was the same as in Trial Mix 2.

Table 8: Mix design for Trial Mix 3

Material	**Cement**	**Fly Ash**	**Sand**	**Water**	**PVA Fiber**	**W/(C+FA)**	**SP**
Fraction by Weight of Cement	1.0	1.2	0.8	0.53	2.2%	0.30	0.9%

The beams had a bigger crack spacing than Trial Mix 2 and thus the new mix was unsatisfactory. This trial batch demonstrated flow of 8.5 inches; all test results are listed in Table 9, Figure 25, and Figure 26:

Table 9: Results from Trial Batch 3 for 36-inch beams

	Beam 3-A	Beam 3-B
Peak Load (lbs)	1100	1180
Deflection @ Peak Load (in)	0.15	0.2
Max Deflection (in)	0.25	0.42

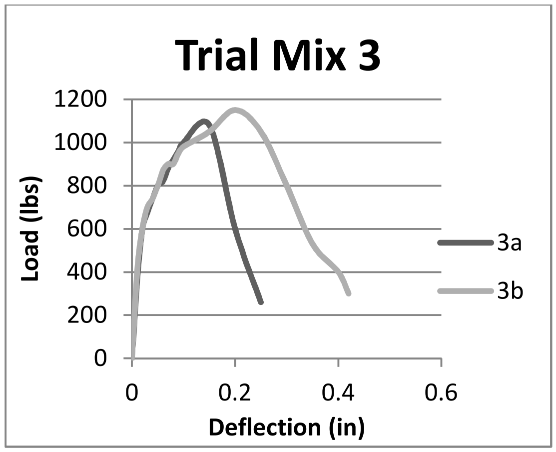
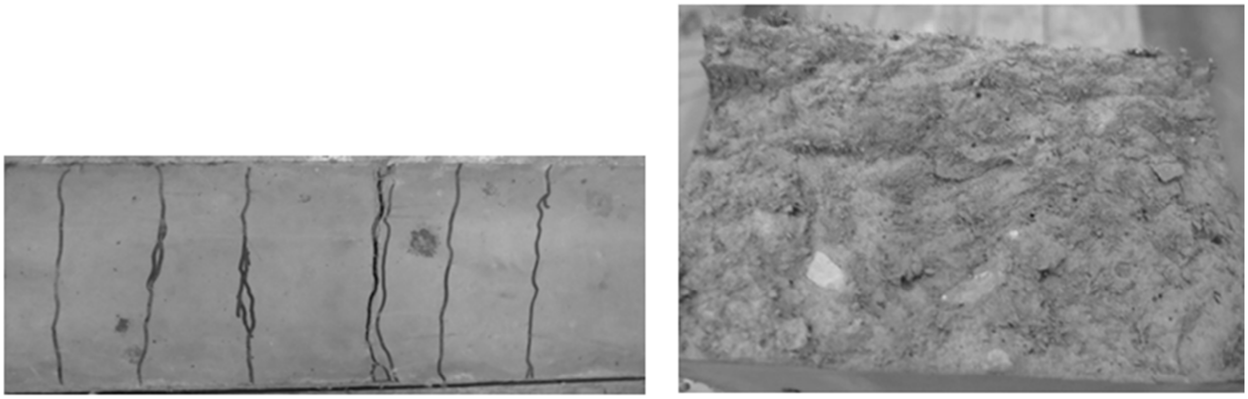


Figure 25: Trial Mix 3 load vs. deflection curves

Crack Spacing: 2-2.5 inches



Crack Spacing: 1.5 – 2.5 inches

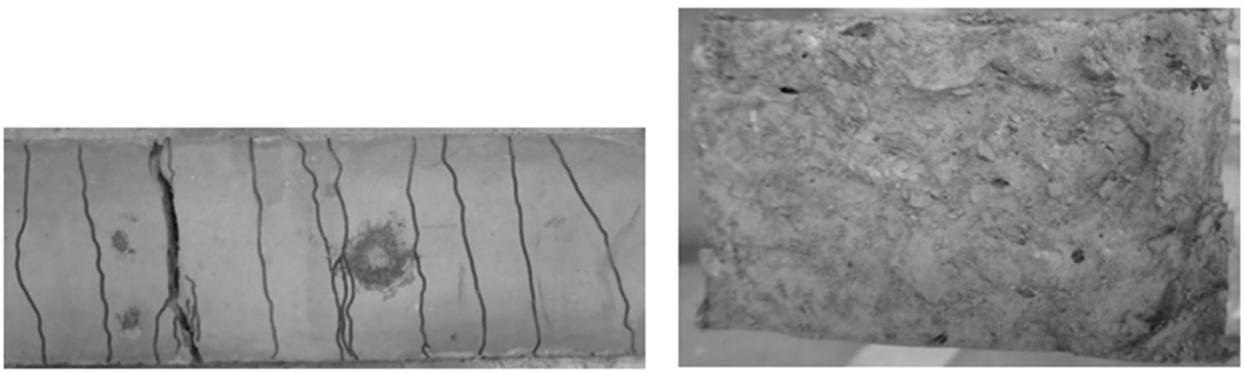


Figure 26: Cracking pattern of beam 3a (top) and 3b (bottom)

Figure 26 shows the crack spacing and cracked sections of the beams. The results of Trial Mix 3 were not satisfactory as the crack spacing did not decrease, but resulted in the loss of flexural strength and reduction in maximum mid-span deflection. It was concluded that increasing the water content in an ECC mix decreases the bond strength of the fibers more than the flexural strength.

Trial Mix 4 was attempted with reduced water content and to counter the possible loss of workability superplasticizer content was increased to 1.3%. Mix design of the mix is shown in Table 10. The procedure used for the mix was the same as in Trial Mix 2.

Table 10: Mix design for Trial Mix 3

Material	Cement	Fly Ash	Sand	Water	PVA Fiber	W/ (C+FA)	SP
Fraction by Weight of Cement	1.0	1.2	0.8	0.53	2.2%	0.24	1.3%

The beams from this mixture performed very well but had low workability reducing the flow to 7 inches. Test results are summarized in Table 11, Figure 27, and Figure 28.

Table 11: Results from Trial Mix 4 for 36-inch beams

	Beam 4-A	Beam 4-B
Peak Load (lbs)	1670	1500
Deflection @ Peak Load (in)	0.35	0.3
Max Deflection (in)	0.6	0.45

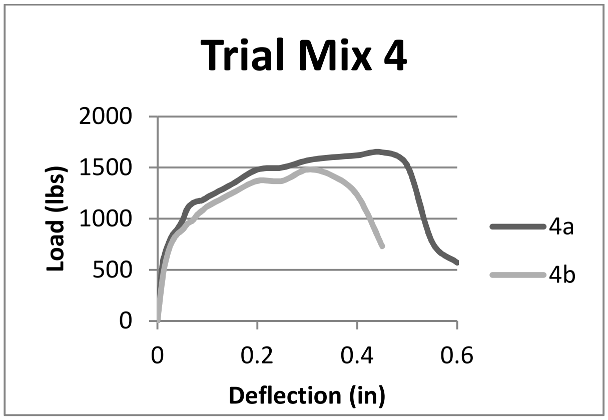
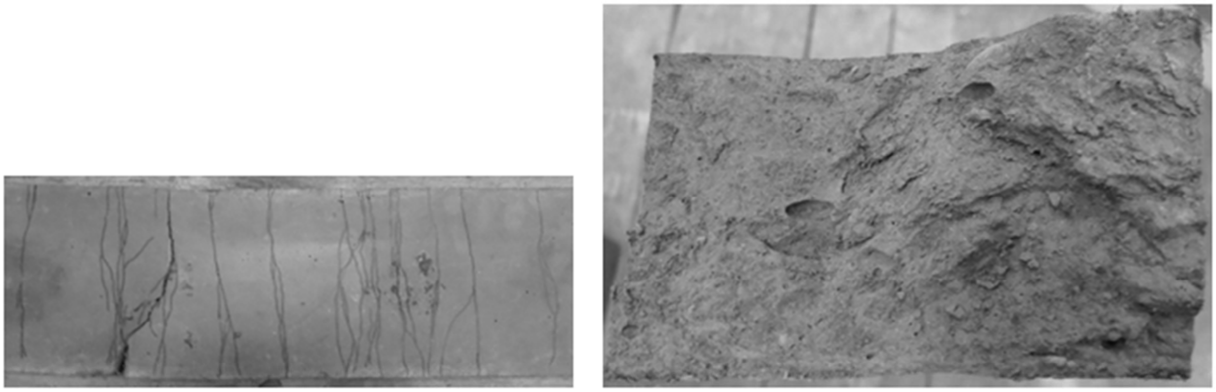


Figure 27: Load vs. deflection curves for Trial Mix 4 for 36-inch beams

Crack Spacing: <1 inch -1 inch



Crack Spacing: <1 inch -1 inch

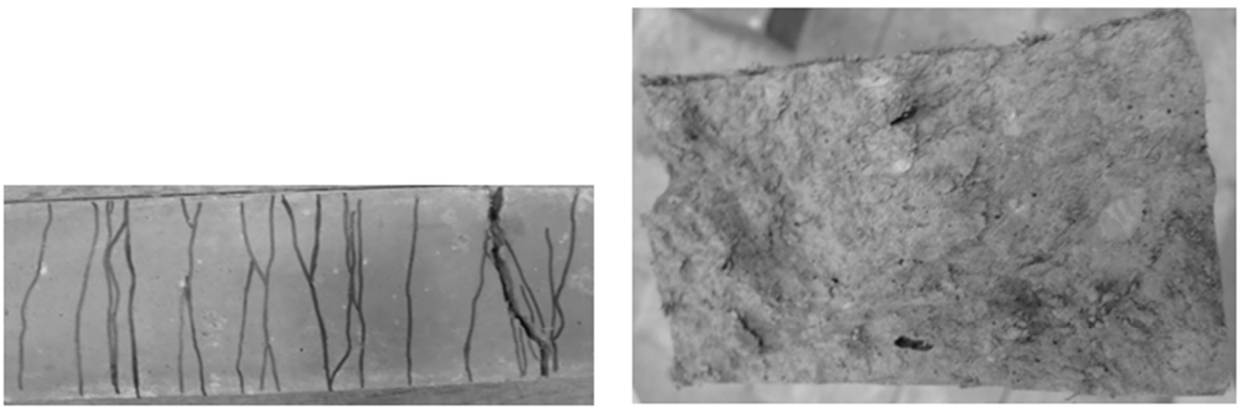


Figure 28: Cracking pattern for beam 4a (top) and 4b (bottom)

Figure 28 shows the crack spacing and cracked sections of the beams. The performance of the mix was good as high flexural strength and mid-span deflections with crack spacing less than 1-inch were observed. Workability of the mix was a bit low as flow of only 7 inches was observed. This was a result of reducing the water content. The reduced workability was still acceptable but another trial mix was attempted to try increase the workability of the mix with the intent to achieve workable mix for actual field applications.

Trial Mix 4 provided the required strength, deflection and crack pattern but workability was low. Therefore another approach was attempted to increase the bond strength by decreasing the fly ash content. Reducing fly ash content was expected to give the same effect of reducing water, but with better workability. Water content was increased (W/C of 0.25) and fly ash content was reduced to 1.1 times the weight of cement. Superplasticizer was unchanged from Mix 4. Mix design of the Trial Mix 5 is shown in Table 12. The procedure used for the mix was the same as in Trial Mix 2. Only 1 beam was cast using this mix as Mix 4 gave desired performance as far as workability (flow of 8 inches) strength, deflection and crack pattern were considered (Table 13, Figure 29, and Figure 30).

