Title Page

Title:
Crack Resistant Concrete Material for Transportation Construction

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Abstract

Most transportation infrastructures are exposed to a combination of mechanical and environmental loads. Normal concrete is brittle and tends to crack, resulting in a lack of durability and frequent repair needs. This paper describes an ultra ductile cementitious composite which is highly crack resistant, with a tensile strain capacity over three hundred times that of normal concrete. Apart from the unique tensile properties, the durability performance of this material subjected to loadings typical to transportation construction will also be presented. It is shown that the material is highly durable under accelerated weathering tests, restrained drying shrinkage tests, freeze-thaw exposures, as well as under fatigue and wheel loads. Recent developments of link-slabs for applications in continuous concrete bridge decks and demonstrative patch repair will be summarized to illustrate the performance of this material in realistic transportation construction settings.

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INTRODUCTION

The transportation infrastructure system is unarguably the most widely used public facility in the United States. In 2000 alone, American drivers drove 2.7 trillion vehicle-miles along nearly 4 million miles of public roadways (*1*). While there is no argument over the need to maintain the infrastructure system in good condition for both economic and national defense reasons, the trend toward serious deterioration of roads and bridges in much of the country is alarming. As recently as 1998, the American Society of Civil Engineers assigned grades of C- and D- to America's bridges and roads, respectively. ASCE sighted that more than half of roadways are in fair, mediocre, or poor condition, and nearly one in three bridges is structurally deficient or functionally obsolete (*2*). The problem facing America's transportation infrastructure is both severe and dire.

To combat this trend in Michigan, Governor Jennifer Granholm recently introduced the "Preserve First" initiative, which directs nearly the entire state transportation budget towards "preservation projects", including preventative maintenance, highway reconstruction or rehabilitation, and bridge rehabilitation. To offset these costs, all "capital improvements" have been deferred until 2007. The goal is to maintain 90% of Michigan roadways in "good" condition by 2007. To this end, in the next year alone, an additional $300 million has been allocated for the preservation of Michigan roads and bridges (*3*).

While additional funding is critical to maintain the infrastructure system, greater amounts of money will not ultimately solve the problems facing departments of transportation nationwide. A more fundamental solution must be sought to fix future durability problems. The vast majority of national infrastructure is built of reinforced concrete. While concrete is both economical and simple to construct, its lack of durability has been problematic. Many methods have been proposed to improve concrete durability, however few solutions have targeted the inherent shortfall of concrete as a brittle material, which cracks under load. These cracks are the cause of most corrosion and durability problems, ultimately leading to oxidation of steel reinforcement, concrete spalling, and structural failure. To effectively solve the serious problems facing the national infrastructure system, a fundamental solution reducing the brittle nature of concrete must be found.

ENGINEERED CEMENTITIOUS COMPOSITES

A new class of cementitious materials, called Engineered Cementitious Composites (ECC), addresses the exact needs presented by the transportation community. This type of ultra-ductile, high performance fiber reinforced cementitious composite (HPFRCC) exhibits ductility similar to metals, along with inherently tight crack widths for excellent durability and corrosion protection (*4*). Additionally, this material shows excellent performance in durability testing. ECC meets nearly every major characteristic sought by highway engineers for a highly durable concrete repair material.

The most distinctive characteristic separating ECC from other concrete repair materials is an ultimate strain capacity between 3% and 5%, depending on the specific ECC mixture. This strain capacity is realized through the formation of many closely spaced microcracks, allowing for a strain capacity over 300 times that of normal concrete. These cracks, which carry increasing load after formation, allow the material to exhibit *strain hardening*, similar to many ductile metals, as seen in a typical uniaxial tensile stress-strain curve (Figure 1) (5). While the mechanism underlying this inelastic strain is not the dislocation slip on crystallographic planes, as in metals, when viewed over a representative gauge length, the numerous microcracks may be interpreted as strain. This is uniquely different from typical concretes or fiber reinforced concretes (FRC) which form a single crack when loaded. In the case of normal concrete, the crack opens wide with a rapid drop in load capacity. In the case of FRCs, the crack opens with a gradual drop in load, exhibiting a *tension softening* behavior. While the mechanism behind concrete and FRC deformation is similar to ECC in that it cracks, all deformation is localized at a single section (i.e. the crack face) and the concept of gauge length, and consequently strain, ceases to exist.

While the components of ECC may be similar to FRC, the distinctive ECC characteristic of strain hardening through microcracking is achieved through micromechanical tailoring of the components (i.e. cement, sand, and fibers), along with controlled interfacial properties between components. Fracture properties of the cementitious matrix are controlled through mix proportions. Fiber properties, such as strength, modulus of elasticity, and aspect ratio have been customized for use in ECC. The interfacial properties between fiber and matrix have also been optimized in cooperation with the manufacturer for use in this material. Typical ECC proportions for concrete repair work are given in Table 1. In this mix design, synthetic poly-vinyl-alcohol (PVA) fiber is used. This unique fiber has been developed with the manufacturer for optimal performance within ECC materials to meet specific micromechanical performance requirements *(6).*

Of equal importance to the strain capacity of ECC is the development of crack widths throughout the straining process. The development of ECC crack widths is also shown in Figure 1. After first cracking, early cracks widen with increasing load to allow for deformation. However, once a strain of approximately 1% is attained, crack widths become steady at roughly 80μm. Past this point, further straining is accommodated through the formation of additional microcracks until the material is saturated with microcracks between 3% and 5%. At failure, a single crack localizes and the load slowly drops with increased deformation, similar to a common tension softening FRC.

Unlike crack widths in reinforced concrete, which are governed by reinforcement ratio, crack widths in ECC are an inherent material property unrelated to reinforcement, if in fact reinforcing is present. This decoupling of crack width control from reinforcement ratio is another characteristic unique to ECC, allowing for exciting new repair possibilities. By eliminating the dependence of crack control upon reinforcement, reinforcing steel may be eliminated altogether from many applications. Furthermore, the inherent steady-state crack width of 80μm is ideal for durability, exhibiting a water permeability of approximately 1.0×10^{-10} m/s (Figure 2) (7), close to that of uncracked concrete. Cracking this small has also been shown to undergo limited self-healing (8,9).

