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Long Term Durability Performance of Engineered Cementitious Composites

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Abstract

The durability of concrete is one of the most significant problems within the civil engineering community. Through the careful design and use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) the durability and long term performance of many concrete structures may be enhanced. However, before implementing these new materials into construction applications, their durability performance must be shown equal or superior to concrete over long durations in harsh service environments. Within this article, the behavior under various environmental loads and the long term performance of a class of HPFRCCs called Engineered Cementitious Composites (ECC) are reviewed. ECC is shown to exhibit exceptional behavior under freeze-thaw cycles, hot-cold temperature cycles, carbonation exposure, fatigue loading, and long term mechanical performance. Additionally, results are presented of an ongoing four year comparison between ECC and concrete roadway patching applications on a Michigan Department of Transportation bridge deck.

Keywords: Engineered Cementitious Composite, ECC, HPFRCC, Durability, Cracking

Langzeitbeständigkeit systematisch entwickelter zusammengesetzter Zement gebundener Werkstoffe

Zusammenfassung

Die Dauerhaftigkeit des Betons ist eines der wichtigsten Problematiken im Bauingenieurwesen. Durch den richtigen Entwurf der Betonmischung und die Verwendung von Hochleistungsfaserbetonen (High Performance Fiber Reinforced Cementitious Composites (HPFRCC)) können die Dauerhaftigkeit und das Langzeitverhalten von Betonbauwerken verbessert werden. Vor der Verwendung dieser Betone muss deren Dauerhaftigkeit untersucht werden und die Leistungsfähigkeit unter langanhaltenden und anspruchsvollen Umgebungsbedingungen als gleichwertig oder besser als die von normalem Beton nachgewiesen werden.

In diesem Beitrag werden die Dauerhaftigkeit und das Langzeitverhalten von sogenannten Engineered Cementitous Composites (ECC) unter verschiedenen Versuchsbedingungen untersucht. ECC ist ein Hochleistungsbeton (HPFRCC) mit besonderen Eigenschaften hinsichtlich der Dauerhaftigkeit unter Frost-Tauwechselbedingungen, Temperaturwechseln, Karbonatisierung und zyklischen mechanischen Belastungen. Desweiteren werden Ergebnisse einer vierjährigen Vergleichstudie zwischen ECC und normalem Beton vorgestellt, welche für die Ausbesserung von Straßenbelägen vom Michigan Department of Transportation verwendet wurden.

Stichwörter: *Systematisch entwickelte zusammengesetzte Werkstoffe, ECC, HPFRCC, Beständigkeit, Rissbildung*

1 Introduction

The importance of the global transportation infrastructure system is unarguable. This complex network of roads, bridges, railways, airports, and canals serves as the backbone of global industry by moving both freight and people around the world in an efficient and convenient manner. Yet while all recognize its necessity, a serious commitment to maintaining these vital systems in developed nations is waning. Within the US, the American Society of Civil Engineers (ASCE) recently released updated 2005 grades of C and D for America's bridges and roads, respectively. ASCE cited that to repair all deficient bridges it will cost in excess of US$ 180 billion over the next twenty years, while poor roads are presently costing US drivers US$ 54 billion annually in additional vehicle repair and operating costs [1]. Such problems are also evident in Australia where road and bridge conditions were assigned an average grade of C as recently as 2005 [2]. The current problems facing transportation infrastructure systems across the developed world are simply overwhelming, and only look to increase as developing nations spark growth by vastly expanding public infrastructure.

At the root of these problems of maintenance costs and poor serviceability is the inherent lack of durability of concrete construction. As a brittle material, concrete cracks under load thereby allowing water, chlorides, and other corrosives to penetrate easily into the material and accelerate destruction. Many improvements have been made with regard to concrete durability, such as air entrainment, sulfate resistant cements, or minimum reinforcement recommendations, but few solutions have targeted the inherent shortfall of concrete as a brittle material. To solve the serious challenges confronting global infrastructure, a fundamental solution reducing the brittle nature of concrete is needed.

Through the use of High Performance Fiber Reinforced Cementitious Composites (HPFRCCs), which display significantly higher ductility than reinforced concrete, durability problems resulting from cracking may be solved [3]. Yet to prove acceptable for infrastructure applications, these materials must not only show high ductility but also more "traditional" material durability by exhibiting such characteristics as excellent protection of embedded steel reinforcement, resistance to freeze thaw cycles, and demonstration of long term mechanical performance. The introduction of materials which provide both ductility and enhanced material and structural durability may likely serve as a watershed development in the design of future infrastructure systems.

2 Poor Durability due to Disjointed Materials Engineering and Structural Design

The design of durable concrete structures must begin at the microstructural level and proceed upwards in scope and scale. Along these lines, the US National Research Council first recognized the need for materials developers to play a prominent role in the design and performance evaluation of materials within structural applications nearly twenty years ago. According to the US NRC, "Materials scientists and engineers have a growing ability to tailor materials from the atomic scale upwards to achieve desired functional properties." [4] This is certainly truer today than two decades ago.

