REFERENCES

[1] RILEM AAC13.1 1994, 'Determination of the specific fracture energy and strain softening of AAC', RILEM Technical Recommendations for the Testing and Use of Construction Materials, pp.156-158

[2] Kitsutaka, Y. 1997, 'Fracture parameters by poly-linear tension softening analysis', *Journal of Engineering Mechanics*, ASCE, **123**[5], pp.444-450

[3] Kitsutaka, Y., Kamimura, K. & Nakamura, S. 1994, 'Evaluation of aggregate properties on tension softening behavior of high strength concrete'. High Performance Concrete, ACI SP149-40, pp.711-pp.727

DURABILITY AND LONG TERM PERFORMANCE OF ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

Durability of concrete structures is one of the most significant problems currently facing the engineering community. The use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) may greatly enhance the durability and long term performance of concrete structures. However, prior to designing HPFRCC materials into practical applications, their durability performance must be shown equal or superior to concrete over long durations in service environments. In this article, the behavior under various environmental loads and the long term performance of a class of HPFRCC called Engineered Cementitious Composites (ECC) is summarized. This material is shown to have 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 two year comparison between ECC and concrete roadway patching applications on a Michigan Department of Transportation bridge deck.

1. INTRODUCTION

While it is widely recognized that civil infrastructure supports the health and wealth of nations, it is disturbing that the general condition of infrastructure in many nations are deteriorating rapidly. In S. Korea, Japan, Thailand, and the US, for example, annual costs for repair and retrofit of infrastructure have surpassed those of new construction. The American Society of Civil Engineers recently released the 2005 report card on US infrastructure, which received an average grade of D. ASCE [1] cited that to repair all deficient bridges it will cost in excess of $180 billion over the next twenty years, while poor roads are presently costing US drivers $54 billion annually in additional vehicle repair and operating costs. The current problems facing US infrastructure systems are simply overwhelming.

At the root of these problems is the poor durability of concrete construction. As a brittle material, concrete cracks under load thereby allowing water and corrosives into the material and accelerating destruction. Many concrete modifications increase durability, such as air entrainment, sulfate resistant cements, or minimum reinforcement, but few solutions target the inherent brittleness of concrete. To solve the serious problem confronting US infrastructure, a fundamental solution which reduces the brittle nature of concrete is needed.

Through the use of High Performance Fiber Reinforced Cementitious Composites (HPFRCC), which display significantly higher ductility than reinforced concrete (R/C), durability problems resulting from cracking may be solved [2]. Yet to prove acceptable for many applications, these materials must show high ductility and enhanced material and structural durability by exhibiting such characteristics as excellent protection of steel reinforcement, resistance to freeze thaw cycles, and demonstration of long term mechanical performance. The introduction of materials which provide both ductility and durability will likely serve as a watershed development in the design of future infrastructure systems.

2. ENGINEERED CEMENTITIOUS COMPOSITES

A new class of HPFRCC materials, called Engineered Cementitious Composites (ECC), addresses many of these needs presented above. This ultra-ductile cementitious composite exhibits ductility similar to metals [3]. Additionally, this material shows excellent performance in durability testing. 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 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 1). Micromechanical tailoring of ECC components for strain hardening performance has been described previously by Li [3].

Along with tensile ductility, the unique crack development within ECC is critical to its durability. Unlike most fiber reinforced concretes (FRC), ECC exhibits self-controlled crack widths under increasing load (Figure 1). 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. The formation of steady-state cracking is the result of micromechanical tailoring of ECC material, mentioned previously.

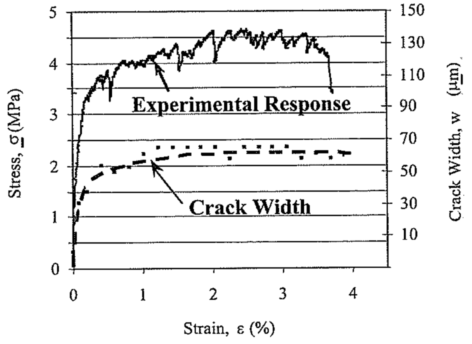

Figure 1. Tensile Stress-Strain Response of ECC and Crack Width Development

3. 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. 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 under 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.

Historically, building codes have given specific consideration to the distribution of reinforcement to minimizing cracking. The 1995 edition of the ACI Building Code [4] (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 [5].

However, the 2002 edition of the American Concrete Institute concrete building code, (hereafter ACI-318-02) [6] (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 [7] which describes corrosion development and deterioration within R/C, cracking represents a final step towards failure by accelerating deterioration. Recently, Miyazato [8] 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.