The composition of ECC is similar to many other FRCs, such 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 practices.

ECC MATERIAL PERFORMANCE IN TRANSPORTATION APPLICATIONS

To evaluate the performance of ECC under typical mechanical and environmental loadings experienced by transportation infrastructure, a number of durability tests and long term performance studies have been performed. These tests include restrained shrinkage tests, fatigue and bonding tests, freeze thaw exposure, wearing/abrasion tests, and accelerated environmental tests. Additionally, the long term strain capacity and early age strength development of ECC were investigated. These reveal that ECC is outstanding for use as a concrete repair/retrofit material in transportation applications.

Restrained Shrinkage

The restrained shrinkage behavior of ECC was examined through ring tests, similar to standard AASHTO shrinkage rings *(10)*, which were carried out for both ECC and normal portland cement concrete. Unlike the AASHTO standard test, strain gauges were not used on the rings since the time to cracking was not being investigated. By observation of the specimens, time to cracking of the ECC and concrete rings was found to be four and seven days, respectively. Due to the high cement content of ECC, significantly higher free shrinkage deformation is exhibited, compared to normal concrete (6). However, restrained shrinkage tests show that although hygral deformation may be higher, crack widths in ECC remain below 50μm (cured at constant 50% relative humidity for 100 days), compared to concrete crack widths of approximately 1mm (Figure 3). This is achieved through the microcracking of ECC, allowing the shrinkage deformation to be distributed over a large number of small cracks, while all shrinkage deformation in concrete localizes at a single crack. Further, the formation of shrinkage cracks at ECC/concrete interfaces is prevented by lower interfacial stresses due to the large deformability of ECC. This phenomenon allows ECC, while exhibiting higher shrinkage deformation, to be used effectively for repair.

Fatigue Testing and Overlay Bond Characteristics

The fatigue characteristics of ECC were investigated in high fatigue scenarios, such as highway repairs. Both ECC/concrete and concrete/concrete overlay specimens were tested in flexural fatigue *(11)*. In an overlay application, reflective cracking propagating through the new layer is a major concern. This reflective cracking reduces load capacity and may result in flexural fatigue. Additionally, these cracks allow corrosives to access the reinforcing. Ultimately, these cracks are the source of corrosion and overlay spalling. Tests show that load carrying capacity of ECC/concrete specimens was double that of concrete/concrete specimens, deformability of ECC/concrete specimens was significantly higher, and fatigue life was extended by several orders of magnitude. Further, the microcracking deformation mechanism of ECC eliminates reflective cracking. ECC provides exceptional performance in the fatigue environment of transportation applications.

In addition to fatigue performance and crack resistance, the bond characteristics of ECC/concrete repairs were investigated. Using ECC as an overlay material, the delamination and spall processes, typically seen in many concrete/concrete repairs, were eliminated. Through a unique kinking-and-trapping crack formation, both the load capacity and energy absorption of the ECC/concrete overlay was increased. In this mechanism, cracks propagate slightly along the bonding interface but are then directed into the ECC overlay and immediately arrested by the high ECC toughness (34 kJ/m^2 (*12*)). This kinking-and-trapping process repeats until the ECC ultimately fails in flexure, unrelated to interfacial debonding. Additionally, the influence of surface preparation on bonding was investigated. Tests show that regardless of a smooth or roughened interface, the bond performance of an ECC/concrete overlay is superior to that of a concrete/concrete overlay (*13*). The bond characteristics of ECC/concrete repair applications prove to be far better than current concrete/concrete repair techniques.

Freeze Thaw

Resistance to freeze thaw deterioration is essential for materials intended for transportation applications. Freeze thaw testing, in accordance with ASTM C666A was performed. Companion series of PVA-ECC and normal concrete specimens (both without air entrainment) were exposed to freeze thaw cycles. In addition to typical dynamic modulus testing of prism specimens outlined in C666A, a series of ECC tensile specimens was also subjected to freeze thaw exposure. This testing series evaluated the effect of these conditions on composite strain capacity. Results from these tensile specimens were compared to tensile coupons of identical age cured in water at 22ºC.

Testing of ECC and concrete prism specimens was conducted concurrently over 14 weeks. After 5 weeks (110 cycles), the concrete specimens had severely deteriorated, requiring removal from the freeze-thaw machine, as mandated by the testing standard. However, all ECC specimens survived the test duration of 300 cycles with no degradation of dynamic modulus (Figure 4). This performance results in a durability factor of 10 for concrete compared to 100 for ECC, as computed according to ASTM C666. In uniaxial tension tests performed on wet cured and freeze thaw exposed ECC tensile coupons at the same age, no significant drop in strain capacity is experienced after 300 cycles. Both wet cured and freeze thaw specimens exhibit a strain capacity of roughly 3%, which, while lower than the 5% strain capacity mentioned above, fits with long term results in specimens of this age.

Abrasion and Wear Testing

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 by 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 a tining 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 (*14*). 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 1.6kN to 2.3kN. The established minimum AWI for Michigan trunkline road surfaces is 1.2kN, 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 2.3kN after 4 million tire passes, is recommended for future ECC surface repairs.

Early Age Strength

Roadway surface repair materials must exhibit rapid early age strength development for infrastructure applications. Obviously, the longer a material cures before achieving adequate strength to withstand service loads, the larger an impact the project will have on traffic congestion and delays. To determine the early age strength development of ECC, a series of compressive cylinders (10cm X 20cm) were tested at various early ages. Tests were conducted up to an age of approximately 100 hours. Tests show that at 24 hours, ECC exhibits a compressive strength of 24MPa, adequate for most repair applications. After another 5 hours of curing the strength has reached 28MPa, a typical required concrete strength in reinforced concrete construction. The ultimate compressive strength of a typical ECC material is 60MPa, well above most transportation needs. From these results, a curing time of one day is recommended for typical repair applications. While the use of hydration accelerators was not included in this study, a variety of acceleration techniques have successfully been used with ECC to achieve adequate compressive strengths after only hours.