Implied within this "growing ability" is a necessity for materials engineers to understand which "desired functional properties" are ultimately sought by structural engineers and end users. For infrastructure, these desired functional properties are increasingly expressed as a structural performance demand, as in the case of durable concrete infrastructures. Regularly, a service lifetime of 75+ years is expected from expensive public works [5, 6]. This "functional property" of lasting durability is then left to the structural designer, not the materials developer, to achieve. It is this disjointed design philosophy, in which material durability is the responsibility of materials developers, but durable structural performance is the responsibility of the structural designer, which causes a breakdown within the overall design. This is shown graphically in Figure 1.

Within this current design philosophy, concrete materials engineers manipulate both material microstructure and processing techniques to create materials which lead to improvements in the durability of individual infrastructure materials (Figure 1: Lower Triangle). Such design of durable material microstructures include the deliberate gradation of particle sizes for densification of concrete [7, 8], or inclusion of silica fume [9, 10] or nitrites [11, 12, 13] to reinforced concrete as corrosion inhibitors. Durable processing techniques, such as air entrainment for concrete freeze-thaw protection [14, 15], or prescribed curing conditions for increased strength and impermeability [16], are also used. Using these tools, materials engineers can develop highly durable infrastructure materials which exhibit superb performance in standard laboratory testing environments, such as concretes with low shrinkage or low permeability [17, 18].

Working nearly independent of this materials development are structural designers who combine "durable" materials with structural shapes and geometries to meet a prescribed structural durability performance target (i.e. 75+ years of service lifetime) (Figure 1: Upper Triangle). Durable materials may include high performance concretes [19] or epoxy coated reinforcing steel [20]. Durable shapes and geometries incorporate the use of adequate concrete cover to protect reinforcing steel from corrosives, and designing appropriate steel reinforcing ratios to prevent cracking due to temperature and shrinkage deformations [21, 22]. Using these tools, structural designers seek to build structures which exhibit the desired highly durable performance.

While this relationship between materials engineers and structural designers has been the status quo for generations of engineers, the lack of durability in existing concrete infrastructure demonstrates its shortfalls [1, 2, 23]. Highly durable concrete materials have been developed in laboratories, but their success in the field has been limited [17, 18]. One cause has been the distinct separation between materials and structural engineers in the design sequence. In most cases, this lack of cooperation results in materials designed irrespective of structural context, and their application into conditions in which they cannot perform.

While the present disconnect between structural designers and materials engineers has proven a poor design philosophy, the effective integration of these disciplines may eliminate this shortfall. As seen in Figure 1, there is a common link between materials developers and structural designers in the form of durable materials. However, the development of these materials must be done in context of structural demands and the selected durability performance target. Conversely, materials must be used in context with their development for a particular durability performance. This integrated structural and materials design concept (ISMD) is shown in Figure 2. The ISMD philosophy, originally proposed by Li and Fischer [24], has already been successfully applied in the design of collapse resistant frames for use in seismic zones [25, 26].

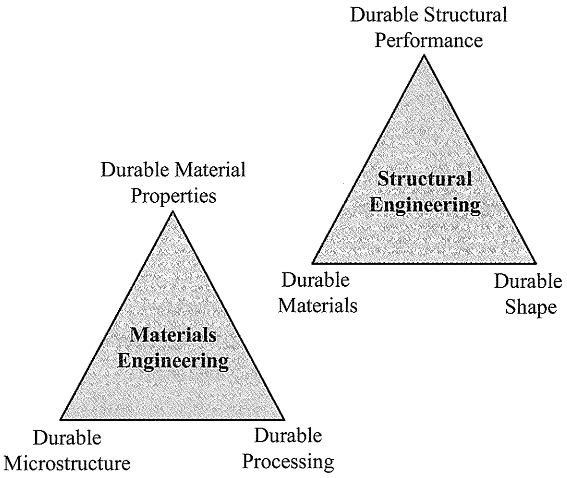

Figure 1: Disjointed materials engineering and structural engineering design philosophies

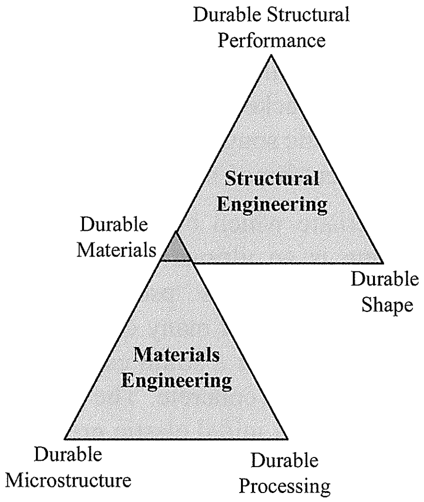

Figure 2: ISMD for durable infrastructure

As evident in this new paradigm, the development of durable materials is no longer conducted independent of the ultimate goal of structural performance. While this integration is very simple in a graphical nature, a distinct shift in materials design philosophy is required. Foremost is the necessity for materials designers to realize the real-world conditions in which their materials must be used, and the resulting impacts on microstructural design and material processing techniques. One such example of this is the understanding that in most applications, concrete cracks due to restrained shrinkage or temperature deformations, accidental overloads, or poor design and construction techniques [27, 28]. Therefore, concrete material design must focus on durability in the cracked state and increasing durability after cracking. This includes considering the durability of infrastructures under combined mechanical loads to induce cracking (i.e. mechanical deterioration) and environmental loads to promote aggressive corrosion and material deterioration (i.e. chloride transport and reinforcement corrosion). Such combined states are inevitable in real applications and materials must be developed with this realization.