Table 12: Mix design for Trial Batch 5 for 36-inch beams

Material	**Cement**	**Fly Ash**	**Sand**	**Water**	**PVA Fiber**	**W/ (C+FA)**	**SP**
Fraction by Weight of Cement	1.0	1.1	0.8	0.53	2.2%	0.25	1.3%

Table 13: Results of Trial Mix 5 for 36-inch beams

	Predicted Values	**Beam 5**
Peak Load (lbs)	1300 -1500	1370
Deflection @ Peak Load (in)	0.25-0.35	0.3
Max Deflection (in)	0.4-0.45	0.45

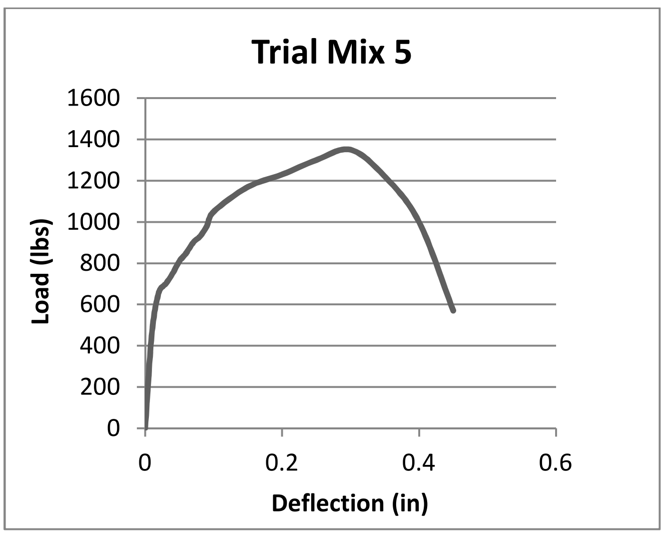


Figure 29: Trial Mix 5 load vs. deflection curve

Crack Spacing: <1 inch -1 inch

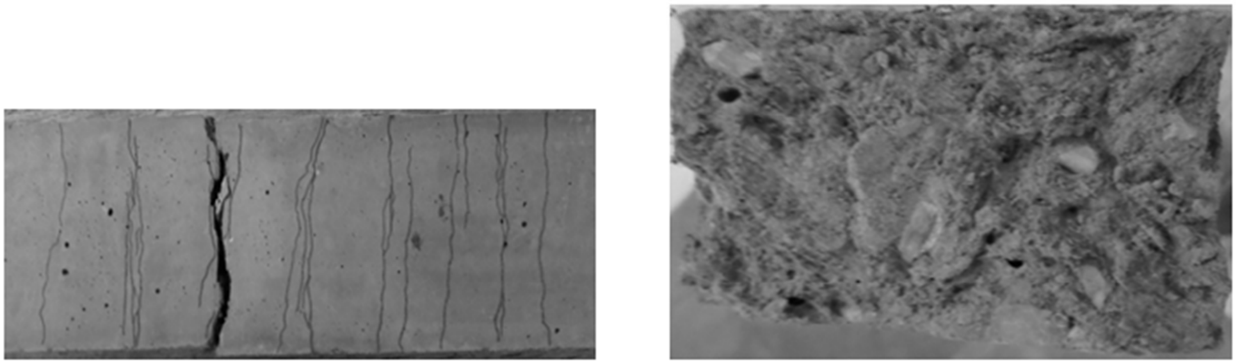


Figure 30: Cracking pattern of beam 5 for 36-inch beams

5.2.2 Finalized Testing

Results from Trial Mix 5 were adequate and were considered to be the finalized mix design. The finalized mix procedure in a drum mixer was as follows:

- Sand + Cement + 70 % of Fly-ash added and mixed → Dry mix;
- Water + Superplasticizer added and mixed → Wet mix;
- PVA fibers added and mixed;
- Remaining 30 % of Fly ash added and mixed.

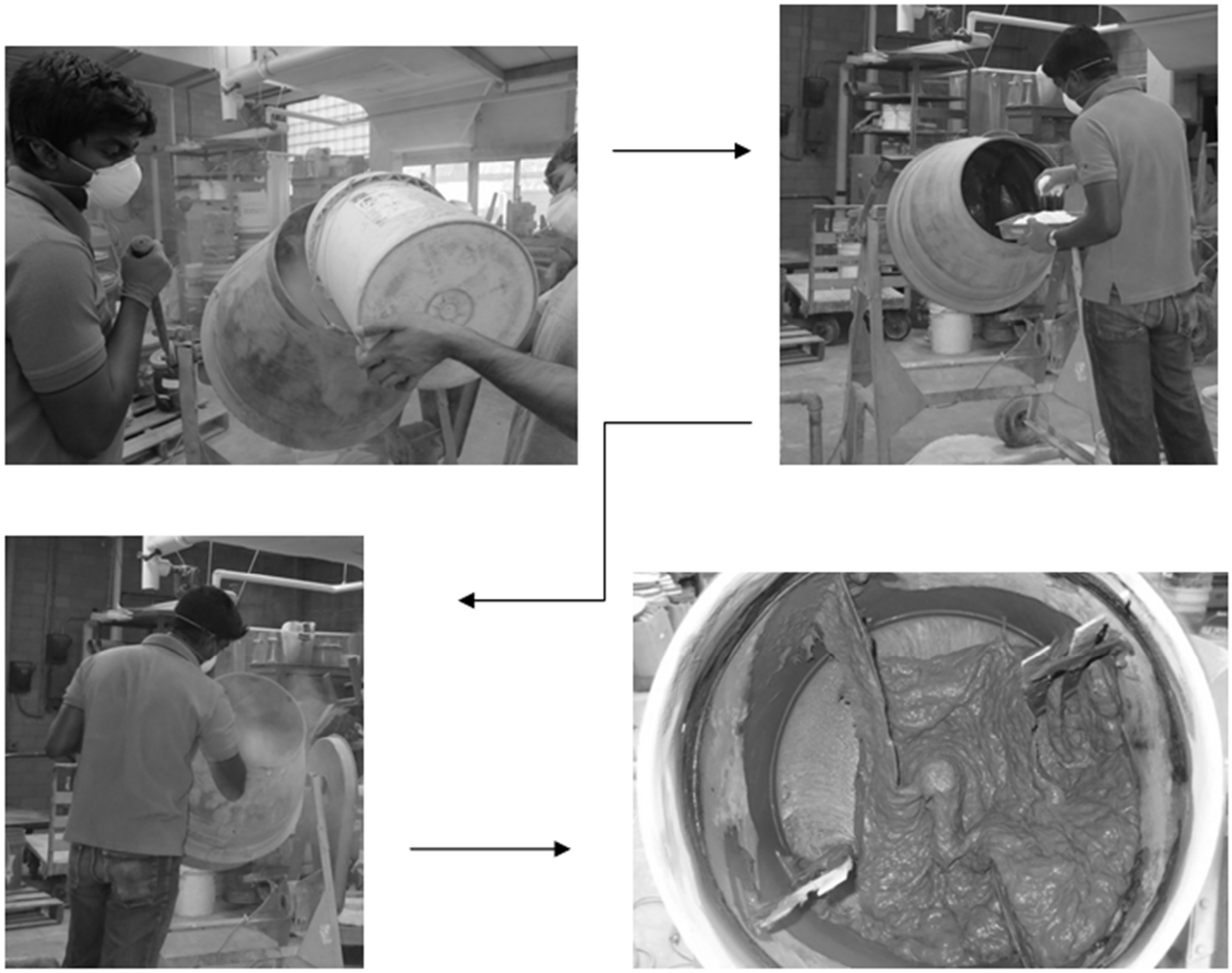


Figure 31: Finalized mix procedure for 36-inch beams

For the final testing process, strain gauges were used to measure the compressive and tensile strains on the beams. Strain gauges were placed in the middle of the top and bottom surfaces of the beams to measure the strains. The beams were tested on the 3-inch side of the beam. This was because of the smooth surface would be on the top and bottom and would facilitate easy attachment for the compression and tension strain gauges. 6 beams were tested for getting a consistent result.

Five beams were not reinforced and one beam was reinforced with carbon fiber reinforced polymer grid at half the depth of the beam.

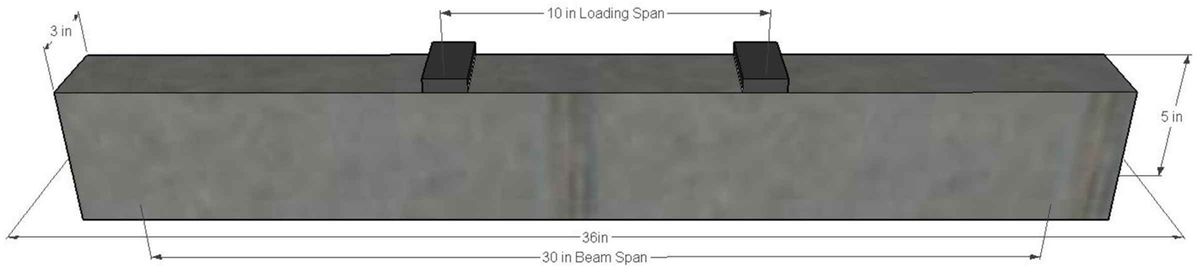


Figure 32: Beam setup for final testing

Five beams were cast and tested using the finalized mix design and procedure. The 60 mm (2.4 in) strain gauges were used to determine the compressive and tensile strains on the top and bottom of the beams respectively. All the beams were tested at 7 days strength. The beams were cured for 3 days covered with a plastic sheet and then the sheet was removed to allow the beams to be cured in the open. None of these beams were reinforced. All the beams were tested till failure.

One beam (8-B) was cast and tested separately. This beam had a reinforcing mesh at mid depth. The primary objective of this research is the use of ECC in bridge approach slabs and the performance of ECC is based on fracture and micromechanics of the cracks. Therefore, the use of steel reinforcement is limited because of the corrosive action of salts used in pavements and expected cracking allowing ingress of these salts, so an alternate to steel such as fiber reinforced polymer (FRP) reinforcing had to be used.

The beam 8-B was reinforced with New Fiber Composite Material for Reinforcing Concrete (NEFMAC) Grids. Table 14 shows the mechanical properties of NEFMAC. Figure 33 shows NEFMAC grid used for reinforcing the beam. The grid was cut into two 36-inch strips and placed at mid depth in the beam. The effective cross section one strip is 17.5 mm^2 (0.03 in^2). Therefore the total area of NEFMAC section is 35 mm^2 (0.05 in^2).

Table 14: Mechanical properties of NEFMAC

Mechanical Properties	Values
Tensile Strength, MPa (ksi)	1,243 (180)
Shear Strength, MPa (ksi)	30 (4.3)
Modulus of Elasticity, MPa (ksi)	100,000 (14,500)

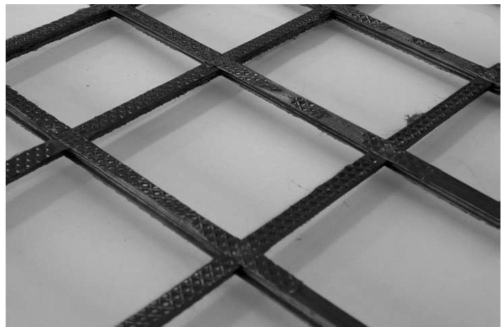


Figure 33: NEFMAC Grid

Results of the final testing process demonstrated the mix design and mix procedure provided consistent workability. The beams were consistent in flexural strength, mid-span deflections and crack pattern. All the beams failed by steady state flat cracking. The results of the testing are tabulated in Table 15 and Figure 34 shows the load vs. deflection curves for the beams. Figure 35 shows the load vs. compressive and tensile strains for the beams. The moment-curvature of the beams is shown in Figure 36. The cracking pattern of the beams can be seen in Figure 37.