Long Term Strain Capacity

To validate the long term effectiveness of ECC, 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 which must be maintained, the strain capacity of ECC material changes during maturing. This is exhibited in a plot of ECC strain capacity versus age (Figure 5). Initially, strain capacity is very low due to the low matrix strength. At roughly 10 days aging, peak strain capacity is achieved due to an optimal balance of matrix, fiber, and matrix/fiber interface properties. As hydration continues, a slight imbalance occurs and remains throughout the material life resulting in a long term strain capacity of 3% for ECC, far above the deformation demand imposed by many repair applications, but significantly less than the maximum capacity of 5% seen at early age. As mentioned before, this long term strain capacity data fits well with the strain capacity exhibited by freeze thaw and wet cured tensile specimens at 14 weeks. While long term tests have only been carried out to 180 days, the long term strain capacity is expected to remain at approximately 3%.

Accelerated Weathering Tests

In contrast to freeze thaw tests discussed earlier, which are designed to simulate temperature changes in winter conditions, hot water immersion tests were conducted to simulate the long term effects of hot and humid environments. To examine the effects of environmental exposure, hot water immersion was performed on individual fibers, single fibers embedded in ECC matrix, and composite ECC material specimens (*15*). Specimens for both individual fiber pullout and composite ECC material were cured for 28 days at room temperature prior to immersion in hot water at 60ºC for up to 26 weeks.

After 26 weeks in hot water immersion, little change was seen in fiber properties such as fiber strength, fiber elastic modulus, and elongation. Interfacial properties, however, experienced significant changes, particularly between 13 and 26 weeks of immersion. During this time, the chemical bonding between fiber and matrix strengthened, while the apparent strength of the fiber dropped. These two phenomena caused fibers within the ECC matrix to delaminate and break during loading after 26 weeks of immersion, rather than pull-out intact, as seen in specimens immersed 13 weeks or less. This change in interfacial properties resulted in a drop of ultimate strain capacity, as predicted from the ECC micromechanical design model. The strain capacity of the ECC dropped from 4.5% at early age to 2.75% after 26 weeks of hot water immersion. While accelerated hot weather testing does result in lower strain capacity of ECC, the 2.75% strain capacity, over 250 times that of normal concrete, seen after 26 weeks remains acceptable for nearly any repair/retrofit application.

ECC TRANSPORTATION APPLICATIONS

The performance of ECC in realistic applications is being evaluated through a number of ECC repair or rehabilitation projects which have recently been completed or are in the planning stages. Two of these projects, in conjunction with the Michigan Department of Transportation, are a bridge deck patch repair and a bridge deck link slab. The patch repair was completed in October 2002, while the link slab demonstration project is scheduled for the summer of 2005.

Bridge Deck Patch Repair

Prior to performing patch work, a site was selected in southeast Michigan suitable for a demonstration project. The requirements for the site were a low traffic volume to accommodate monitoring, and a bridge requiring limited shallow patching of a deteriorated concrete deck. An MDOT owned two-lane bridge overpassing a four-lane expressway was selected. This bridge, constructed in 1976, is a four span, simply supported, steel girder bridge with a nine inch thick reinforced concrete deck. Average daily traffic (ADT) for this structure was recently counted at 3000 vehicles per day (unpublished data), meeting the requirement of low ADT for observation purposes. However, while ADT is relatively low, a large number of 11-axle gravel trucks use this structure, greatly increasing loads on the bridge. Required patch work consisted of roughly a 7m X 9m section of severely deteriorating asphalt patching, which had previously been used as a temporary repair.

Only a section of the patch was repaired with ECC while the remaining portion was repaired with a commercially available concrete patching material commonly used by MDOT maintenance crews for comparison. This repair scenario allowed for a unique comparison between ECC and concrete subjected to identical environmental and traffic loads. The concrete repair material used by MDOT crews was a pre-packaged mixture of Portland cement and plaster of paris. This binder is field mixed with sand, coarse aggregates, and water, producing a concrete material which achieves 22MPa compressive strength after 1 hour, making it ideal for roadway repairs requiring limited lane closures.

Prior to casting the patching material, the deteriorated asphalt was removed, along with any remaining deteriorated concrete, using a pneumatic hammer to a depth of 7.5cm, just below the top layer of reinforcement. This area was then sandblasted to clear any debris and clean it in preparation for patching. Any exposed deteriorated reinforcing was also replaced. Additionally, the saw cut edges of the patch area were roughened using a pneumatic hammer and the entire area was wetted to increase bonding between the patch material and the existing deck. MDOT maintenance crews then cast the concrete into a section of the patching area, leaving an adjacent section empty for the ECC patch. Once cast, the concrete was steel troweled to a smooth finish and textured transversely with a tining rake. After tining, the patch was sprayed with a latex-based curing compound to prevent moisture loss, and covered with wet burlap and plastic tarps to prevent rapid drying.

The morning following the concrete patching, the ECC patch was cast. Using a 340L drum mixer, pre-batched ECC components were mixed onsite. Prior to field operations, a simple mixing regime and mixing time were established to allow for easy operation and optimal fresh properties. After approximately 25 minutes of mixing, the ECC achieved the creamy viscosity, good flowability, and fiber dispersion necessary for casting. While longer than typical concrete mixing times, the typical mixing time for ECC is approximately 10 minutes. A longer mixing time was used in initial demonstrations to ensure material consistency. ECC was then cast into the remaining patch area, steel troweled to a smooth finish, transversely tined with a rake, sprayed with a latex-based curing compound, and covered with wet burlap and plastic tarps. The use of curing compound, along with wet burlap and plastic to keep the material from drying too fast was found to be very important, particularly in windy bridge deck sites. No vibration was applied, as the ECC is self-consolidating. The complete ECC patching procedure took roughly 1 hour, and the lane was re-opened to traffic after 2 days of curing.