2.1 Engineered Cementitious Composites: Durable Materials through Integrated Design

A new class of HPFRCC materials, called Engineered Cementitious Composites (ECC), addresses many of these current needs of infrastructure designers for an alternative to brittle concrete materials. This ultra-ductile cementitious composite exhibits ductility similar to some metals [29]. Additionally, this material shows excellent performance in durability testing. Designed using the integrated structural and materials design approach outlined previously, and taking into account durability in the loaded (i.e. cracked) state, ECC meets nearly every characteristic sought by engineers for a highly durable cement-based material.

The characteristic which best distinguishes ECC from concrete is an ultimate strain capacity between 3 % and 5 %. This "pseudo-strain" occurs through the formation of many closely spaced microcracks, allowing for a strain capacity over 300 times that of normal concrete. The typical tensile response exhibits an initial elastic pre-cracking regime, followed by a large strain-hardening branch during which microcracks saturate the material. Once the strain capacity is exceeded, a single crack ultimately localizes and the material continues to tension-soften throughout failure (Figure 3). Micromechanical tailoring of ECC components for strain hardening performance, which encompasses the microstructual portions of the integrated durability design methodology, has been described previously by Li [29].

Along with tensile ductility, the unique crack development within ECC is critical to its durability under mechanical load. Unlike most fiber reinforced concretes (FRCs), ECC exhibits self-controlled crack widths under increasing load (Figure 3). After initial loading, a small number of cracks form within the material and begin to widen. This widening continues until they have reached an average width of 60 μm. Following this, the initial cracks do not widen further as additional tensile deformation is accommodated by the formation of new microcracks until the material is saturated with cracks. Regardless of the ultimate tensile strain, average crack widths remain at 60 μm. This is possible through the formation of steady-state "flat cracks" which exhibit a constant crack width independent of crack length, in contrast to Griffith-type cracks present in most FRC and HPFRCC materials which widen as the crack grows.

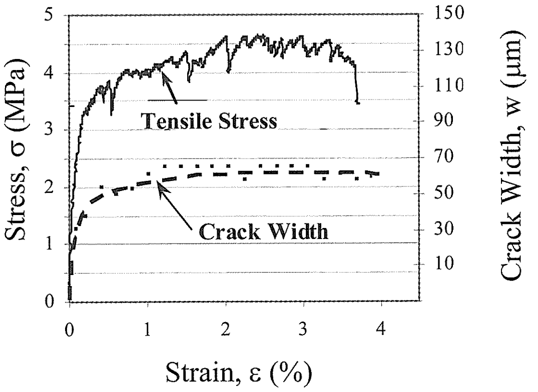

Figure 3: Tensile stress-strain response of ECC and crack width development

The material ingredients which make up ECC are similar to many other FRCs, in that it is a mixture of cement, sand, water, fibers, and a small amount of commercial admixtures. Coarse aggregates are not used due to their adverse effect on performance. These large aggregates are found to dominate the micromechanical properties of the composite leading to poor fiber dispersion and lower overall performance. While most HPFRCCs rely on a high fiber volume to achieve high performance, ECC uses low amounts, typically 2 % by volume, of short, discontinuous fiber. This low fiber volume, along with the common components, allows for conventional mixing in a gravity mixer. Many HPFRCCs with fiber fractions exceeding 5 % cannot conform to conventional mixing and placement practices.

3 Applying ISMD: Designing Crack Width for Durability

An important consideration for concrete durability is its resistance to cracking, and after cracking its ability to continue protecting reinforcement from corrosion [30, 31]. Sound, uncracked concrete cover is nearly impermeable and adequately protects reinforcement from surface exposure and corrosives such as deicing salts, aggressive soil conditions, and seawater. However, cracking is inevitable due to mechanical overloads, environmental loads, or a combination of the two. Once wide cracks have formed, the protection provided by the concrete cover drops rapidly, making it essential to design for tight crack widths [32, 33].

Historically, building codes have given specific consideration to the distribution of reinforcement to minimizing cracking. The 1995 edition of the ACI Building Code [34] (Section 10.6.4), recommends a maximum crack width of 400 μm and 330 μm for interior and exterior exposure conditions, respectively. The calculation of crack width within ACI is based upon the Gergely-Lutz expression and results in the computation of a minimum "z" factor which must be satisfied and is directly related to crack width. This "z" factor is a function of the stress in the rebar, the cover thickness, and the effective tension area of the concrete. A similar expression and limit is also suggested by the 1998 AASHTO code [35].