Table 15: Results of final testing for 36-inch beams

	6-A	**6-B**	**7-A**	**7-B**	**8-A**
Workability Flow (in)	8	8	8	8	8.5
Peak Load (lbs)	2700	2650	2780	2300	2785
Deflection @ Peak Load (in)	0.250	0.22	0.25	0.2	0.3
Max Deflection (in)	0.35	0.3	0.38	0.383	0.44

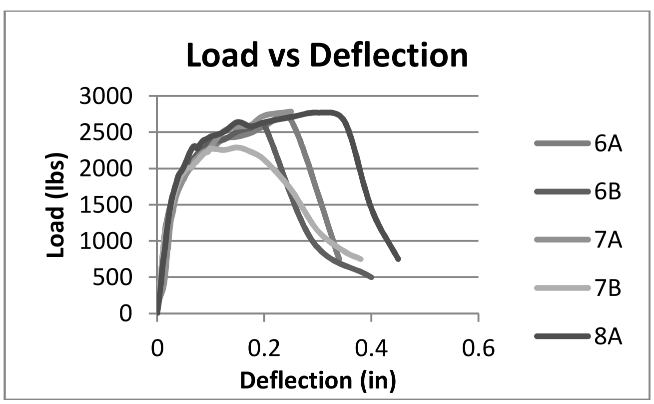


Figure 34: Load vs. deflection curves of final testing for 36-inch beams

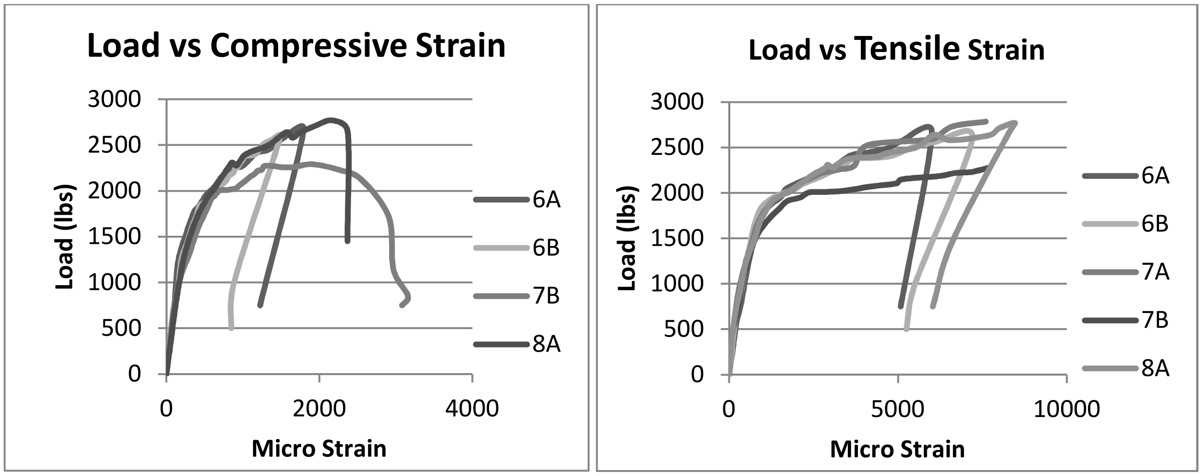


Figure 35: Load vs. strain curves of final testing for 36-inch beams

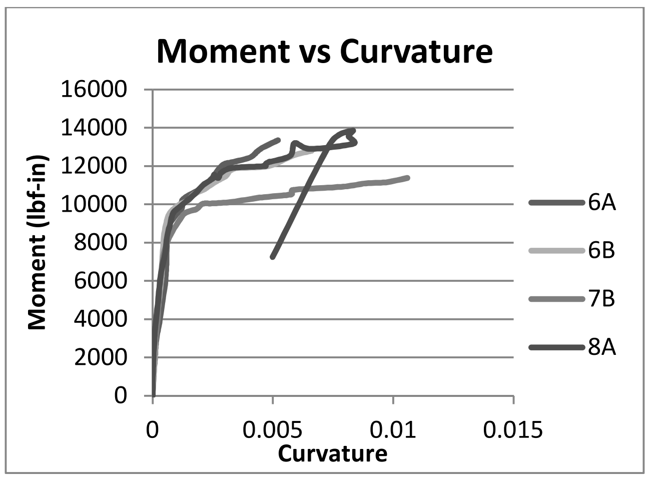


Figure 36: Moment curvature curves for final testing of 36-inch beams

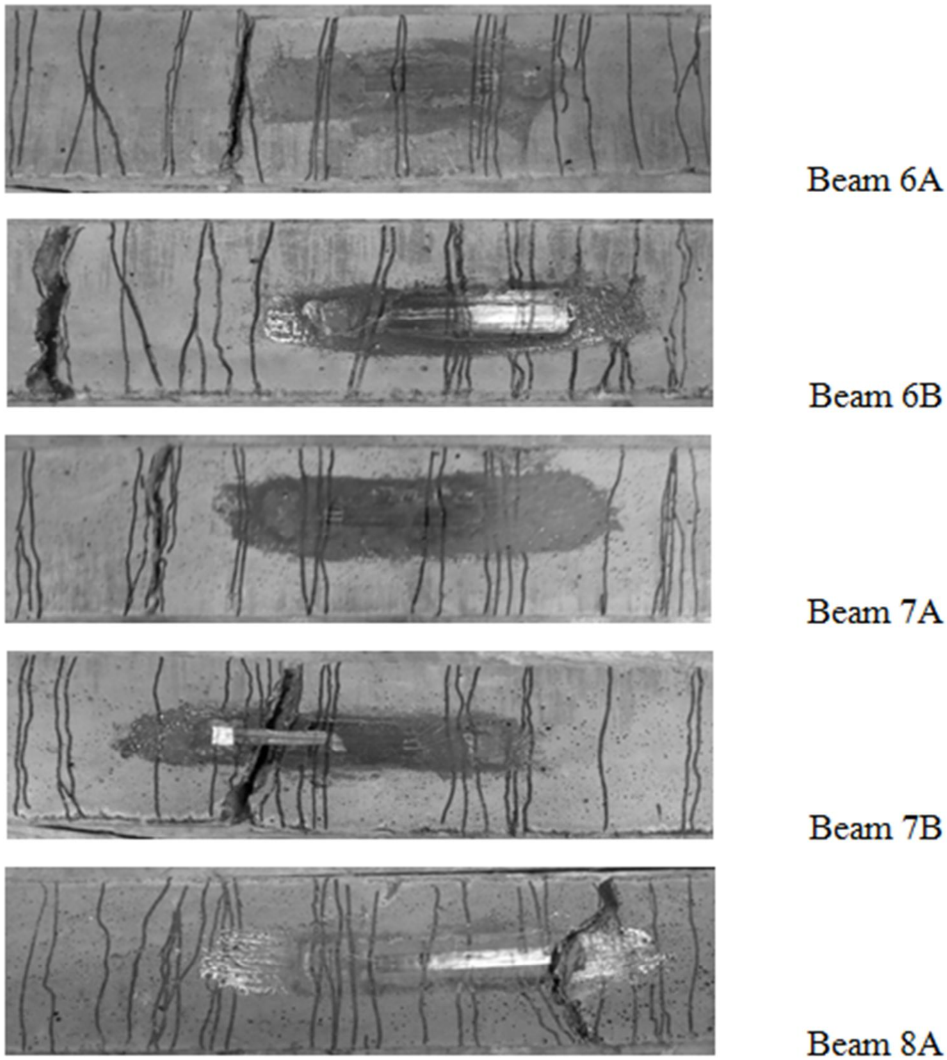


Figure 37: Cracking pattern of beams for final testing of 36-inch beams

The beams with the reinforced mesh demonstrated high flexural strength and high mid-span deflection. The results of the test compared to unreinforced beam of the same mix are tabulated in Table 16.

Table 16: Test results of the mesh reinforced beam compared to unreinforced beam

	Beam 8-A	**Beam 8-B**
Peak Load (lbs)	2785	5750
Deflection @ Peak Load (in)	0.3	0.8
Max Deflection (in)	0.44	2.5

From the above values it can be seen that reinforcing ECC improves its performance by more than 5 times as far as flexibility and ductility are concerned compared to unreinforced ECC.

Figure 38 shows the beam deflecting during testing. Figure 39 shows the crack pattern along the bottom and sides of the beam. Figure 40 shows the cracked section of the beam after failure.

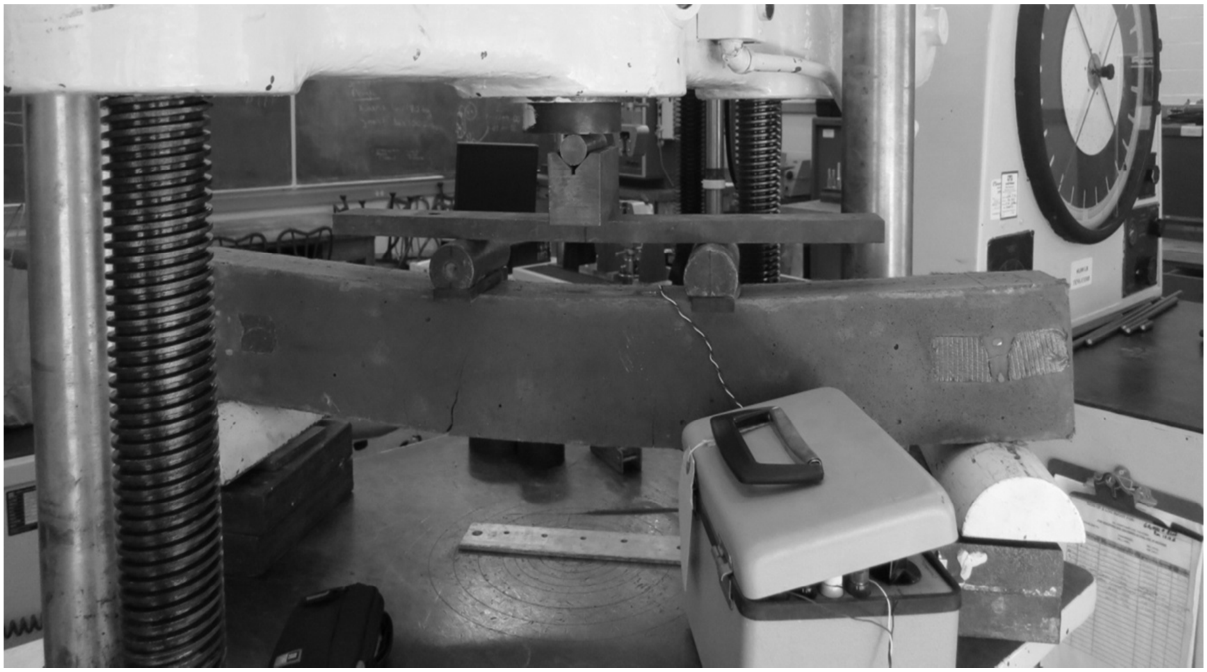


Figure 38: Testing of Beam 8-B

Figure 39: Cracking pattern along the bottom (top) and side (bottom) of Beam 8-B

Figure 40: Cracked surface of Beam 8-B

Figure 41 shows the load vs. deflection curve for beam 8-B. The loads vs. compressive and tensile strains are shown in Figure 42.