Long term performance of both the ECC and adjacent concrete patch has been recorded through a series of site visits. During visits, pictures were taken to document crack development and crack patterns, cracking along the interface between existing deck and repair material, and the overall condition of both repairs. Initial visits conducted 2 days after patching showed no visible cracking in the ECC, while a clearly visible crack, approximately 300μm 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 50μm wide, had formed within the ECC, while the concrete crack observed shortly after casting had widened to 2mm and was surrounded by deteriorated and spalling concrete. Most recently, observations made 10 months after patching revealed a maximum ECC crack width of 50μm, while sections of the concrete patch were severely deteriorating. The development of crack width over time in both ECC and concrete is shown in Figure 6. From this unique comparison of adjacent patch sites subjected to identical loading, ECC was shown to be far superior to concrete immediately after casting, and improving over time, establishing ECC as a preferable repair material.

Link Slab Application

A serious concern facing bridge owners is the maintenance and repair of bridge expansion joints. While necessary to accommodate thermal deformations, these joints often fall into disrepair and eventually leak. This leaking is frequently the cause of damage to the superstructure, allowing water and other corrosives to penetrate below the deck and corrode the bridge beams. After a time, this deterioration requires not only a replacement of the joint to stop the leaking, but also the badly damaged beams, which is costly and time consuming. To combat this problem, many bridge owners have looked to eliminate problematic bridge joints through the use of continuous bridge decks and integral abutment bridges, which call for a continuous deck with no expansion joints. While these technologies have been effective, they are only useful for new bridges and cannot be used on the thousands of simple span bridges currently in service across the nation.

To construct a continuous bridge deck surface, without reconstruction of the entire bridge, an excellent alternative is a bridge deck link slab (*16*). This slab forms a connector between two adjacent simple bridge spans, creating a continuous deck to prevent leaking, while absorbing the thermal deformations of the spans which are typically accommodated by an expansion joint (Figure 7). This technology has been demonstrated in a number of states, including Michigan, using ordinary concrete link slabs. These slabs use heavy reinforcing ratios to limit crack widths in the slab while undergoing tensile strains imposed by shortening adjacent bridge spans during cold winter months. However, these link slabs form a very stiff link between adjacent simple spans, significantly changing moment distributions within the spans, and creating loading patterns outside of the intended simple span design, making the design procedure complex and difficult. Furthermore, effective crack control within these concrete link slabs is difficult.

Many of the difficulties resulting from ordinary concrete link slabs are eliminated by using ECC for link slabs (*17,18*). With a tensile strain capacity between 3% and 5%, over 300 times that of normal concrete, ECC is ideal for accommodating the types of tensile strain deformations associated with link slab technology. Furthermore, due to the inherent steady-state crack width of ECC discussed earlier, the decoupling of crack width to reinforcement ratio allows ECC link slabs to use low reinforcement ratios, if any steel reinforcement at all, resulting in a very flexible link slab. This flexibility is desirable in comparison to concrete link slabs, since it allows the link slab to act as a hinge between adjacent simple spans, minimally changing the original design moment distributions. This results in a much simpler design methodology along with better crack width control.

Currently, studies in collaboration with MDOT are exploring the use of ECC link slabs in Michigan. A typical expansion joint between two simple spans would be replaced by an ECC link slab. To accommodate thermal deformation, the length of an ECC link slab would be approximately 5% of each adjacent span. Therefore, for two adjacent 30m spans, the link slab would be 3m long (1.5m from each adjacent span). Simple calculations accounting for thermal deformation, shrinkage strains, bending deformation due to loading, and a generous safety factor show that an ECC link slab must provide a strain capacity of approximately 1.4%, well below the ultimate strain capacity exhibited by ECC material. Current laboratory testing of full scale ECC link slabs show far superior performance over concrete link slabs, exhibiting no loss of stiffness in fatigue loading, while maintaining steady-state crack widths at 50μm after 100,000 loading cycles. By comparison, concrete link slabs showed cracks widths of 0.6mm after 100,000 loading cycles (*16*). The use of ECC link slab technology looks to be a major development in the future rehabilitation of existing simple span bridges.

MATERIAL COST

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 easiest and 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. For the patch application, the cost of the MDOT repair material is roughly \$540/m^3. While the cost of ECC may seem high in comparison to normal concrete, it is far less than many polymer concretes commonly used in repair applications, or certain high strength FRC, which may cost \$2000/m^3-\$5000/m^3. With judicious incorporation of industrial waste material, lower cost and greener ECC materials are also being developed at the University of Michigan (*19*).

As mentioned earlier, it is essential for the transportation community to seek a fundamental solution to the dire state of the national infrastructure. Proven by initiatives such as Michigan's "Preserve First", the need and resources for an improved transportation infrastructure are present. Designers must look beyond the initial cost of materials used in repair and rehabilitation, and look to highly durable materials, such as ECC, which may have higher initial costs than conventional materials. These high performance materials offer longer service lives with reduced lifetime costs associated with frequent maintenance, repair, and replacement. It is crucial for transportation planners and designers to look to new "smarter" materials for the next generation of infrastructure development.

CONCLUSION

Engineered Cementitious Composites (ECC) exhibit many of the characteristics sought by transportation infrastructure owners and designers including excellent durability and high ductility. ECC material tests show outstanding performance for repair and rehabilitation applications in shrinkage behavior, fatigue and bond testing, freeze thaw exposure, abrasion and wear testing, early age strength, long term material performance, and accelerated weather tests. Furthermore, the use of ECC materials in both completed and planned demonstration projects with the Michigan Department of Transportation, including bridge deck patching and a link slab project, reveal that ECC is a plausible and preferable repair/retrofit material for various transportation applications. The introduction of high performance materials, such as ECC, is expected to set a new standard for transportation repair materials resulting in fewer repairs, less maintenance, and lower lifetime costs.