The 2002 edition of the American Concrete Institute concrete building code, (hereafter ACI-318-02) [36] (Section 10.6.4), suggests direct computation of maximum reinforcement spacing rather than determining crack width. This is due to the high variability of crack widths within structures. ACI-318R-02 [6] states "...the current provisions for spacing are intended to limit surface cracks to a width that is generally acceptable in practice but may vary widely in a given structure." Further, it suggests that due to the lack of a clear relation between crack width and reinforcement corrosion rate at service stress levels, the direct focus on minimizing crack width for increased durability has been eliminated.

While it is true that crack widths within a structure may vary widely, the independence of reinforcement corrosion rates from crack width remains controversial. Within the widely accepted Tuuti model [37] which describes corrosion development and deterioration within R/C, cracking represents a final step towards failure by accelerating deterioration. Recently, Miyazato et al [38] found that materials which formed many microcracks (such as ECC) under load were more effective in limiting rebar corrosion in the cracked state when compared to concrete which forms widely spaced large cracks.

Regardless of the effect of crack width on corrosion rate, it is generally agreed that limiting the transport of water and corrosives will improve the durability of any concrete structure. Along these lines, ECC materials designed for self-controlled crack widths become a crucial defense against poor durability. Independent of the strain level, maximum ECC crack widths inherently remain at 60 μm.

As mentioned previously, this is accomplished through the suppression of Griffith type cracks which grow wider as they propagate in favor of flat type cracks which are more conducive to crack width control. Tight crack widths are realized through manipulation of the fiber bridging versus crack width curve (σ–δ curve), essentially a spring law describing the stress transferred across a crack as the width grows [39, 40, 41]. Through manipulation of the fiber bonding and slip behaviors [42, 43, 44, 45] which make up the σ–δ relation, materials engineers can effectively design cementitious materials which intentionally meet specifications (i.e. crack width, etc.) for robust self-healing.

Recently, Lepech and Li [46] found that cracked ECC materials with self-controlled crack widths averaging 60 μm exhibit nearly the same permeability as sound concrete, even when strained in tension to several percent (Figure 4). Within this study, both ECC and reinforced mortar specimens were stretched in tension to identical deformation, 1.5 % deformation in this case, resulting in a variety of crack widths and number of cracks among the various specimens. The permeability of these cracked materials was then determined under hydraulic head. As seen, there is a dramatic rise in permeability with increasing crack width. Further, when normalized by number of cracks within the specimen, the comparable permeability of cracked ECC with sound material becomes more apparent.

In addition to improving transport properties, Lepech and Li [46] along with Yang et al [47] have found that ECC materials also show great promise

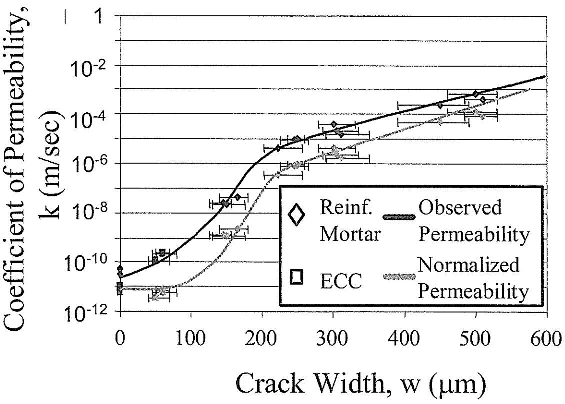

Figure 4: Coefficient of permeability vs. crack width for ECC and reinforced mortar series. Grey symbols indicate data normalized by number of cracks.