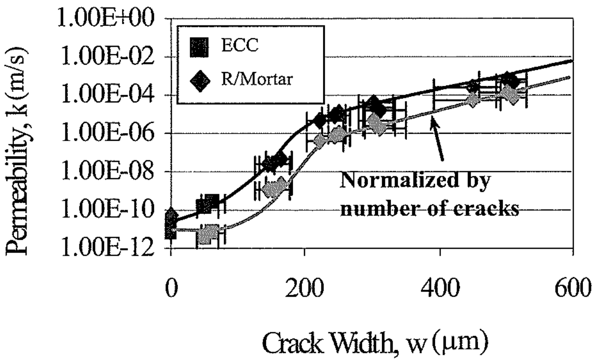

Figure 2. Permeability of cracked and uncracked ECC and Reinforced Mortar (R/Mortar) Specimens

Regardless of the effect of crack width on corrosion rate, it cannot be argued that limiting the transport of water and corrosives will improve the durability of any concrete structure. Along this line, ECC self-controlled crack widths (Figure 1) become a crucial defense against poor durability. As mentioned, independent of the strain level, maximum ECC crack widths remain at 60 µm.

Recently, Lepech and Li [9] found that cracked ECC exhibits nearly the same permeability as sound concrete, even when strained in tension to several percent (Figure 2). 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. The ability of cracked ECC to demonstrate autogenous healing is also promising. These results suggest that due to the self-controlled crack widths, significant strides in durability can be made by replacing concrete with ECC.

4. MATERIAL DURABILITY TESTING

Aside from designing for crack width, durable structures require material durability against freeze thaw, corrosion, and harsh environmental exposure. 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 [6] 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 [10]. 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 applications.

4.2 Sulfate Resistance

For structures contacting soil, specifically foundations and concrete piles, resistance to sulfate attack is essential. This is addressed is Section 4.3 of ACI-318-02 [6]. Adequate resistance to sulfate attack is achieved through limiting the water to cement ratio within the concrete, requiring a minimum compressive strength, and using either Type II or Type V cement specially blended for sulfate resistance. Within ACI-318-02 [6], appropriate preventative recommendations are given for levels of sulfate exposure ranging from negligible to very severe. With limited C_3A content, Type II and V cement has proven very effective in minimizing the effect of sulfates on concrete. While no research has been done on the durability of ECC in sulfate rich environments, the use of these cements should prove effective in maintaining durability. However, the effect of these cements on micromechanical properties of the matrix, fibers, and matrix/fiber interface will have to be investigated.

4.3 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 [11]. 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.

4.4 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 [12]. In overlay applications, reflective cracking through the new layer is of 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 specimens was double that of concrete/concrete 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 [13]. In many applications, particularly concrete infrastructure, fatigue failure can significantly shorten service-life. The exceptional fatigue performance of ECC proves it a preferable material for fatigue-prone structures.

4.5 Long Term Strain Capacity

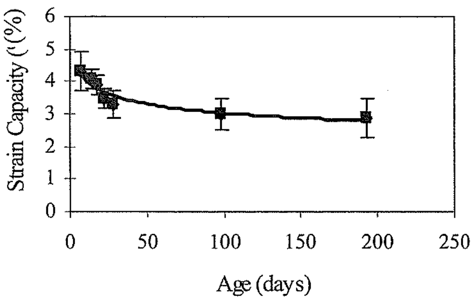

Figure 3. Long Term Strain Capacity of ECC

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 3). 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, 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%.

5. CORROSION PROTECTION OF REINFORCEMENT

The ability to protect reinforcement from corrosion greatly impacts the durability of an R/C member. According to the Tutti model discussed previously and expanded by Thoft-Christensen [14], 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 [6] 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 proposed by Thoft-Christensen [14] 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. 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 [8] 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 [15]. 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 three 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 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 30 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 4. 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.

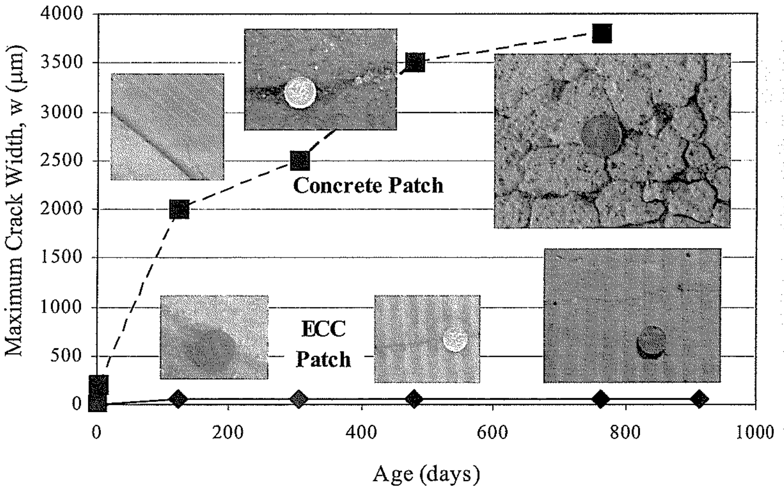

Figure 4. Comparison of ECC and concrete crack widths in MDOT field patch application

7. 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. 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. 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.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] American Society of Civil Engineers "2005 Report Card on America's Infrastructure" Accessed April 23, 2005. http://www.asce.org/reportcard/2005/page.cfm?id=103

[2] Li, V. C. and Henrik Stang, "Elevating FRC material ductility to infrastructure durability" *Proceedings of BEFIB*, Varenna, Lake Como, Italy, Sept. 2004, pp 171-186.