More information on ECC technology and applications can be found at http://ace-mrl.engin.umich.edu.

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LIST OF TABLES AND FIGURES

TABLE 1 Typical Mix Design of ECC Material (kg/m^3)

Material	Quantity (kg/m^3)
Cement	583
Sand	467
Fly Ash (Type F)	700
Water	298
Superplsticizer	17.5
Fiber	26

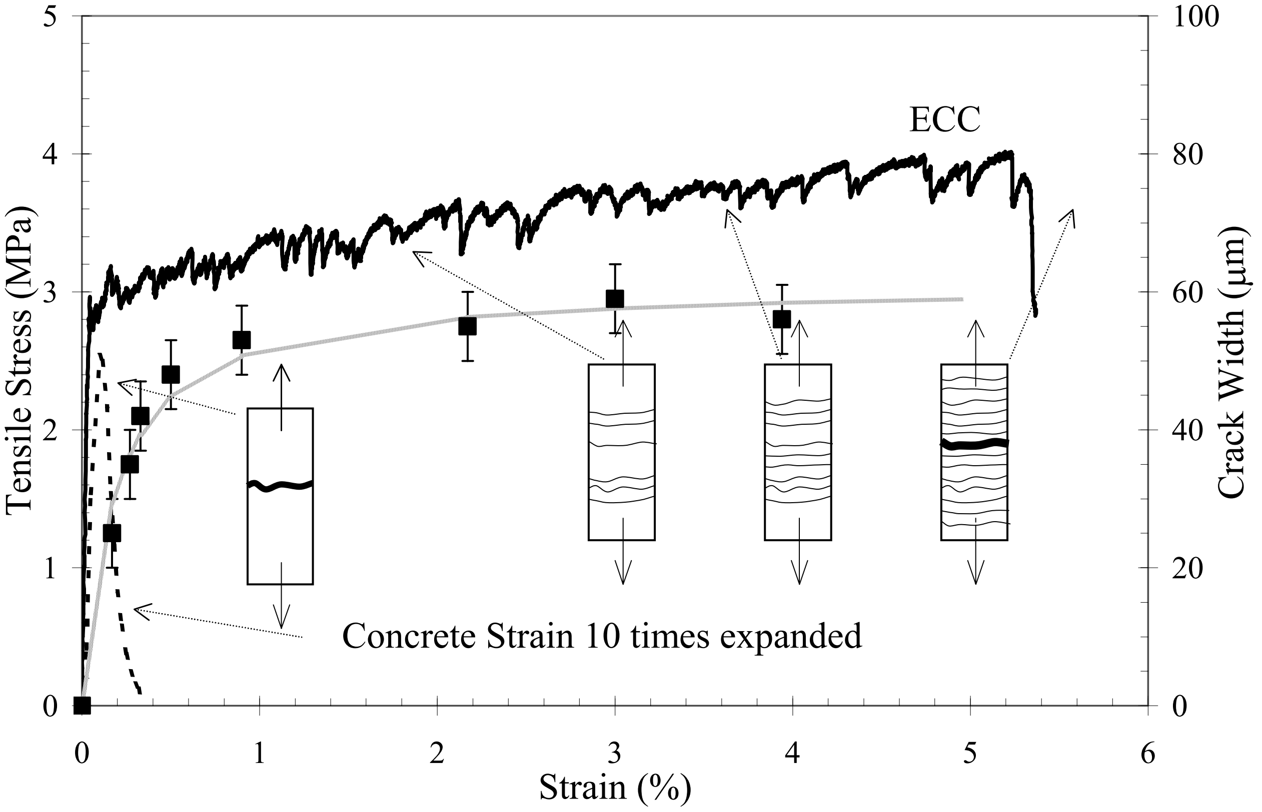

FIGURE 1 Representative Uniaxial Tensile Stress-Strain Curve and Crack Width Development for ECC Material. For Comparison, the Tensile Behavior of Concrete Is Also Shown