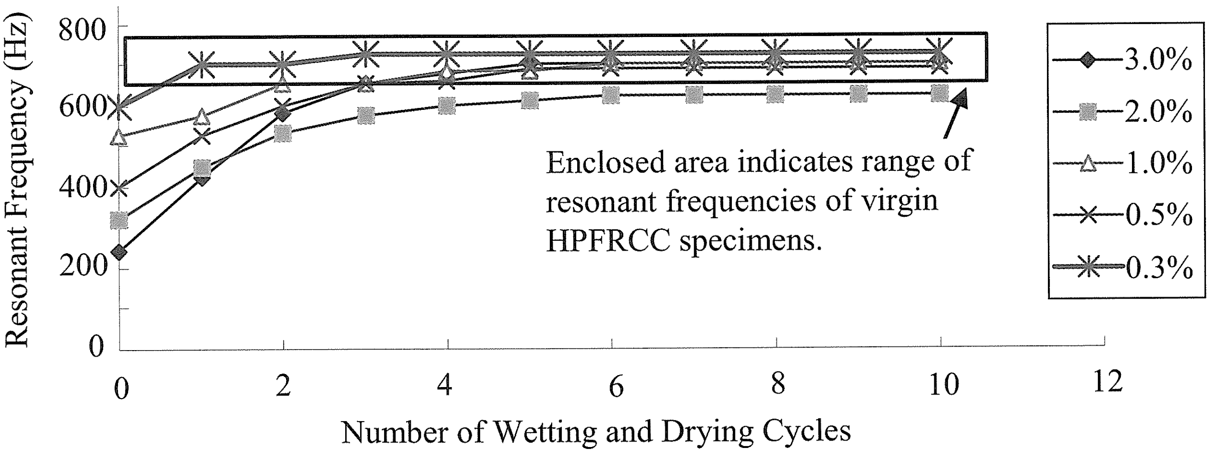

Figure 5: Resonant Frequency vs. Number of Wetting and Drying Cycles

for autogenous material self-healing. Self-healing in concrete materials has been studied in various laboratory conditions ranging from underwater and cyclic wet-dry exposures to extreme chemical conditions. Yet most important to achieving robust self-healing, and most difficult for reinforced concrete materials, is the ability to tightly control crack widths. While field environmental exposures (i.e. cyclic wet-dry exposures) and the presence of essential chemical species (i.e. calcium and carbonate ions) are quite commonplace in many concrete applications, inability to consistently restrain crack widths below roughly 200 μm prohibits the reliable formation of self-healing products in most concretes.

In ECC self-healing studies conducted by Yang et al [47], ECC specimens were first pre-cracked in tension to a pre-determined deformation level ranging from 0.3 % to 3 % strain, resulting in crack numbers between 9 and 80, and maximum crack widths between 40 μm and 90 μm. The experimental program consisted of specimen submersion in 20 °C water for 24 hours, 55 °C oven drying for 22 hours, and cooling in laboratory air at 21±1 °C for 2 hours. This was used to simulate cyclic outdoor environments such as sunshine and high temperatures.

To evaluate the rate and extent of self-healing, resonant frequency measurements were made of uncracked specimens and repeated throughout wet-dry exposures according to ASTM C215 "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequency of Concrete Specimens". Due to the tight crack widths, a significant amount of self-healing was observed (Figure 5). Regeneration of mechanical properties was most apparent among the heavily damaged specimens, which experienced a 70 % loss after initial loading and returned to over 90 % of original stiffness through self-healing. Additionally, uniaxial tension tests of self-healed materials showed the formation of new cracks adjacent to previously healed cracks, verifying the high quality of the observed self-healing products.

These studies suggest that ECC has the ability to eliminate even the microcracks after large imposed deformation, via self-healing, and therefore maintain transport properties equivalent to that of sound ECC. Additional studies are currently being conducted along these lines.

4 Material Durability Testing

Aside from designing tight crack widths for low transport and self-healing properties, durable structures require material durability against freeze thaw, corrosion, harsh environmental exposure, and abrasive wear. Various researchers have investigated the durability performance of ECC. This research further supports the use of ECC as a durable construction material in a wide range of environmental conditions.

4.1 Freeze Thaw Exposure

One of the most damaging environmental conditions to concrete is cyclic freezing and thawing. To combat the effects of freeze thaw cycles, ACI-318-02 [36] stipulates in Section 4.2 both a minimum entrained air content and maximum water to cement ratio. By adhering to these recommendations, along with proper placement and curing, very durable concrete can be cast. However, concrete durability remains very sensitive to the amount of air entrainment and the curing conditions. Therefore, if this sensitivity can be overcome through an ECC material solution, the ultimate result will be overall improved structural durability.

Freeze thaw testing, in accordance with ASTM C666A was comprised of companion series of ECC and normal concrete specimens (both without air entrainment). In addition to typical dynamic modulus testing of prism specimens outlined in C666A, a series of ECC tensile specimens were also subjected to freeze thaw exposure. These tests evaluated the effect of freeze thaw conditions upon composite strain capacity. Results from these tensile specimens were compared to tensile coupons of identical age cured in water at 22 °C.

Testing of ECC and concrete prisms was conducted concurrently over 14 weeks [48]. After 5 weeks (110 cycles), the concrete specimens had severely deteriorated, requiring removal from the test. However, all ECC specimens survived 300 cycles with no degradation of dynamic modulus. This performance results in a durability factor of 10 for concrete compared to 100 for ECC, as computed according to ASTM C666. Recall that this high durability was achieved without deliberate air entrainment into the ECC. In uniaxial tension tests performed on wet cured and freeze thaw exposed ECC coupons, no significant drop in strain capacity is experienced after 300 cycles. Both sets of specimens exhibited a strain capacity of roughly 3 %, well above the capacity needed by most structural applications.

4.2 Accelerated Weather Testing

In contrast to freeze thaw tests which are designed to simulate winter conditions, hot water immersion tests were conducted to simulate hot and humid environments. To examine the effects, hot water immersion was performed on individual fibers, single fibers embedded in ECC matrix, and composite ECC specimens [49]. Specimens for individual fiber pullout and composite ECC were cured for 28 days at 60 °C prior to hot water immersion for 26 weeks.

After 26 weeks, little change was seen in fiber properties such as strength, modulus, and elongation. Interfacial properties, however, experienced significant changes, particularly between 13 and 26 weeks. During this time, the chemical bonding between fiber and matrix strengthened, while the fiber apparent strength dropped. These two phenomena caused fibers within ECC to delaminate and break under load after 26 weeks, rather than pull-out intact as seen in specimens immersed 13 weeks or less. This change in interfacial properties resulted in a drop of strain capacity from 4.5 % at early age to 2.75 % after 26 weeks of immersion. While accelerated hot weather testing results in lower strain capacity, the 2.75 % capacity, over 250 times greater than concrete, seen after 26 weeks of accelerated conditioning (equivalent to 70+ years of hot and humid exposure) is acceptable for nearly any application.