[3] Li, V.C. "From Micromechanics to Structural Engineering – The Design of Cementitious Composites for Civil Engineering Application", *JSCE J. of Structural Mech. and Earthquake Eng.*, 10(2). pp. 37-48,1993.

[4] American Concrete Institute, *Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary(ACI 318R-95)*, American Concrete Institute. Farmington Hills, MI. 1995

[5] American Association of State Highway and Transportation Officials "AASHTO LFRD Bridge Design Specifications: Second Edition." *AASHTO*. Washington, D.C., USA 1998. pp. 5-41

[6] American Concrete Institute, *Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02)*, American Concrete Institute. Farmington Hills, MI. 2002

[7] Tuuti, K. "Corrosion of Steel in Concrete" Swedish Cement and Concrete Research Institute, Stockholm., 1982

[8] Miyazato, S. and Hiraishi, Y. "Transport Properties and Steel Corrosion in Ductile Fiber Reinforced Cement Composites" *Proceedings of the Eleventh International Conference on Fracture*. Turin, Italy. March 20-25, 2005.

[9] Lepech, Michael, and V.C. Li, "Water Permeability of Cracked Cementitious Composites", *Proceedings of Eleventh International Conference on Fracture*, Turin, Italy. March 20-25, 2005.

[10] Li, V.C., Fischer, G., Kim, Y.Y., Lepech, M., Qian, S., Weimann, M., Wang, S., "Durable Link Slabs for Jointless Bridge Decks Based on Strain-Hardening Cementitious Composites", Report for Michigan Department of Transportation RC-1438, November 2003.

[11] Li, V.C., T. Horikoshi, A. Ogawa, S. Torigoe and T. Saito, "Micromechanics-based Durability Study of Polyvinyl Alcohol-Engineered Cementitious Composite (PVA-ECC)," *ACI Materials J.*, 101(3), pp. 242-248, 2004

[12] Zhang J., Li, V.C., "Monotonic and Fatigue Performance in Bending of Fiber Reinforced Engineered Cementitious Composite in Overlay System ," *J. of Cement and Concrete Res.*, 32(3), pp. 415-423, 2002

[13] Suthiwarapirak, P., T. Matsumoto, and T. Kanda, "Flexural Fatigue Failure Characteristics of an Engineered Cementitious Composite and Polymer Cement Mortars," J. Materials, Conc. Struc. Pavements, JSCE No. 718/V-57, pp. 121-134, November 2002

[14] Thoft-Christensen, P. "Modeling of the Deterioration of Reinforced Concrete Structures" IFIP Conference on "Optimization and Reliability of Structural Systems", Ann Arbor, MI, USA, pp. 15-26 September 25-27, 2000

[15] Li, V.C., and M. Lepech, "Crack Resistant Concrete Material for Transportation Construction," in *TRB 83rd Annual Meeting, Washington, D.C., Compendium of Papers CD ROM*, Paper 04-4680, 2004.

THE INFLUENCE OF SURFACE PREPARATION ON THE BEHAVIOR OF ECC/CONCRETE LAYER REPAIR SYSTEM UNDER DRYING SHRINKAGE CONDITIONS

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Abstract

The paper presents the effect of concrete substrate surface preparation on the performance of Engineered Cementitious Composites (ECC)/concrete layer repair system under restrained drying shrinkage. In repair applications where "new" repair materials are bonded with "old" concrete, drying shrinkage often induces surface cracking in the repair materials, together with interface delamination between the repairs and the concrete substrates. Experimental study shows that when a "smooth" concrete substrate surface was present, the interface delamination was large. However, when an adequate bond was achieved by roughing the surface and/or using bonding agent, the high ductility of ECC could suppress large surface cracks and interface delamination, therefore greatly improving durability and structural integrity of the repair system.

The performance of ECC repair, which is dependent on concrete substrate surface preparation, is significantly different from repairs made of brittle or quasi-brittle materials. Discussions are made on the potential impact on the current ACI Repair Guide with the application of ECC as innovative concrete repair material.

1. INTRODUCTION

1.1 Motivation

A large number of existing concrete structures worldwide, including previously repaired ones, are suffering deterioration or distress. These structures are in urgent need of effective and durable repairs, which should address underlying concrete deterioration problems and protect underlying concrete from aggressive environment in the long term.

Concrete repair is a complex process, and current experiences with concrete repair are not satisfying. It has been estimated that almost half of all concrete repairs fail in field [1]. They are often perceived to lack both early age performance and long-term