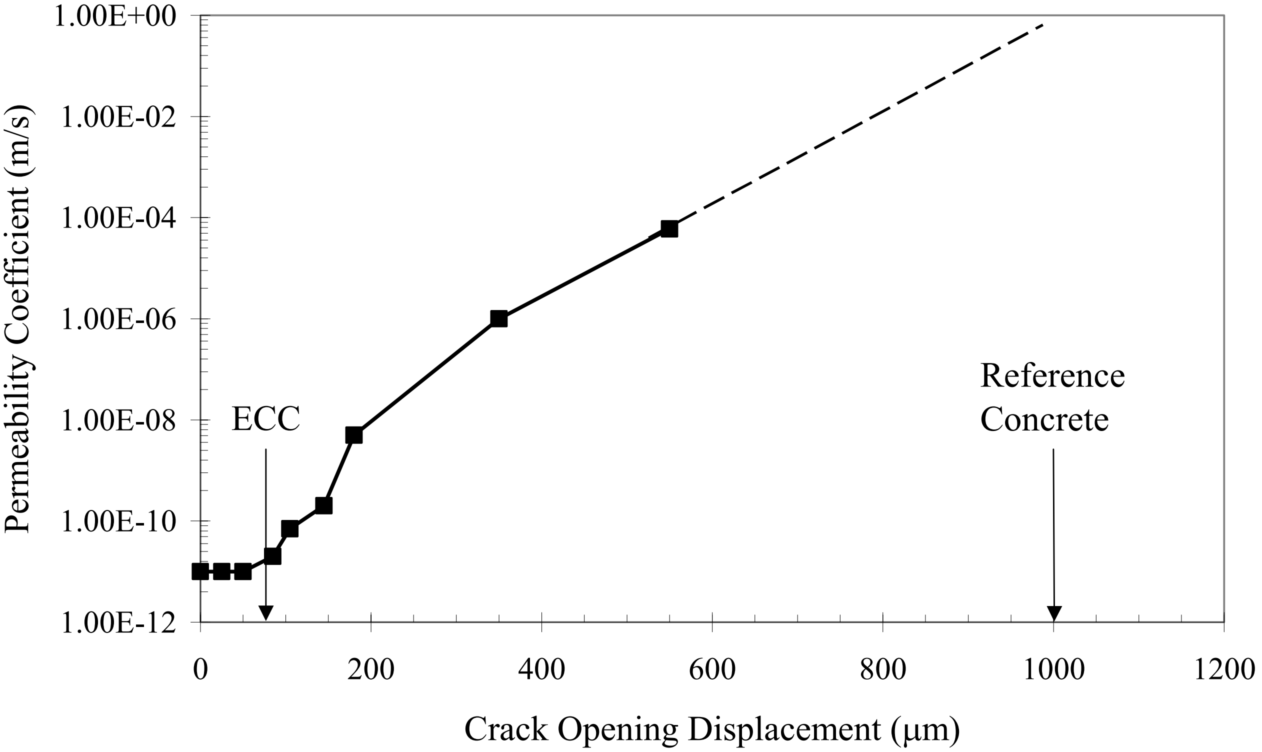

FIGURE 2 Permeability Coefficient as a Function of Crack Width

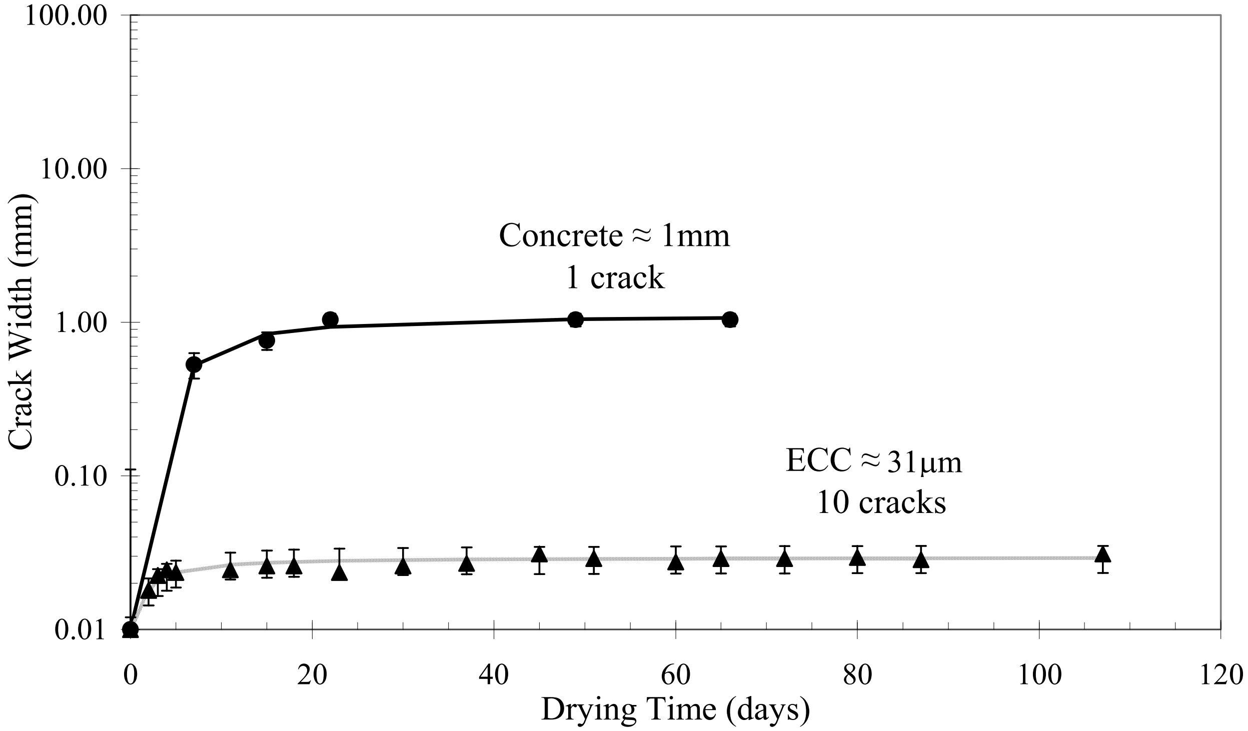

FIGURE 3 Crack Width Development as a Function of Drying Time (RH=50%)