4.3 Fatigue

ECC was investigated in high fatigue scenarios, such as highway repairs. Both ECC/concrete and concrete/concrete overlay specimens were tested in flexural fatigue [50]. In overlay applications, reflective cracking through the new layer is of great concern. This cracking reduces load capacity and may result in flexural fatigue. Additionally, these cracks transport corrosives to the reinforcing and result in spalling. Tests show that the load capacity of ECC/concrete overlay specimens was double that of concrete/concrete overlay specimens, the deformability of ECC/concrete specimens was significantly higher, and the fatigue life was extended by several orders of magnitude. Further, the microcracking deformation mechanism of ECC eliminates reflective cracking. The fatigue resistance of ECC has also been found to be improved over polymer cement mortar [51]. In many applications, particularly concrete infrastructure, fatigue failure can significantly shorten service-life. Its exceptional fatigue performance highlights ECC as a preferable material for fatigue-prone structures.

4.4 Long Term Strain Capacity

For a construction material to be considered truly durable, its mechanical properties must remain constant over time. To validate ECC long term effectiveness, a series of tensile tests were performed to determine long term strain capacity. Due to the delicate balance of cement matrix, fiber, and matrix/fiber interface properties, the strain capacity of ECC changes during maturing. This is exhibited in a plot of ECC strain capacity versus age (Figure 6). At roughly 10 days aging, peak strain capacity is achieved due to an optimal balance of matrix, fiber, and matrix/fiber interface properties. As hydra-

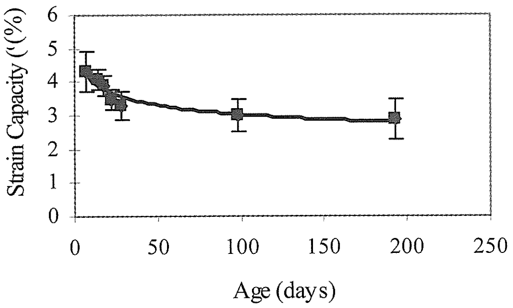

Figure 6: Long term strain capacity of ECC

tion continues, the high matrix toughness leads to a reduced composite ductility. Maturity of matrix and fiber/matrix properties eventually results in an ECC long term strain capacity of 3 %, far above the deformation demand imposed by many applications, but significantly less than the 5 % capacity seen at early age. While long term tests have only been carried out to 180 days, the long term strain capacity is expected to remain at approximately 3 %.

4.5 Abrasion and Wear

For roadway surface repairs, ECC must provide an adequate surface for driving and breaking, while withstanding traffic abrasion. Surface friction and wear track testing was conducted in conjunction with the Michigan Department of Transportation (MDOT) to evaluate ECC capability to withstand wheel abrasion and provide sufficient braking friction. A set of four ECC roadway surfaces were cast corresponding to various types of surface texturing. One specimen was tined with grooves using a rake; another was cured under a textured cloth to simulate curing under burlap; a third was textured with Astroturf® to roughen the surface, a practice common in Michigan; and a final specimen was topped with coarse sand on the surface. Due to the fibers, tining or dragging items across the surface proved difficult, resulting in removal of the top layer of fresh material, effectively ruining the finished surface. However, with a number of trials, adequate texturing was achieved.

Specimens were cured for 28 days and subjected to both static friction testing and wear track testing according to Michigan Test Method 111 [52]. Initial friction forces between vehicle tires operating at 65kph and the textured ECC specimens were determined using an MDOT static friction tester. All static friction tests were conducted on a wet pavement surface. Following initial friction testing, ECC specimens were subjected to 4 million tire passes to simulate long term wear. After wearing, friction forces were again determined to assess deterioration or surface polishing during wearing. These final friction forces are called the Aggregate Wear Index (AWI). AWI values for the textured ECC samples tested range from 1.6 kN to 2.3 kN. The established minimum AWI for Michigan trunkline road surfaces is 1.2 kN, significantly lower than all ECC surfaces tested, making it suitable for roadway surface repairs. From this testing, a transverse tined surface treatment, exhibiting an AWI of 2.3 kN after 4 million tire passes, is recommended for future ECC surface repairs.

5 Corrosion Protection of Reinforcement

The ability to protect reinforcement from corrosion greatly impacts the durability of a reinforced concrete member. According to the Tutti model discussed previously and expanded by Thoft-Christensen [53], reinforcement corrosion progresses through various stages. Initially, the concrete cover provides excellent protection. However, over time the passive layer protecting the reinforcement degrades due to high chloride ion content or carbonation of the concrete. Following depassivation, oxidation of the reinforcement ultimately cracks the cover through expansion of corrosion products. Once cracked, the decrease in cover protection spurs faster corrosion until the concrete spalls. The exposed reinforcement then corrodes rapidly.