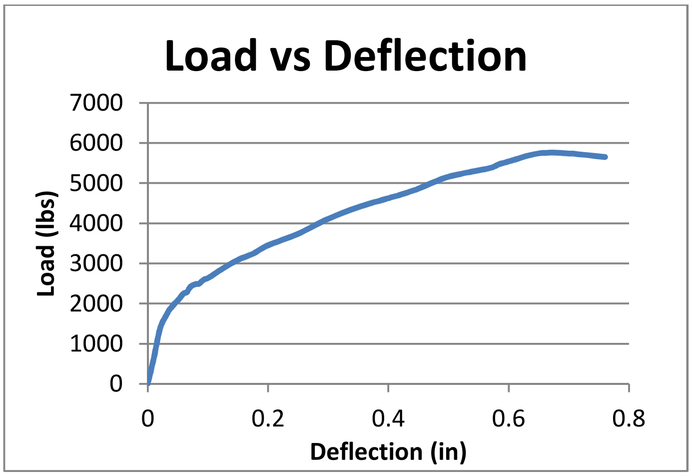


Figure 41: Load vs. deflection of beam 8-B

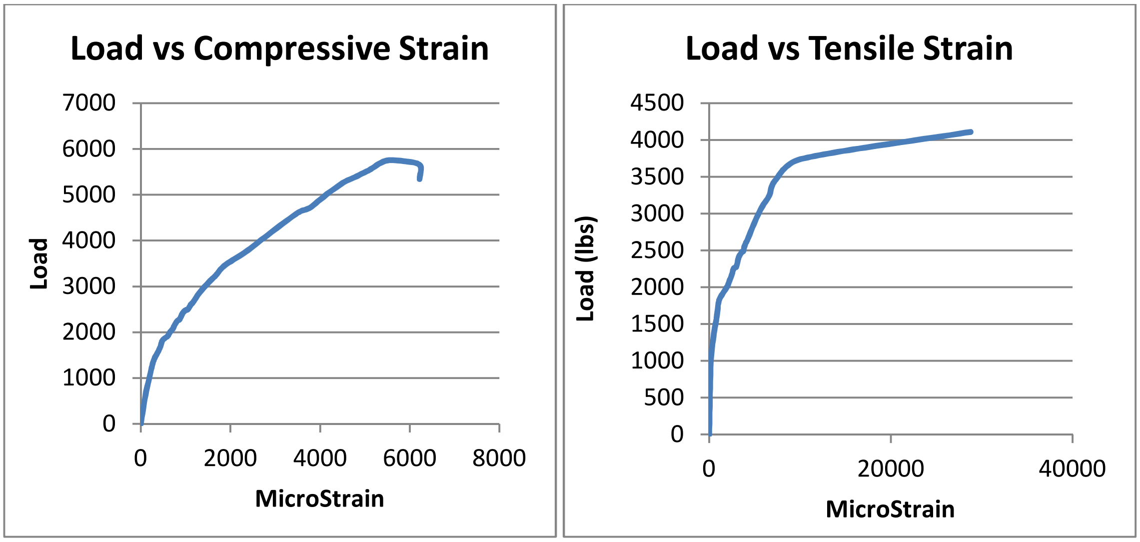


Figure 42: Load vs. strain of Beam 8-B

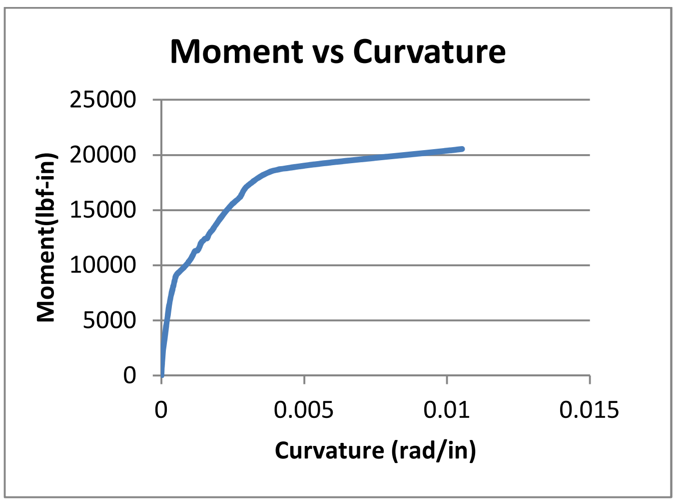


Figure 43: Moment vs. curvature of Beam 8-B

Figure 43 shows the moment vs. curvature curve of beam 8-B. From the curve the neutral axis locations were determined. In the elastic region the neutral axis location varied from 1.7 to 1.5 inches to the top of the beam. In the plastic region the position of the neutral axis varied from 1.2 to 1 inches from the top of the beam.

The results show that the reinforced beam has a very high load capacity compared to the unreinforced beams for the curvature on the beam.

5.3 IMPLEMENTATION OF SECC AS A SLAB AT UW-MILWAUKEE

A pilot scale slab repair project was conducted on the campus of UW-Milwaukee. A portion of a slab on a ramp leading to a parking structure was replaced with a SECC to demonstrate its superior performance compared against the conventional concrete adjacent to the slab. The location for the slab was chosen in a location with severely deteriorated concrete. A main reason for the deterioration of the previous slab was the poor subgrade. Additionally, the slab experiences heavy traffic as it is the route taken by several trucks accessing two different loading docks and is the route for heavy waste removal (including heavy concrete waste removal) equipment. This location ensures that the slab will experience severe conditions throughout its monitoring. The SECC slab also incorporated a layer of electrically conductive material to monitor if any cracks form within the slab, if any chlorides are present, and, potentially, monitor the weight and number of trucks or vehicles passing over the slab. This electrically conductive layer is made of SECC with carbon nano-fibers to ensure the consistency throughout the slab.

The placement of this slab will serve several purposes. First, by successfully pouring a slab, it will be demonstrated that SECC can be incorporated into an existing infrastructure and that the material can be mixed at a large scale instead of small scale laboratory experiments. Next, the slab was created with hollow core section, thus allowing the material to deform under the stress. The ability to deform will be essential as adjacent slabs will generate thermal stresses allowing the SECC slab to dampen and accommodate the deformations of adjacent slabs. When adjacent slabs typically contract due to thermal deformation, a void will form between the slabs allowing water to ingress. When adjacent slabs expand due to thermal expansion, the slabs will push against each other causing buckling and cracking. Construction joints are typically used between the slabs to avoid this problem. By allowing the SECC to deform in either direction, there would be no need for construction joints and no additional joints would form when the adjacent slabs contract due to cold weather. This jointless connection would stop water ingress and help to avoid serious durability issues. Often, steel dowel bars are used to attach the adjacent concrete slabs. If there is a joint allowing water to come in contact with these dowel bars, the steel will begin to corrode, resulting in cracking of the concrete and thus unfavorable driving conditions on pavements. Previous CFIRE projects on SECC have demonstrated the ability of the material to deform without losing any load carrying capacity; therefore, this material will be ideal for creating a jointless concrete pavement.

5.3.1 Design of SECC Slab

The SECC slab was designed to cover a severely damaged connection area 54” wide by 14’ long. The depth of the SECC portion of the slab was designed to be 7” while a 1” section of conventional concrete was placed beneath followed by a layer of intermediate sized aggregate below that. The slab has 8 hollow core sections that are 2” wide by 3” deep with a 2” clear spacing between them. The top of the hollow core sections are 1 ¾” below the surface of the slab, allowing for a ¾” layer of electrically conductive material and a 1” layer of SECC cover. A drawing of the SECC slab section can be seen in Figure 44 where all values are in inches.

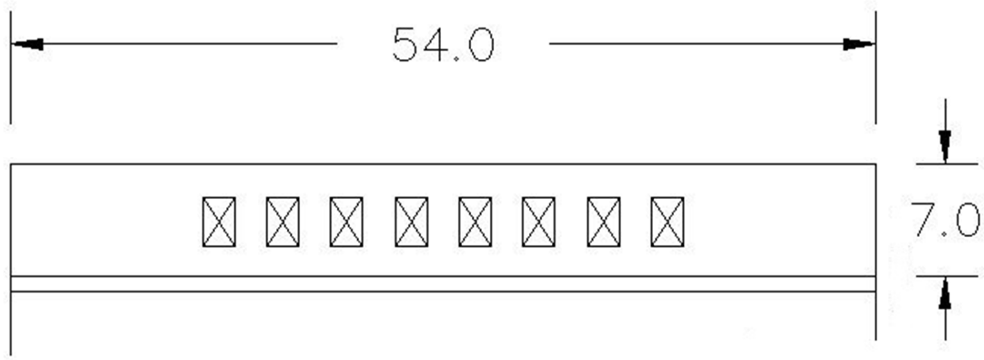


Figure 44: Cross-sectional view of SECC slab (units in inches)

The layer of electrically conductive material was ¾" deep and covered the full width and length of the slab. In this layer, 100 electrodes were spaced 6" apart across the width of the slab and 8" apart across the length. A PVA fiber mesh was placed on the bottom of this layer for mounting the electrodes and for additional reinforcement.

5.3.2 Material used for SECC Slab

The slab that was placed at UW-Milwaukee utilized the same concepts for SECC as discussed by previous CFIRE reports with a few differences in materials. The cementitious materials used for the slab included Type I portland cement from St. Mary's, ground granulated blast furnace slag (slag cement) from Lafarge, metakaolin from Burgess Optipozz, and silica fume from Elkem. Instead of using standard graded silica sand as was done in previous CFIRE research, DOT grade sand was used as the aggregate. The fibers used as reinforcement were polyvinyl alcohol (PVA) RECS 15 x 12 mm Kuralon K-II fibers from Kuraray Japan. The properties of the fibers can be found in Table 17. Commercially available polycarboxylate superplasticizer (PCE/SP, 39% concentration, supplied by Handy Chemicals) was used as modifying admixtures.

Table 17: The properties of PVA fibers

Fiber	**Length (mm)**	**Thickness (dtex)**	**Diameter (mm)**	**Young's Modulus (kN/ mm^2)**	**Tensile Strength (GPa)**
RECS 15x12 mm	12	15	0.040	40	1.6

The superhydrophobic admixture was the same as the one described in CFIRE 05-10 with nano-SiO_2. Polyvinyl alcohol (PVAS), 98% hydrolyzed with molecular weight of 16,000 (Across Chemicals) was used as a surfactant for emulsions. Deionized water (DI water) was used as the dispersion medium for production of emulsions. A polymethyl hydrogen siloxane oil (XIAMETER MHX-1107) from Dow Corning with a specific gravity of 0.997 (at 25°C) and a viscosity of 30 cSt was used as hydrophobic agent. This product contains 85-100% of methyl-hydrogen siloxane as an active agent. Metakaolin from Burgess Optipozz and nano-SiO_2 were used for preparation of the emulsion.

The electrically conductive layer that was used in the slab consisted of the same sand, Type I portland cement, PCE/SP, and PVA fibers listed above. This layer did not include any superhydrophobic admixture but did include a slurry of carbon nano-fibers (CNF) so that the material will become electrically conductive. These CNF are PR-24-XT-PS from Pyrograf Products [22].

A layer of PVA mesh was used to hold in the electrodes used for collecting data in the electrically conductive layer as well as an additional reinforcement. This was a Kuralon PVA filament mesh with 7 mm mesh size and 1000 mm width. The electrodes connected to this PVA mesh were 50 x 5 mm 24 gauge stainless steel. These were connected to 20 gauge wire and transferred to a control box to collect the conductivity data. By measuring the conductivity between these electrodes, the performance of the slab can be monitored [22].

Other materials that were used in the slab included extruded polystyrene rigid foam insulation for the hollow cores, and ASLAN600 glass fiber reinforced polymer (GFRP) dowel bars (1 ¼" diameter x 18" long) from Hughes Bros were used to attach the adjacent slabs. It was critical to have non-steel dowel bars for the slab as the steel would interfere with electrical conductivity readings throughout the slab.

5.3.3 Preliminary Trials of Large Volume Mixes

Several different preliminary trials attempted at different volumes to determine the best mix proportions to use at a large scale. First, a few small trials were run to determine the if the portland cement that was to be used for the actual slab has different properties then the portland cement that was used in previous studies. Small batches were created to test the flow, consistency and admixture compatibility. After running these tests, it was determined that the difference between the two portland cements is minimal and can be neglected. Knowing this, the mix designs that were used for previous studies could be the same as for the large batches that would be used for creating the SECC slab.