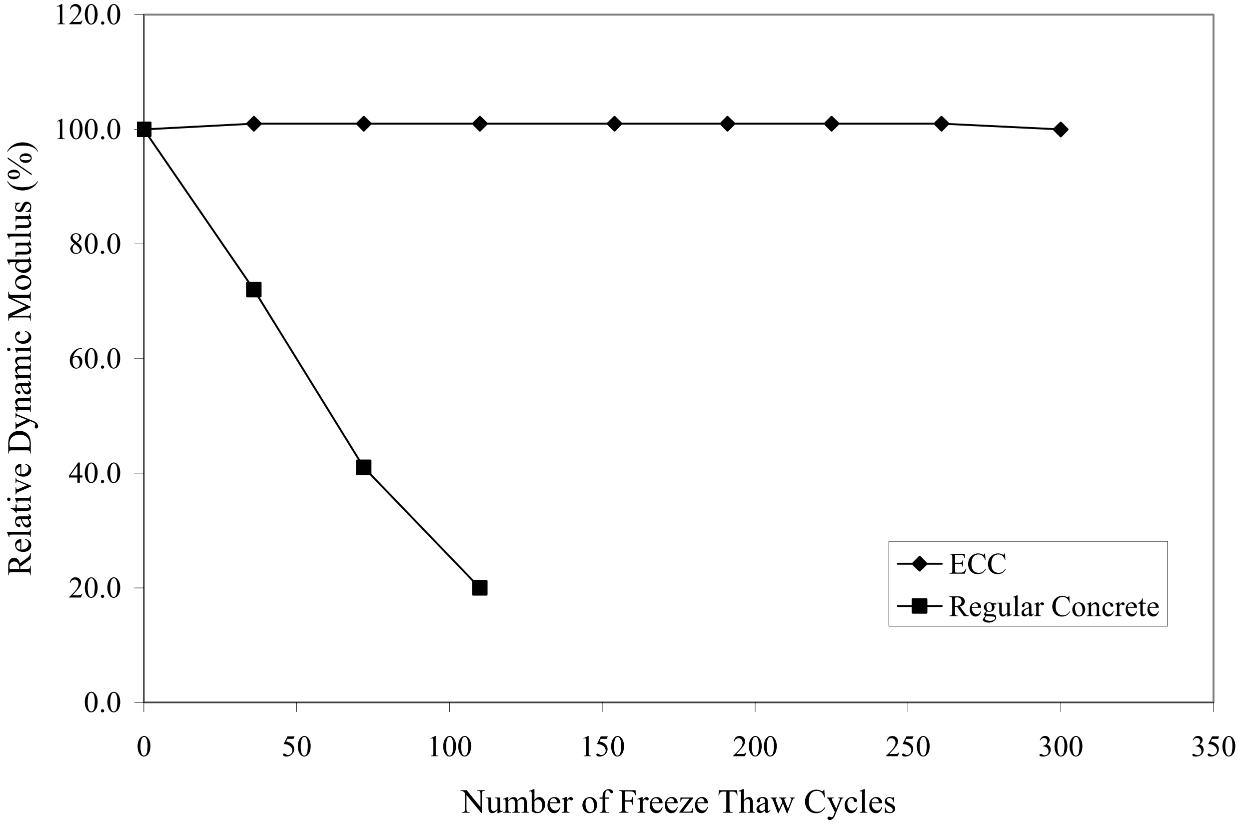

FIGURE 4 Relative Dynamic Modulus of ECC and Concrete Specimens Throughout Freeze Thaw Testing