To combat this scenario, ACI-318-02 [36] in Sections 4.4.1 and 4.4.2 specify a maximum initial chloride content, maximum water to cement ratio, minimum compressive strength, and minimum cover thickness in "conditions exposed to chlorides from deicing chemicals, salt, saltwater, brackish water, seawater, or spray from these sources." Initially, the chloride content is kept low to lengthen the time to critical concentration for depassivation. The water to cement ratio, compressive strength, and cover thickness recommendations decrease transport properties, increase cracking strength, and increase ion transport distances, respectively. However, the formation of cracks due to mechanical overload, environmental conditions, or a combination of the two can negate these efforts at very early age.

Along with the ability of ECC to reduce the transport of corrosives through the cover even after cracking, enhanced durability may be provided through the high ductility of the material itself. As

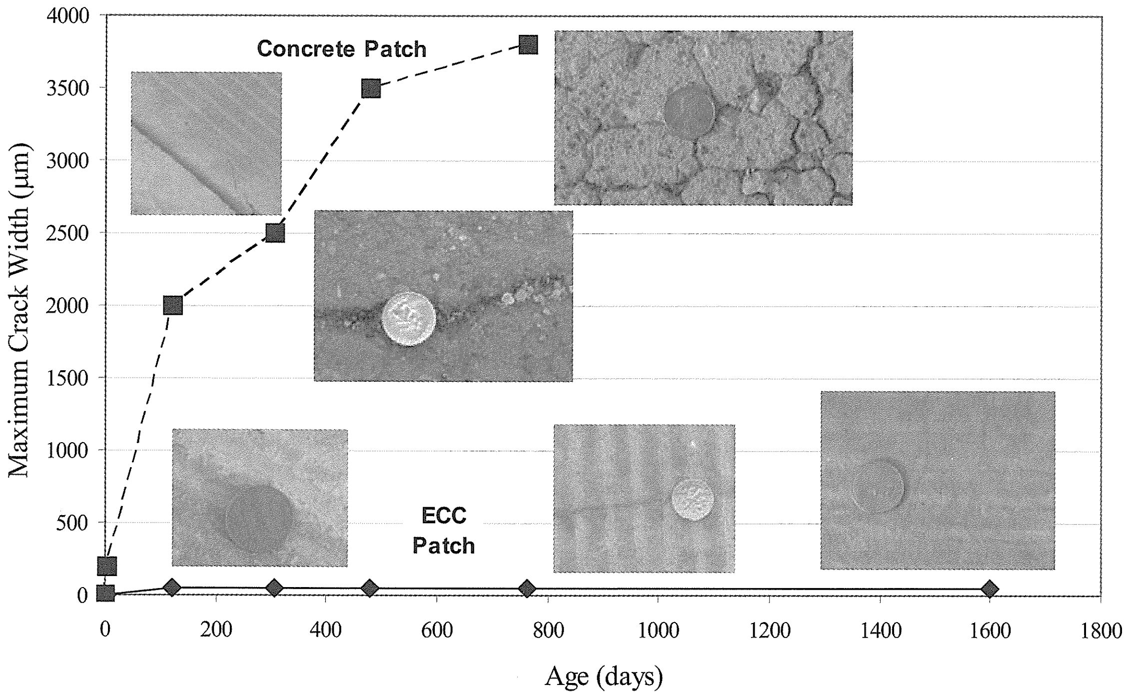

Figure 7: Comparison of ECC and concrete crack widths in MDOT field patch application

proposed by Thoft-Christensen [53] and others, the presence of cracks increases the rate of deterioration of R/C members, which is further increased after cover spalling. With a tensile ductility on the order of 3 %-5 %, the spalling of ECC cover is highly unlikely, as shown by Li through simulated ECC spalling tests [54]. By preserving low transport properties after cracking, and eliminating spalling through high ductility, the ability of ECC material to effectively protect reinforcement from corrosion significantly longer than concrete is expected. This protection is further supported by the work previously mentioned by Miyazato and Hiraishi [38] in which ECC material was effective in reducing the rate of corrosion of steel embedded in ECC after cracking when compared to concrete.

6 Field Verification of Durable ECC Performance

To verify the field durability of ECC, a concrete bridge deck patch has been completed in cooperation with the Michigan Department of Transportation (MDOT). A complete summary of this work was outlined by Li and Lepech [55]. During this work, one section of a deteriorated bridge deck was repaired with ECC while the remaining portion was repaired with a commercial concrete patching material commonly used by MDOT. This repair scenario allowed for a unique ECC/concrete comparison subjected to identical environmental and traffic loads. The concrete repair material used was a pre-packaged mixture of portland cement and plaster of paris. At this writing, the repaired bridge deck has experienced four complete Michigan winter cycles of freezing and thawing, in addition to live loads.

Short term and long term performance of both the ECC and adjacent concrete patch have been recorded through site visits. Initial visits conducted 2 days after patching showed no visible ECC cracking, while a clearly visible crack, approximately 300 µm wide, had appeared within the concrete, most likely due to shrinkage deformation. After 4 months of winter exposure, a number of small microcracks, each roughly 50 µm wide, had formed within the ECC, while the concrete crack observed shortly after casting had widened to 2 mm and was surrounded by deteriorated and spalling concrete. Most recently, observations made four years after patching revealed a maximum ECC crack width of 50 µm, while sections of the concrete patch had already been replaced. The development of crack width over time in both ECC and concrete is shown in Figure 7. From this unique comparison of adjacent patch sites subjected to identical loading, ECC was shown to be superior to concrete immediately after casting, and improving over time, establishing ECC as a durable material for construction.