After determining the mix designs to be used, large volume mixes were created to determine if the mix proportions would have to be changed to consider the differences in mix volumes. After performing a few tests, not only was it determined that the water content had to be increased from a W/CM of 0.30 to 0.32 and the PCE/SP content was increased from 0.125 to 0.17% by weight of the cementitious material, but it was determined that the volume of the mix has to be limited to 1.25 ft^3 for proper mixing. The material was mixed in a 7 ft^3 industrial mortar mixer. Additionally, the research performed at UW-Madison provided a successful mix design using a drum mixer; however the flexural behavior was not as good as previous studies. For these reasons, an industrial mortar mixer was used to provide the best dispersion of fibers throughout the mixture.

5.3.4 Placing of SECC Slab

The first process in the construction of the SECC slab was to demolish the existing deteriorated portion of the slabs by certified subcontractors. Since only a 4 ½' x 15' section composed of the ends of two adjacent slabs were to be considered, they had to be saw cut and extracted through the use of a jackhammer. Next, the holes for the dowel bars were drilled along with a 2" hole through the adjacent wall for the wires from the electrically conductive layer to be connected to the housing box (Figure 45). After this process was complete, the subgrade was prepared through compaction and a layer of intermediate size (3/4 in) aggregate was applied to cover the subgrade and then compacted until a stable subgrade was achieved. This process need to be repeated several times in some areas because of the soft subgrade below the slab.

Figure 45: Drilling of the dowel bars for the SECC slab by the subcontractor

After the subgrade had been prepared, the dowel bars were inserted into place and wood formwork was created on one side of the cut area which would later be filled with a typical DOT grade concrete. Next, a small, 1" layer of conventional concrete was placed on the surface of the aggregate to ensure that the SECC would not be absorbed within the aggregate requiring additional material. This will also ensure that the SECC will be able to bend if required. Upon completing these tasks, the SECC was ready to be placed.

Prior to mixing of the material, a slurry of silica fume was prepared to ensure proper dispersion of the material within the mix. This was prepared by mixing 1 part of the silica fume and combining it with 3 parts of water. Finally, the SF slurry was mixed and ready for use in SECC.

The mixing procedure was the same as in previous studies. First, 90% of the water was added along with PCE/SP and the silica fume slurry. Next, the sand was added and mixed while the fibers were slowly added over the course of approximately 60 seconds. Next, cementitious materials were slowly added and finally, the remainder of the water was added along with the superhydrophobic emulsion.

After mixing, the material was transported to the slab, where it was compacted in layers (Figure 46). This process took approximately 15 mixes until the material had reached the top of the hollow core sections.

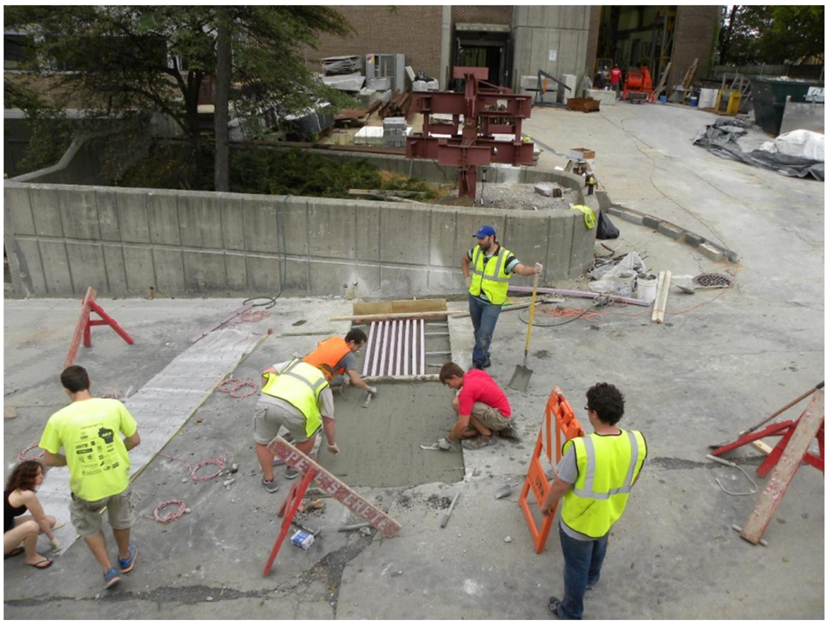


Figure 46: Placing (bottom of picture) and mixing (top right of picture) of SECC

At this point, the PVA fiber mesh was placed (the electrodes were embedded into the PVA mesh prior to casting of the slab) as seen in Figure 47. The wires from each electrode were carefully placed so that they could be threaded together and collected in one location for connection to data acquisition.

Figure 47: Placing of the PVA mesh on the slab

After the PVA mesh was in place, the layer of electrically conductive ECC material [22] was placed on a thin layer ensuring that the sensors would be embedded in this material (Figure 48). The material was mixed in the same order as the SECC for the previous trials; however, the only difference was that the CNF were premixed in a slurry prior to adding to the fiber reinforced concrete. To create this slurry, the CNF were combined with PCE/SP and diluted with water. They were then placed in a vibratory grinding mill for 60 minutes. Next, the slurry was placed in an ultrasound unit for 5 minutes to ensure proper dispersion of the CNF throughout the slurry. After ultrasonication, the material was ready to be mixed with the rest of the fiber reinforced concrete.

Two batches, each of approximately 1.25 ft^3 were required to create the electrically conductive layer. The final proportions of each mix are as follows:

- W/C = 0.32
- S/C = 0.5
- PCE/SP = 0.175 (percent of solid SP by weight cement)
- PVA fiber volume = 2.5%
- CNF = 0.1% (by weight of cement)

Figure 48: Placing the electrically conductive material on the SECC slab

After placement of the electrically conductive layer, an additional 3 layers of SECC were used to complete the slab. The slab was then finished to create a smooth, flat surface and allowed to cure overnight. For the first 7 days of casting, the slab was watered to ensure proper curing and covered by plastic film to avoid moisture loss. The area adjacent to the slab and retaining wall (which was left empty to allow the wires from the electrically conductive layer to pass) was filled with a standard DOT concrete mix a few days after initially placing the SECC. After 7 days of the SECC slab curing, two layers of superhydrophobic coating were placed on the surface of the slab to increase the hydrophobicity and allowed to cure for 2 days. After this point, the slab was reopened for traffic.

6. CONCLUSIONS AND RECOMMENDATIONS

The exceptional mechanical and durability performance of superhydrophobic engineered cementitious composites (SECC) was established by CFIRE 04-09 and CFIRE 05-10 projects. These reports demonstrated significantly improved properties that SECC has compared with conventional concrete. Moreover, it was demonstrated that SECC can be efficiently created with up to 50% of supplementary cementitious materials to reduce the costs, reduce CO_2 emissions, and utilize waste products that would otherwise be placed in landfills. The use of the supplementary cementitious materials also provided an improved durability and mechanical properties of the developed SECC.

The developed SECC is a new cementitious material with both high strengths and high ductility. The high strength capabilities of the material were achieved through the use of a high strength and dense matrix. The addition of superhydrophobic admixtures not only creates tailored air voids to help resist against freezing and thawing, but introduces small, well-spaced voids that act as artificial flaws to promote multi-cracking and strain hardening behavior. Previously, strain hardening behavior in cementitious composites was achieved by weakening the cementitious matrix so that the maximum tensile strength of the composites does not exceed the maximum fiber bridging strength [14]. Moreover, the use of a high strength matrix will lead to lower permeability and lower absorption properties, thus improving the materials durability. The tailored air voids also have hydrophobic properties. The 3-dimensional hydrophobization of the material has many benefits that cannot be achieved with typical concrete sealers. If concrete sealers are used to reduce permeability, the water absorption reduces. However, once cracks occur in the material, water will easily be able to penetrate the material, making the sealer far less effective. By introducing a 3-dimensional hydrophobization, concrete can still crack, while maintaining its water repellant nature and not allowing water transport causing damage upon freezing. The hydrophobic nature of the air voids reduce the amount of water that enters the capillaries prior to the formation of cracks as well.

With two previous reports demonstrating the benefits of SECC, the technology transfer and implementation of the developed material are the key aspects towards utilizing the material in infrastructure. Several international conference and workshop presentations and new research collaborations should definitely help to introduce the material into construction practice. Moreover, the successful implementation of a link slab at UW-Milwaukee demonstrated that the material can be used for infrastructure applications. This pilot slab can also be a showcase for members of industry helping to promote the material as a superior alternative to conventional concrete in critical infrastructure areas. The professional video showcasing the production and benefits of SECC is under development by a professional UW-Milwaukee team.

The creation of a dedicated web-platform, which can be found at super-beton.com, serves as a promotion of the material helping to facilitate the collaboration with other researchers working on similar materials. The web-platform is a place for other researchers and members of industry to have a non-technical overview on the benefits of SECC. Links are also provided for those interested in more technical representations of the data obtained through CFIRE 04-09 and CFIRE 05-10 projects. Demonstration videos will also be uploaded to the website demonstrating the benefits and uses of the material.

The successful implementation of a SECC slab may also serve as a step towards implementing the material to be used as a jointless concrete pavement. Joints in concrete pavements often lead to serious durability issues and producing a material with no joints would significantly improve the durability of concrete pavements. The ability of SECC to deform without losing load carrying capacity would make it an ideal candidate for creating a jointless concrete connection.

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APPENDIX A: WORKSHOP PROGRAMS

In Partnership With
Center for By-products Utilization
(CBU)

CFIRE National Center for Freight & Infrastructure Research & Education

Workshop on "Smart Materials for Sustainable Infrastructure"

Friday, 30th November 2012 * EMS E237 1:00 to 5:00pm.

Controlling Properties of Concrete through Nanomodification
Surendra P. Shah, Emeritus Walter P. Murphy Professor of Civil Engineering, Northwestern University, Illinois.

High Performance Superhydrophobic Engineered Cementitious Composites (SECC) for use in Highway Applications
Scott Muzenski, Research Assistant, Ph.D. Student, UW-Milwaukee
Ismael Flores-Vivian, Post-Doctorate Associate, UW-Milwaukee
Konstantin Sobolev, Associate Professor, UW-Milwaukee

Quantum-Chemistry Based Atomistic Study of Asphalt Oxidation and Antioxidants: a nanomechanics approach for evaluating sustainable infrastructure
Yang Lu. Ph.D. Research Associate, Engineering Laboratory
National Institute of Standards and Technology

Functionalization of Carbon Nanotubes for Improvement of Concrete Strength
Sergey Petrunin, Ph.D. Student, Vladimir State University
Victor E. Vaganov, Professor, Vladimir State University

Smart Carbon Nano-/PVA Fiber-Reinforced Composites Capable of Stress Sensing and Chloride Ion Detection
Joshua Hoheneder, MS Student, UW-Milwaukee
Ismael Flores-Vivian, Post-Doctorate Associate, UW-Milwaukee
Konstantin Sobolev, Associate Professor, UW-Milwaukee

Engineered Cementitious Composite to Enhance the Durability of Bridge Approach Slabs
Rehan Rauf, MS Student, University of Wisconsin-Madison
Michael G. Oliva, Professor, University of Wisconsin-Madison

Contact: Konstantin Sobolev
Tel: 414-229-3198 | E-mail: sobolev@uwm.edu

UNIVERSITY of WISCONSIN UWMILWAUKEE

in partnership with **Center for Byproduct Utilization - CBU**

CFIRE National Center for Freight & Infrastructure Research & Education

Workshop on "Advanced and Sustainable Materials for Infrastructure Renewal"

Friday, May 3rd 1:00-4:45pm

UW-Milwaukee Engineering and Mathematical Sciences Building (EMS) Room E237

PROGRAM:

1:00pm **Welcome:** Konstantin Sobolev, UW-Milwaukee

1.05pm ***Keynote:* History and Design of Engineered Cementitious Composites**
Victor C. Li, University of Michigan, Ann Arbor

2:00pm **Nano Particles in High Performance Cement-Based Materials**
Konstantin Sobolev, Ismael Flores-Vivian, Rani G.K. Pradoto, UW-Milwaukee