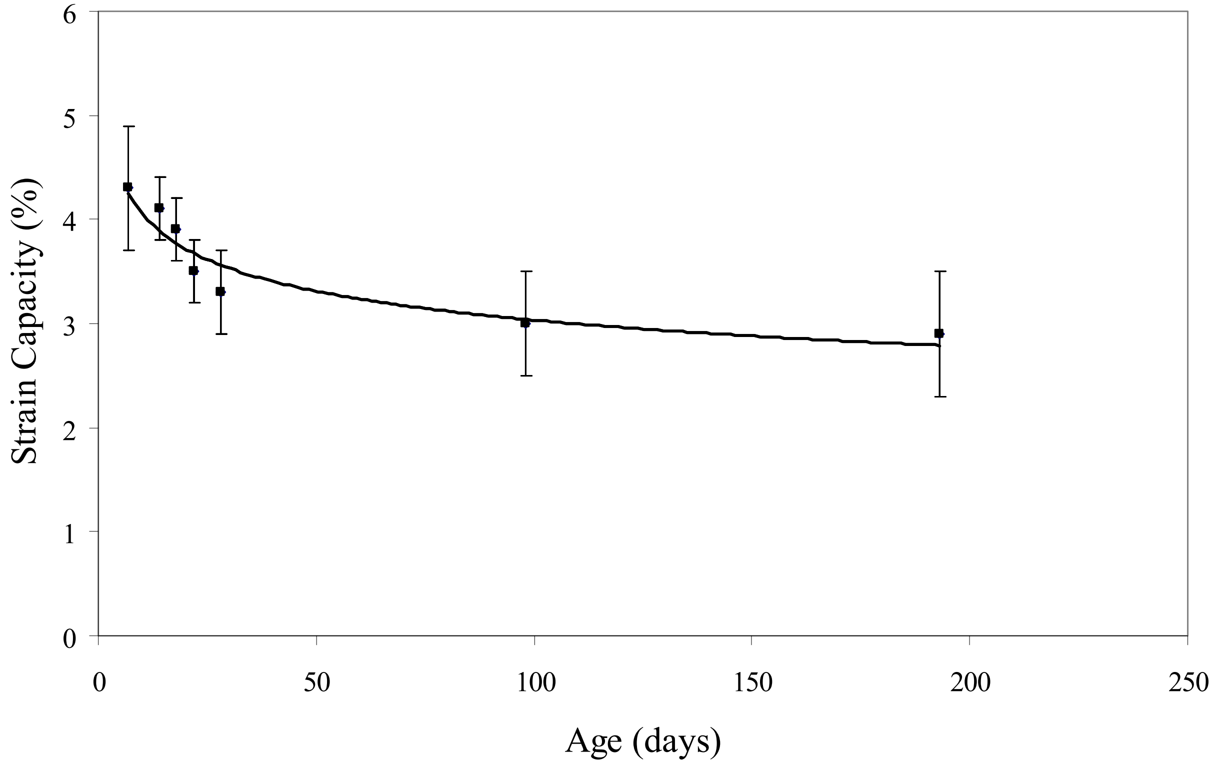

FIGURE 5 Tensile Strain Capacity Development of ECC Material

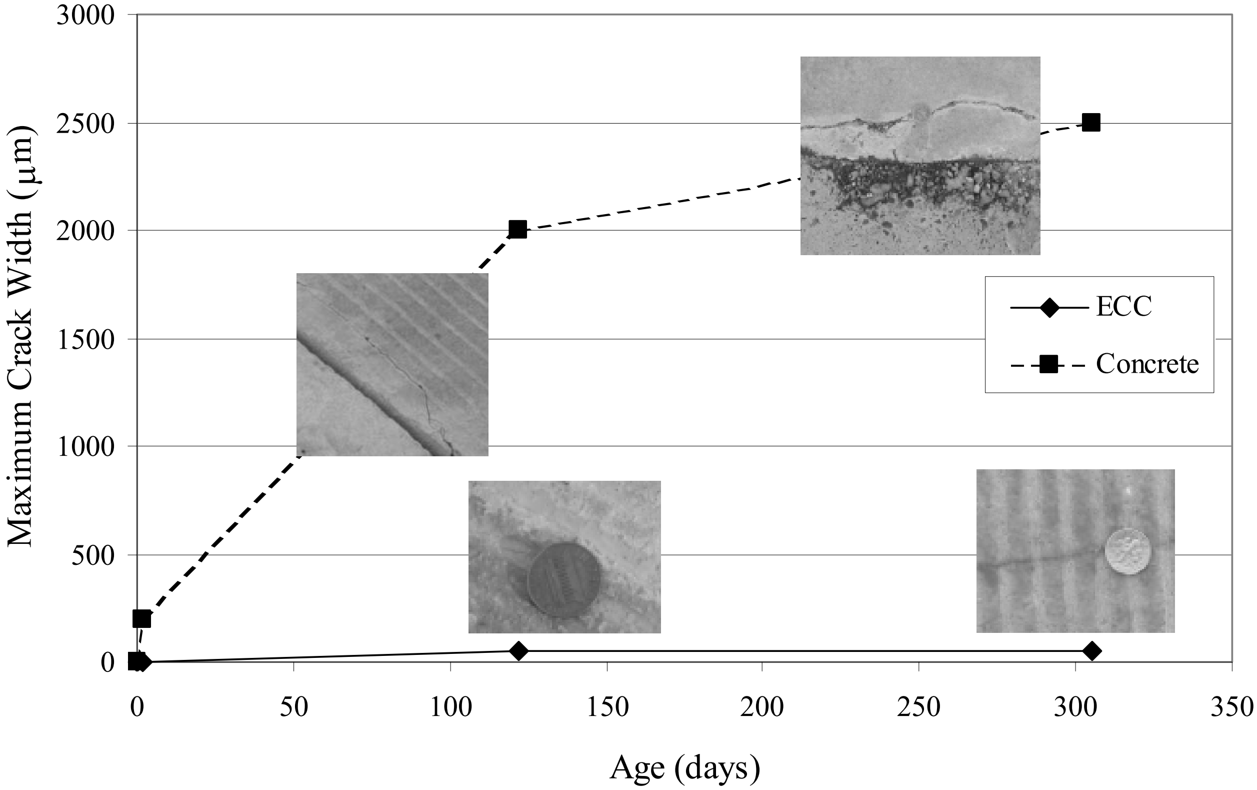

FIGURE 6 Development of Crack Width over Time in ECC and Concrete Patch

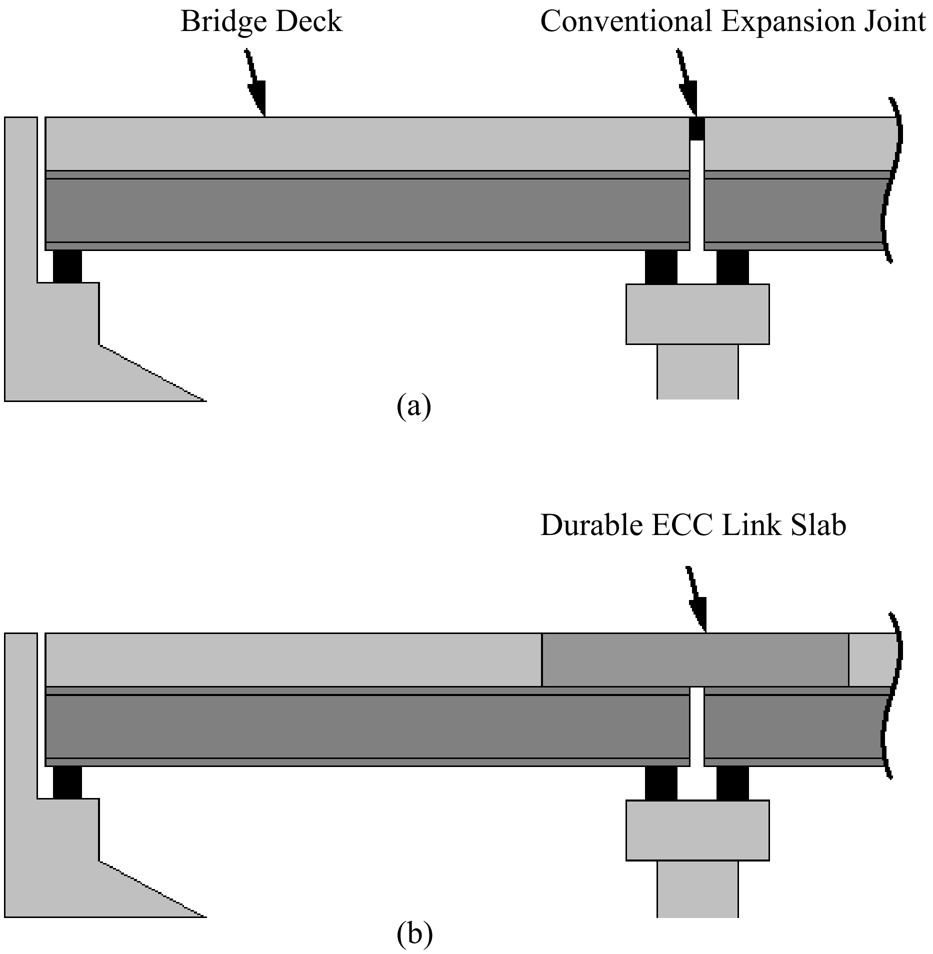

FIGURE 7 ECC Link Slab Application (a) Conventional Expansion Joint (b) Durable ECC Link Slab