7 Cost Impacts of ECC Material Durability

The cost of new technologies in comparison to existing materials is of major importance to any department of transportation or infrastructure owner. With a cost of roughly \$100/m^3, ordinary Portland cement concrete is one of the most cost effective materials for use in infrastructure design. However, as discussed earlier, this material has significant shortfalls, causing it to require more maintenance at higher lifetime costs. High strength concretes, which are generally thought to have increased durability over normal concrete, or typical steel fiber reinforced concrete may cost up to \$200/m^3. The current cost of PVA-ECC material is approximately \$350/m^3.

While these ECC material costs are higher than concrete the potential life cycle cost savings are substantial. Research conducted by Keoleian, et al [56] addressing the total life cycle cost of bridges using ECC link slabs to replace failure-prone mechanical expansion joints has looked to quantify these costs for a bridge site near Detroit, Michigan USA. Within this analysis, costs borne both by the governmental agency for construction and maintenance (i.e. agency costs) are combined with costs borne by commuters using the bridge for wasted fuel, increased vehicle wear, and lost time (i.e. user costs). These user costs have been found to dominate the total life cycle cost due to the long service life of such structures. The estimated total life cycle cost (including agency costs and user costs) of a bridge with conventional expansion joints is US\$35.7 million, while for an ECC link slab bridge it is US\$22.5 million. If only life cycle agency costs (costs borne by the department of transportation) are examined, totals are US\$750,000 for the conventional system and US\$490,000 for the ECC system. As seen, even though ECC materials are more expensive than concrete, the accompanying increase in service life and decrease in maintenance costs adequately make up for higher initial costs.

However, potentially more important than these economic costs are both the environmental and social costs which are reduced by the ECC bridge system. Due to less maintenance over the life cycle, less overall material is used in the ECC system along with less traffic congestion due to less construction. This represents a great savings over the service life in terms of 37 % reduction in traffic backups, a 40 % reduction in total primary energy consumed, 30 % reduction in global warming potential, 43 % reduction in carbon monoxide emissions, and a 45 % reduction in sulfur dioxide emissions (a precursor to acid rain). These costs do not include the strain on motorists and society in general due to seemingly never ending construction backups. In developing counties, such as China and India, looking to invest heavily in infrastructure development such environmental and public health savings are virtually incalculable.

While cost savings resulting from durability are substantial, some commercial projects involving bridge decks, building cores, and pipes as well as repair applications have demonstrated initial cost savings using ECC through a combination of reduced dimensions (and therefore lesser volume of cementitious material use), less or no steel reinforcement, reduced construction time and labor, and elimination of alternative method of structural protection, by taking advantage of the unique properties of ECC and strategic application of this material. When long-term infrastructure durability is taken into account, as pointed out above, the advantage of ECC becomes even more apparent.

8 Conclusion

There remains little argument concerning the dire state of concrete infrastructure systems within the US and around globe. The low durability of brittle concrete materials is a major concern when attempting to combat this problem. Rather than focus on the endless repair of brittle concrete with brittle cement-based repair materials, a unique materials solution can be found by using ductile HPFRCCs, such as ECC. Through their ductility, many durability challenges confronting concrete can be overcome.

To arrive at these solutions, a dramatic shift in design for durable concrete structures is essential. This includes an integration of the materials design and structural design phases of many building projects. Within this integration is an appreciation for the combined mechanical and environmental loads to which nearly all structures are subjected, requiring high durability of concrete materials after cracking.

In particular, the demonstrated ability of ECC to self-control crack widths under load, resist freeze thaw and hot-cold exposures, withstand fatigue loading, maintain mechanical performance over the long term, and protect steel reinforcement from corrosion suggests this material may be an effective solution to the problems of poor concrete durability. Further, the capacity of ECC to far outperform concrete in a real-world repair application verifies the potential of this material. In particular, potential impacts of ECC materials on global concrete infrastructure construction and repair look toward unequaled sustainability for years to come. While significant work remains to be done in quantifying transport properties in cracked and uncracked ECC materials, investigating the role of steel reinforcement after being heavily corroded, and the effect of combined mechanical and environmental loading, the promise exhibited by ECC looks to help solve the worldwide problem of rapidly deteriorating concrete infrastructures.

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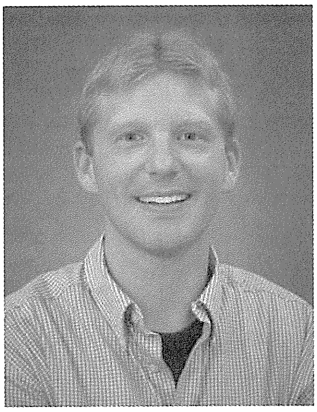

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