2:20pm **Overhydrophobic and Superhydrophobic Engineered Cementitious Composites**
Scott Muzenski, Ismael Flores-Vivian, Konstantin Sobolev, UW-Milwaukee

2:45pm ***Tea/Coffee Break - 15 minutes***

3:00pm **Towards Superhydrophobicity and Icephobicity of Concrete**
Ismael Flores-Vivian, Vahid Hejazi, Sunil Rao, Michael Nosonovksy, UW-Milwaukee

3:20pm **Ashphalt: Performance of Fly Ash in Asphalt**
Ahmed Faheem, UW-Platteville, Art Covi, We Energies

3:45pm **The Use of Engineered Cementitious Composites in Bridge Approach Slabs**
Michael G. Oliva, UW-Madison

4:15pm **Fracture testing of carbon fiber and nanotube reinforced mortar**
Pete Stynoski, Paramita Mondal, University of Illinois at Urbana-Champaign; US Army Corps of Engineers ERDC-Champaign

4:45pm **Summary and Closing Remarks:**
Konstantin Sobolev, UW-Milwaukee

Contact: Ismael Flores-Vivian Tel: 414-229-3229 | E-mail: ismaelfv@uwm.edu
Contact: Konstantin Sobolev Tel: 414-229-3198 | E-mail: sobolev@uwm.edu

PRESENTER RESEARCH INTERESTS

- **Art Covi, We Energies:** He has over 28 years of experience with We Energies. He has managed a variety of MGP, PCB, Ash landfill, and other site investigations and remediation projects including budgeting, risk assessment and contractor management. He holds a BS in Civil Engineering degree from UW-Milwaukee**.**

- **Ahmed Faheem, Assistant Professor, UW-Platteville:** Highway PCC/HMA construction; application of mineral fillers in hot mix asphalt; by-product utilization.

- **Ismael Flores, Postdoc Associate, Department of Civil Engineering and Mechanics, UWM:** Innovative design and characterization of state-of-the-art construction materials. Utilization of supplementary cementitious materials for high performance materials. Investigation of fresh and hardened properties of construction materials. Development of green sustainable alternatives to conventional concrete. Fiber-reinforced composites and Nano-fiber/smart composites.

- **Vahid Hejazi, Research Assistant, PhD Candidate, UWM:** Biomimetics, superhydrophobicity, oleophobicity, icephobicity, Self-organization at the interface (self-healing, self-lubrication, self-cleaning), Adhesion science, and Experimental heat transfer.

- **Victor Li, FASCE, FASME, FWIF, FACI. The E. Benjamin Wylie Collegiate Professor of Civil Engineering, University of Michigan, Ann Arbor:** Research interests are in multifunctional concrete materials targeted at enhancing infrastructure sustainability and resiliency. He led the research team that invented Engineering Cementitious Composites, popularly known as "Bendable Concrete". Professor Li's research and societal impacts have been featured in the CBS Evening News, the Discovery Channel, the Architectural Record, the American Ceramic Society, the Portland Cement Association, and the Forbes Magazine, amongst many other public media. http://www.engin.umich.edu/acemrl/

- **Scott Muzenski, Research Assistant, UWM:** Ph.D candidate in Civil Engineering and Mechanics. He received a B.S. in Civil Engineering and Mechanics (Structural Emphasis) and M.S. in Engineering (Structural and Construction Materials Emphasis) from UWM. Research interests include mechanical behavior and durability of fiber reinforced concrete, use of nano-particles to improve concrete performance, and by-product utilization for cement-based materials.

- **Michael Nosonovsky, Assistant Professor, Department of Mechanical Engineering, UWM:** Self-organization at the interface (self-healing, self-lubrication, self-cleaning). Biomimetic surfaces, including novel applications of the Lotus effect (omniphobicity, anti-fouling). Adhesion and capillary force. Contact mechanics and dynamic friction. Fundamentals of friction and classical mechanics, History of classical mechanics.

- **Michael G. Oliva, Professor, Department of Civil and Environmental Engineering, College of Engineering, University of Wisconsin-Madison**: Highway bridge design, innovative bridge systems. Design and connections in precast concrete structural systems**.** Structural dynamics, vibration of structures and dynamic analysis**.** Sustainability of infrastructure, material usage and recycling, energy consumption and energy analysis.

- **Konstantin Sobolev, Associate Professor, Department of Civil Engineering and Mechanics, UWM:** High-performance cement based composites, application of nanomaterials in construction, by-product utilization and waste utilization.

- **Pete Stynoski, University of Illinois at Urbana-Champaign:** He holds a BS in Engineering Mechanics and an MS in Civil Engineering from UIUC. Pete is a recipient of the SMART Scholarship for Service in coordination with the US Army ERDC Construction Engineering Research Laboratory.

THANK YOU!

APPENDIX B: ABSTRACTS/POSTERS FROM INTERNATIONAL CONFERENCES

ACI Fall 2012 Convention (ACI committee 236D: Nanotechnology of Concrete), Toronto, Canada, October 2012

The Application of Superhydrophobic Admixtures with Nanoparticles in Engineered Cementitious Composites

The requirements for a precisely engineered air void structure are essential for cementitious materials designed to serve under severe freezing and thawing cycles. Many conventional air-entraining admixtures used in concrete often tend to produce large, non-spherical, poorly dispersed air voids. Poor air void characteristics are not sufficient for concrete exposed to harsh freezing and thawing cycles at the edge and beyond standard specifications. A hydrogen-containing siloxane emulsion can be engineered to produce desired air void system in a cementitious matrix with small, well-dispersed voids. Moreover, the addition of nano-particles forms a more stable emulsion and produces voids with superhydrophobic walls capable to further improve the freeze-thaw resistance. Unlike conventional air entraining admixtures, the use of the emulsions creates a material with adequate amounts of air and only minor reductions in compressive strength. Combining the developed emulsions with fiber reinforced composites produces a cementitious material capable of multi-cracking and strain hardening behavior as the well-dispersed air voids act as artificial flaws to initiate cracking. This research demonstrates the improved air void structure of cementitious materials with polymethyl hydrosiloxane emulsions with little to no reduction in compressive/flexural strength.

ACI Fall 2012 Convention (ACI committee 544F: Durability of Fiber Reinforced Concrete),Toronto, Canada, October 2012

High Performance Superhydrophobic Engineered Cementitious Composites (SECC) for Highway Applications

The United States infrastructure is in desperate need of repair, especially in regions exposed to harsh environments. Freezing and thawing cycles in northern regions lead to early need for repair or failure of bridges. A more durable concrete is required in order to increase the service life of roadways and to minimize the need for repair. The use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) creates a durable concrete capable of withstanding large deformations from temperature variations, freezing and thawing cycles, and cyclic loading; greatly extending the service life of roadways. This is achieved by the increased deformability created by the multi-cracking behavior of the ECC. Combining ECC with superhydrophobic admixtures (SECC) creates a material with water repellant air voids to even further increase the materials resistance to freezing and thawing cycles. Additionally, the application of superhydrophobic admixtures creates a well distributed air void system that acts as artificial flaws to promote multi-cracking and strain-hardening behavior.

This research demonstrates that the durability of the developed material can exceed performance of conventional concrete, since cracks that inevitably form within cementitious materials are held small enough so that minimal amounts of water can penetrate the crack while at the same time the water repellant nature of the crack eliminates water from freezing within the crack.

The developed SECC materials are perfectly suited for structural and repair applications in critical elements of transportation infrastructure where high-performance and reliability are required.

Workshop on "Smart Materials for Sustainable Infrastructure," Milwaukee, WI, November 2012

High Performance Superhydrophobic Engineered Cementitious Composites (SECC) for Highway Applications

The United States infrastructure is in desperate need of repair, especially in regions exposed to harsh environments. Freezing and thawing cycles in northern regions lead to early need for repair or failure of bridges. A more durable concrete is required in order to increase the service life of roadways and to minimize the need for repair. The use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) creates a durable concrete capable of withstanding large deformations from temperature variations, freezing and thawing cycles, and cyclic loading; greatly extending the service life of roadways. This is achieved by the increased deformability created by the multi-cracking behavior of the ECC. Combining ECC with superhydrophobic admixtures (SECC) creates a material with water repellant air voids to even further increase the materials resistance to freezing and thawing cycles. This research demonstrates that the durability of the developed material can exceed performance of conventional concrete, since cracks that inevitably form within cementitious materials are held small enough so that minimal amounts of water can penetrate the crack while at the same time the water repellant nature of the crack eliminates water from freezing within the crack. Additionally, the addition of superhydrophobic admixtures creates a well distributed air void system that acts as artificial flaws to promote multi-cracking and strain-hardening behavior.

Transportation Research Board Annual Meeting, Washington DC, January 2013

Superhydrophobic Fiber-Reinforced Composites for Highway Applications

The requirements for a precisely engineered air void structure are essential for cementitious materials designed to serve under severe freezing and thawing cycles. Many conventional air-entraining admixtures used in concrete often tend to produce large, non-spherical, poorly dispersed air voids. Poor air void characteristics are not sufficient for concrete exposed to harsh freezing and thawing cycles at the edge and beyond standard specifications. A hydrogen-containing siloxane emulsion can be engineered to produce desired air void system in a cementitious matrix with small, well-dispersed voids. Moreover, the addition of nano-particles forms a more stable emulsion and produces voids with superhydrophobic walls capable to further improve the freeze-thaw resistance. Unlike conventional air entraining admixtures, the use of the emulsions creates a material with adequate amounts of air and only minor reductions in compressive strength. Combining the developed emulsions with fiber reinforced composites produces a cementitious material capable of multi-cracking and strain hardening behavior as the well-dispersed air voids act as artificial flaws to initiate cracking. This research demonstrates the improved air void structure of cementitious materials with polymethyl hydrosiloxane emulsions with little to no reduction in compressive/flexural strength.

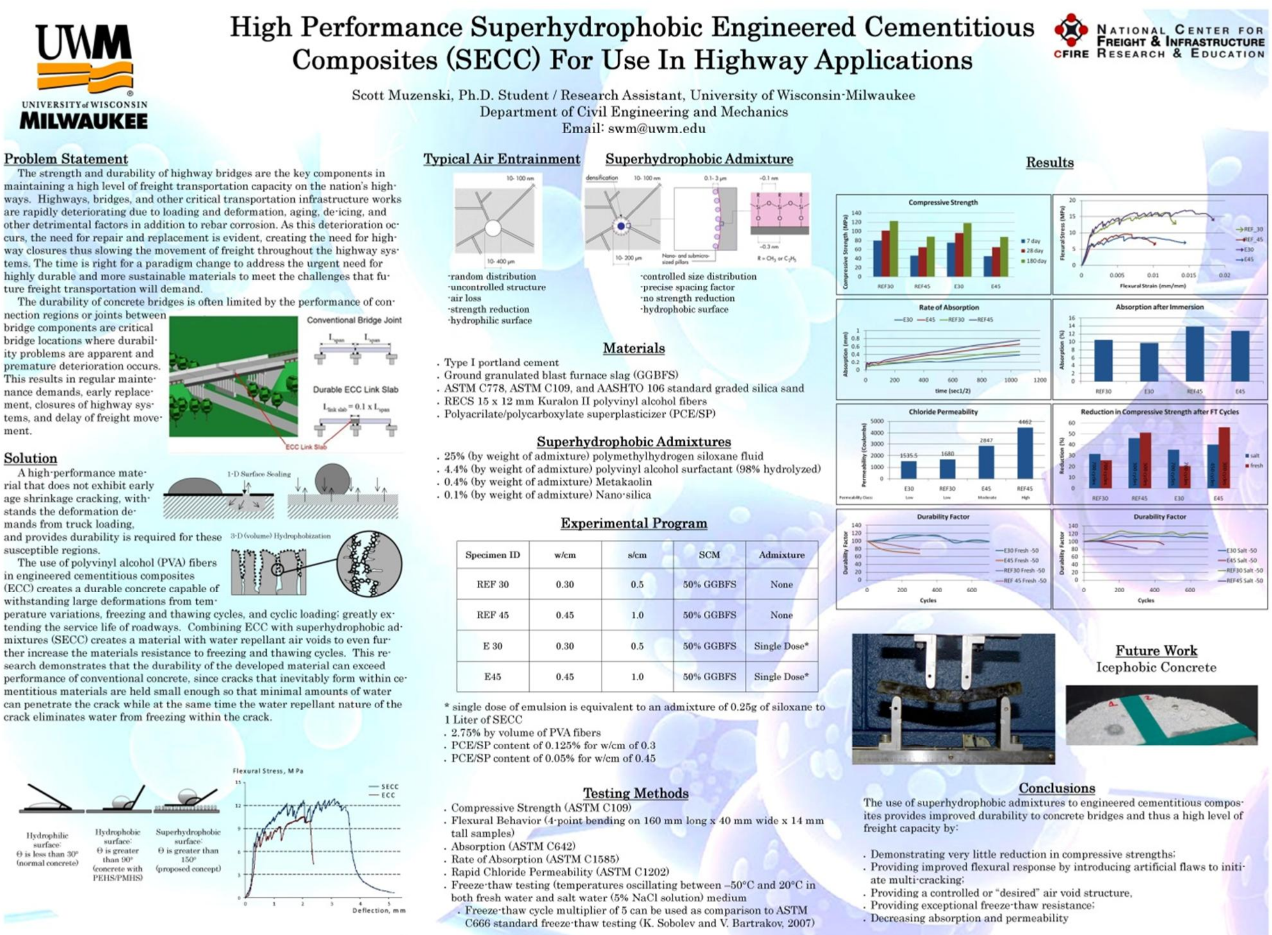
CFIRE Student Freight Symposium, Memphis, TN, February 2013

High Performance Superhydrophobic Engineered Cementitious Composites (SECC) for Highway Applications

The strength and durability of highway bridges are the key components in maintaining a high level of freight transportation capacity on the nation's highways. Highways, bridges, and other critical transportation infrastructure works are rapidly deteriorating due to loading and deformation, aging, de-icing, and other detrimental factors in addition to rebar corrosion. As this deterioration occurs, the need for repair and replacement is evident, creating the need for highway closures thus slowing the movement of freight throughout the highway systems. The time is right for a paradigm change to address the urgent need for highly durable and more sustainable materials to meet the challenges that future freight transportation will demand.

The durability of concrete bridges is often limited by the performance of connection regions or joints between bridge components, especially in decks. The connection between an approach slab and bridge deck, or joints in the bridge deck, or the portion of bridge deck bending in a negative curvature above mid-span bridge piers, are critical bridge locations where durability problems are apparent and premature deterioration occurs. This results in regular maintenance demands, early replacement, closures of highway systems, and delay of freight movement. A high-performance material that does not exhibit early age shrinkage cracking, withstands the deformation demands from truck loading, and provides durability is required for these susceptible regions.

The use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) creates a durable concrete capable of withstanding large deformations from temperature variations, freezing and thawing cycles, and cyclic loading; greatly extending the service life of roadways. Combining ECC with superhydrophobic admixtures (SECC) creates a material with water repellant air voids to even further increase the materials resistance to freezing and thawing cycles. This research demonstrates that the durability of the developed material can exceed performance of conventional concrete, since cracks that inevitably form within cementitious materials are held small enough so that minimal amounts of water can penetrate the crack while at the same time the water repellant nature of the crack eliminates water from freezing within the crack.

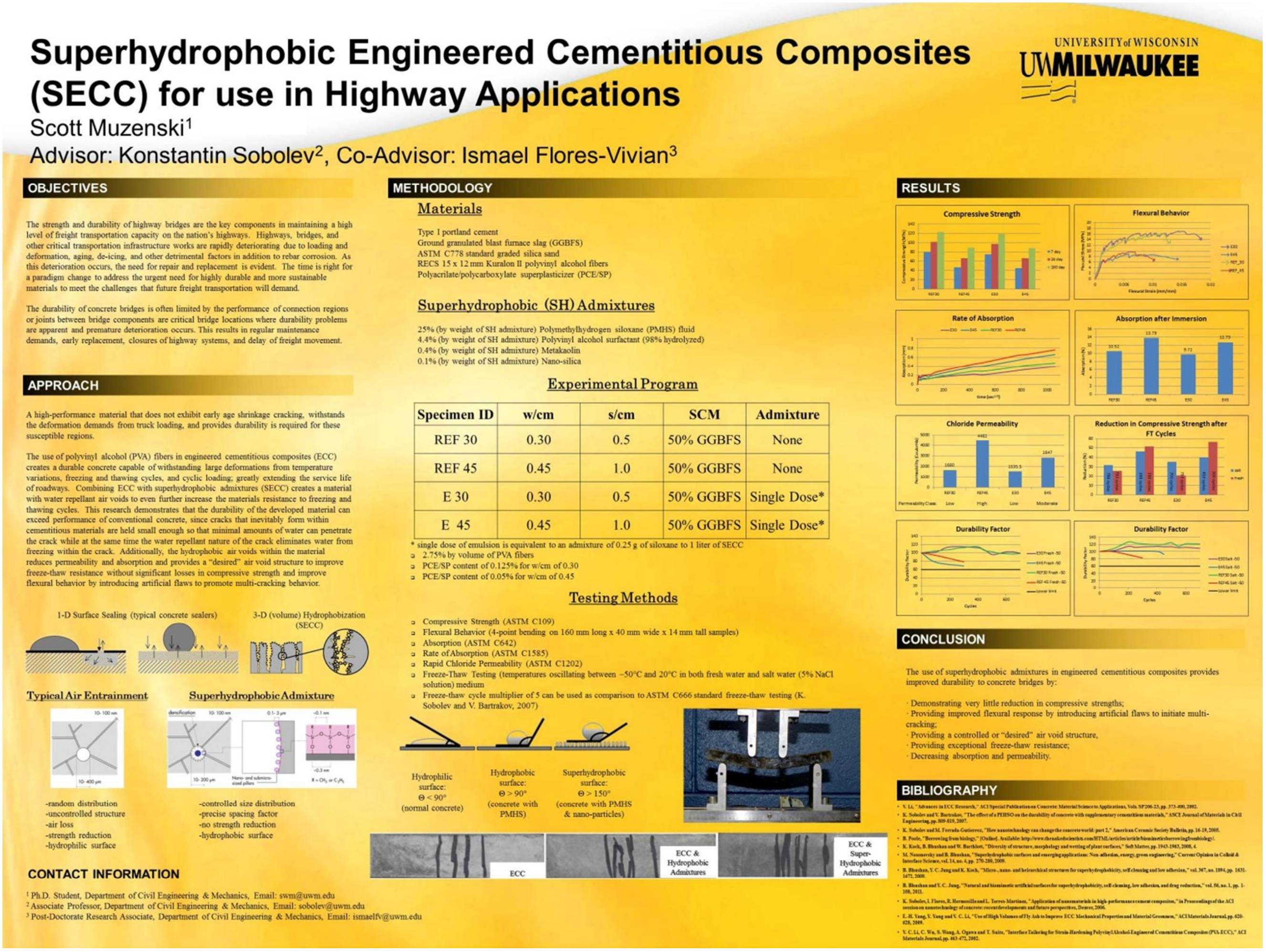


Workshop on "Advanced and Sustainable Materials for Infrastructure Renewal," Milwaukee, WI, May 2013

Overhydrophobic and Superhydrophobic Engineered Cementitious Composites
The key elements of infrastructure throughout the United States are showing poor durability, especially in northern regions where freeze-thaw damage is prevalent. One main factor leading to the early deterioration of concrete materials is the infiltration of water into the porous space. To account for this, sealers or water repellant coatings are often placed on the surface of cementitious materials to reduce the ingress of water into the material. However, when the material cracks, which is inevitable, water can easily penetrate and saturate the material. By incorporating a 3-dimensional hydrophobic admixture within the concrete, water is not allowed to enter the capillary voids and porous space, where, upon freezing, damage occurs. This type of modification is achieved in superhydrophobic engineered cementitious composites (SECC) designed with water repellant air voids evenly distributed throughout the cementitious matrix, providing the best protection against water infiltration. Moreover, SECC incorporates fiber reinforcement which effectively limits the crack opening. The reported research demonstrates the improved durability in fiber reinforced cementitious materials by creating a 3-dimensional hydrophobization to reduce the water absorption and permeability and improve the freeze-thaw performance.

ACerS Cement Division 4th Advances in Cement-based Materials: Characterization, Processing, Modeling and Sensing, Champaign, IL, July 2013 (Winning Poster)

Superhydrophobic Engineered Cementitious Composites (SECC) for Highway Applications
The United States infrastructure is in desperate need of repair, especially in regions exposed to harsh environments. Freezing and thawing cycles in northern regions lead to early need for repair or failure of bridges. A more durable concrete is required in order to increase the service life of roadways and to minimize the need for repair. The use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) creates a durable concrete capable of withstanding large deformations from temperature variations, freezing and thawing cycles, and cyclic loading; greatly extending the service life of roadways. This is achieved by the increased deformability created by the multi-cracking behavior of the ECC. Combining ECC with superhydrophobic admixtures (SECC) creates a material with water repellant air voids to even further increase the materials resistance to freezing and thawing cycles. This research demonstrates that the durability of the developed material can exceed performance of conventional concrete, since cracks that inevitably form within cementitious materials are held small enough so that minimal amounts of water can penetrate the crack while at the same time the water repellant nature of the crack eliminates water from freezing within the crack. Additionally, the addition of superhydrophobic admixtures creates a well distributed air void system that acts as artificial flaws to promote multi-cracking and strain-hardening behavior.



Superhydrophobic Engineered Cementitious Composites (SECC) for use in Highway Applications

Scott Muzenski[1]
Advisor: Konstantin Sobolev[2], Co-Advisor: Ismael Flores-Vivian[3]

UNIVERSITY of WISCONSIN
UWMILWAUKEE

OBJECTIVES

The strength and durability of highway bridges are the key components in maintaining a high level of freight transportation capacity on the nation's highways. Highways, bridges, and other critical transportation infrastructure works are rapidly deteriorating due to loading and deformation, aging, de-icing, and other detrimental factors in addition to rebar corrosion. As this deterioration occurs, the need for repair and replacement is evident. The time is right for a paradigm change to address the urgent need for highly durable and more sustainable materials to meet the challenges that future freight transportation will demand.

The durability of concrete bridges is often limited by the performance of connection regions or joints between bridge components are critical bridge locations where durability problems are apparent and premature deterioration occurs. This results in regular maintenance demands, early replacement, closures of highway systems, and delay of freight movement.

APPROACH

A high-performance material that does not exhibit early age shrinkage cracking, withstands the deformation demands from truck loading, and provides durability is required for these susceptible regions.

The use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) creates a durable concrete capable of withstanding large deformations from temperature variations, freezing and thawing cycles, and cyclic loading; greatly extending the service life of roadways. Combining ECC with superhydrophobic admixtures (SECC) creates a material with water repellant air voids to even further increase the materials resistance to freezing and thawing cycles. This research demonstrates that the durability of the developed material can exceed performance of conventional concrete, since cracks that inevitably form within cementitious materials are held small enough so that minimal amounts of water can penetrate the crack while at the same time the water repellant nature of the crack eliminates water from freezing within the crack. Additionally, the hydrophobic air voids within the material reduces permeability and absorption and provides a "desired" air void structure to improve freeze-thaw resistance without significant losses in compressive strength and improve flexural behavior by introducing artificial flaws to promote multi-cracking behavior.

1-D Surface Sealing (typical concrete sealers) — 3-D (volume) Hydrophobization (SECC)

Typical Air Entrainment

- -random distribution
- -uncontrolled structure
- -air loss
- -strength reduction
- -hydrophilic surface

Superhydrophobic Admixture

- -controlled size distribution
- -precise spacing factor
- -no strength reduction
- -hydrophobic surface

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METHODOLOGY

Materials

Type I portland cement
Ground granulated blast furnace slag (GGBFS)
ASTM C778 standard graded silica sand
RECS 15 x 12 mm Kuralon II polyvinyl alcohol fibers
Polyacrilate/polycarboxylate superplasticizer (PCE/SP)

Superhydrophobic (SH) Admixtures

25% (by weight of SH admixture) Polymethylhydrogen siloxane (PMHS) fluid
4.4% (by weight of SH admixture) Polyvinyl alcohol surfactant (98% hydrolyzed)
0.4% (by weight of SH admixture) Metakaolin
0.1% (by weight of SH admixture) Nano-silica

Experimental Program

Specimen ID	w/cm	s/cm	SCM	Admixture
REF 30	0.30	0.5	50% GGBFS	None
REF 45	0.45	1.0	50% GGBFS	None
E 30	0.30	0.5	50% GGBFS	Single Dose*
E 45	0.45	1.0	50% GGBFS	Single Dose*

* single dose of emulsion is equivalent to an admixture of 0.25 g of siloxane to 1 liter of SECC

- 2.75% by volume of PVA fibers
- PCE/SP content of 0.125% for w/cm of 0.30
- PCE/SP content of 0.05% for w/cm of 0.45

Testing Methods

- Compressive Strength (ASTM C109)
- Flexural Behavior (4-point bending on 160 mm long x 40 mm wide x 14 mm tall samples)
- Absorption (ASTM C642)
- Rate of Absorption (ASTM C1585)
- Rapid Chloride Permeability (ASTM C1202)
- Freeze-Thaw Testing (temperatures oscillating between −50°C and 20°C in both fresh water and salt water (5% NaCl solution) medium
- Freeze-thaw cycle multiplier of 5 can be used as comparison to ASTM C666 standard freeze-thaw testing (K. Sobolev and V. Bartrakov, 2007)

Hydrophilic surface: Θ < 90° (normal concrete)
Hydrophobic surface: Θ > 90° (concrete with PMHS)
Superhydrophobic surface: Θ > 150° (concrete with PMHS & nano-particles)

ECC — ECC & Hydrophobic Admixtures — ECC & Super-Hydrophobic Admixtures

RESULTS

Compressive Strength
Flexural Behavior
Rate of Absorption
Absorption after Immersion
Chloride Permeability
Reduction in Compressive Strength after FT Cycles
Durability Factor
Durability Factor

CONCLUSION

The use of superhydrophobic admixtures in engineered cementitious composites provides improved durability to concrete bridges by:

- Demonstrating very little reduction in compressive strengths;
- Providing improved flexural response by introducing artificial flaws to initiate multi-cracking;
- Providing a controlled or "desired" air void structure,
- Providing exceptional freeze-thaw resistance;
- Decreasing absorption and permeability.

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Concreep9, Cambridge, MA, September 2013

Freeze-Thaw Resistance of Fiber Reinforced Composites with Superhydrophobic Admixtures

The United States' infrastructure is in desperate need of repair, especially in areas exposed to harsh environments. Freezing and thawing cycles in northern regions lead to serious durability issues in bridges and early need for repair of replacement. The use of polyvinyl alcohol (PVA) fibers in cementitious composites creates a durability concrete capable of withstanding large deformations from temperature variations such as freezing and thawing cycles and heavy loading. Greater longevity is achieved in the service life of roadways due to the increased deformability created by the multi-cracking and strain hardening behavior of PVA fibers in cementitious composites. The addition of fibers alone to a cementitious may not be adequate in providing resistance to freezing and thawing far beyond the recommended 300 cycles. The addition of superhydrophobic admixtures to fiber reinforced composites in this research creates an air void system with many, small, well-dispersed air voids to allow for better resistance to freezing and thawing. Moreover, the superhydrophobic nature of these air voids create a water repellant surface to the voids ensuring water does not freeze within capillaries and only minimal internal stresses occur during freezing. This research demonstrates that the addition of superhydrophobic admixtures to fiber reinforced cementitious composites provides similar if not improved stiffness and compressive behavior of cementitious materials through as many as 700 accelerated freeze-thaw cycles.

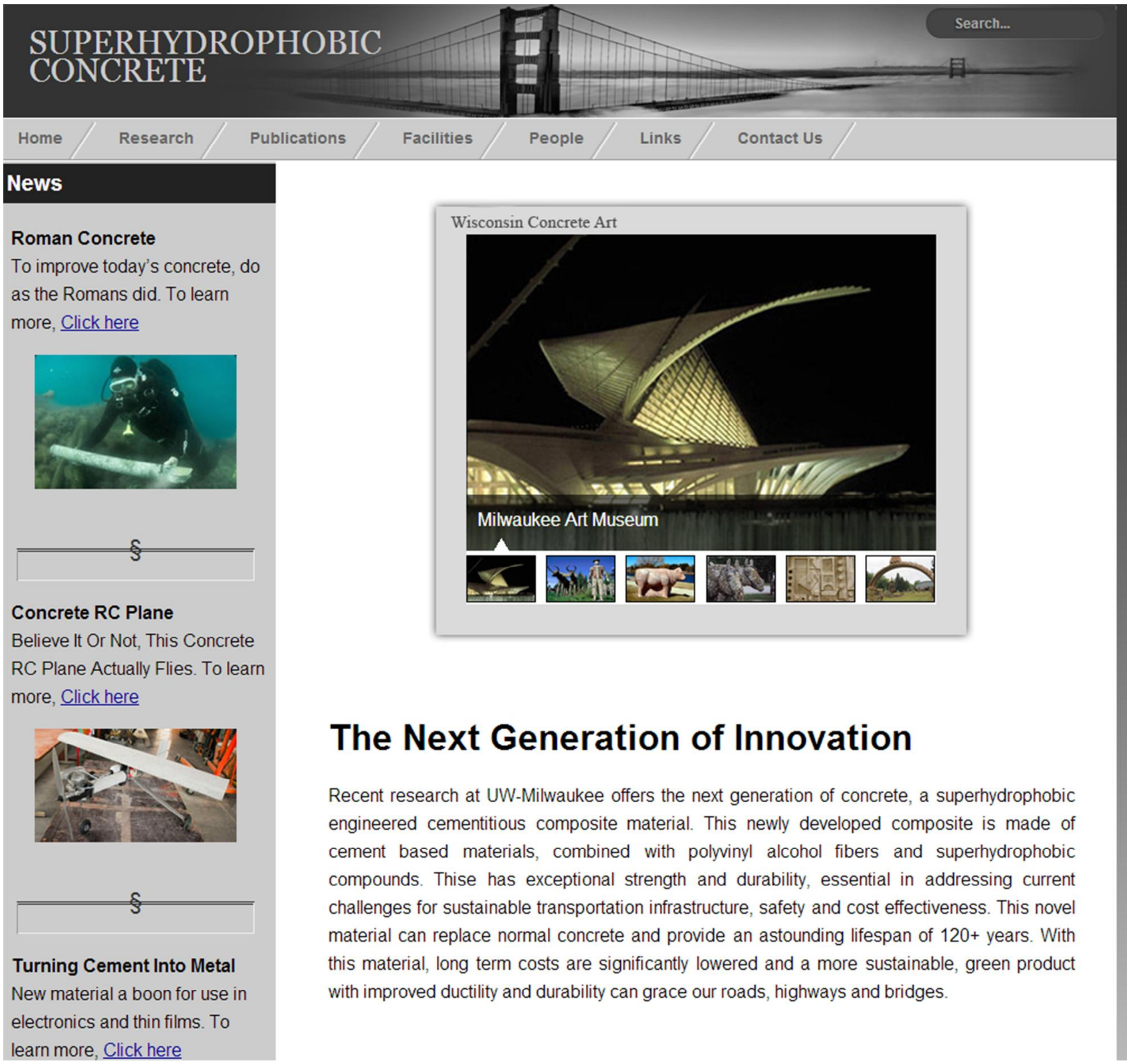
The material was tested in both fresh water and salt water (5% NaCl) medium with temperatures ranging from -50°C to 20°C. This accelerated testing method in fresh water provides a freeze-thaw cycle multiplier of approximately 5 when comparing results from standard testing methods with temperatures ranging from -18°C to 4°C. The same accelerated testing method in salt water is assumed to provide a freeze-thaw cycle multiplier of even higher as surface scaling in NaCl is significantly higher. Samples within this research maintaining a durability factor of approximately 100 through 700 accelerated freeze-thaw cycles would be equivalent to 3500 or more freeze-thaw cycles tested in a standard form.

Internally placed strain-gauges were also used for freeze-thaw testing to determine the elongation of the material during freezing and thawing. In the past, tests would only be performed when samples are in the thawed state, whereas now the strains can be determined during freezing and then modelled against durability factors to determine the performance of the material in the frozen state.

These advanced and accelerated testing methods to test freezing and thawing cycles show that the addition of superhydrophobic admixtures to fiber reinforced cementitious composites create a very durability material as it can resist several thousand freeze-thaw cycles without losing stiffness of compressive strength. Moreover, the addition of these admixtures displays improved performance to other durability factors such as chloride permeability, absorption, and flexural behavior.

APPENDIX C: SUPER-BETON.COM WEB-PLATFORM

Front-page of Super-beton.com



APPENDIX D: PUBLICATION ABSTRACTS

HYDROPHOBIC ENGINEERED CEMENTITIOUS COMPOSITES FOR HIGHWAY APPLICATIONS

The U.S. highway infrastructure is in desperate need of repair, especially in areas exposed to harsh environments. Freezing and thawing cycles in northern regions lead to serious durability problems in bridges and early need for repair or replacement. The effective use of polyvinyl alcohol (PVA) fibers in engineered cementitious composites (ECC) enables one to design a durable concrete capable of withstanding large deformations from heavy loading and temperature variations such as freezing and thawing. Greater longevity is achieved in the service life of roadways due to the increased ductility induced by the multi-cracking and strain hardening behavior of the ECC. Combining ECC with overhydrophobic and superhydrophobic admixtures results in a material with controlled, evenly-spaced air voids and improved multi-cracking response. In superhydrophobic engineered cementitious composites (SECC), small, evenly spaced air voids act as artificial flaws, promoting crack formation while still maintaining high flexural and compressive strength. This research demonstrates that high ductility can be achieved in ECC with a stronger cementitious matrix.

FREEZE-THAW RESISTANCE OF FIBER REINFORCED COMPOSITES WITH SUPERHYDROPHOBIC ADMIXTURES

Freezing and thawing cycles in northern regions lead to serious deterioration in bridges and dictate the need for early repair or replacement. The use of polyvinyl alcohol (PVA) fibers in cementitious composites improves durability because of its ability to withstand large deformations due to its strain hardening and multi-cracking ability. However, the addition of fibers alone to a cementitious matrix may not be adequate in providing resistance to freezing and thawing beyond the standard 300 cycles. The addition of superhydrophobic admixtures to fiber reinforced composites results in an air void system with small, well-dispersed air voids allowing for better resistance to freezing and thawing. Moreover, the superhydrophobicity of the of the air void surface provides a water repellant effect ensuring that water does not attach to the surface of the air voids. This research demonstrates that the addition of superhydrophobic admixtures to fiber reinforced composites provides improved freeze-thaw resistance by demonstrating a durability factor of 100 through as many as 700 accelerated (-50°C to 20°C) freeze-thaw cycles in fresh water and 5% NaCl solution. Additionally, the accelerated freeze-thaw testing provides a more efficient method for testing freezing and thawing in cementitious materials.

CFIRE

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