Durability performance of ductile concrete structures

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ABSTRACT: Engineered Cementitious Composite (ECC), a ductile concrete material with about 300 times the tensile ductility of normal concrete, is emerging in full-scale infrastructure applications. One of the first applications in the field was in a patch repair on a bridge deck in Michigan, USA, in 2002. This patch has been monitored since its placement, side-by-side with a repair mortar used on the same bridge deck. This paper reviews the durability performance of this patch repair having experienced six winter's worth of freezing and thawing, de-icing salt application, and heavy truck loads. Recent studies on repair durability, and creep, shrinkage, salt-scaling resistance, wear-resistance and transport properties of ECC are used to provide the background for the observed durability in the field application of ECC. It is suggested that the tensile ductility and intrinsically tight crack width of ECC, achieved via microstructural tailoring, are fundamentally responsible for the improved durability performance.

1 INTRODUCTION

Concrete infrastructure, both new and repaired, often suffers excessive deterioration due to a combination of mechanical and environmental loading. The American Society of Civil Engineers (ASCE) 2005 Report Card for US Infrastructure assessed 12 infrastructure categories and assigned an average grade of D (poor). ASCE estimated that USD 1.6 trillion was needed over the next five years for repair and retrofit. Correspondingly, repair and retrofit cost has been estimated to be USD 2 trillion for Asia's infrastructure. In Germany, Japan, Korea, and Thailand, the annual cost for repair has exceeded that for new construction.

Deteriorating infrastructure has become a looming threat that could jeopardize the world's prosperity and our quality of life. Unfortunately, current experiences with concrete structure repairs have not been satisfactory. It has been estimated that almost half of all concrete repairs fail prematurely (Vays-burd et al., 2004) as they do not address the underlying deterioration problems under combined effects of mechanical and environment loading.

At the root of poor durability of concrete structures and repairs is the inherent brittleness of concrete material. Concrete tends to crack and spall under applied structural loads, shrinkage, chemical attack and thermal deformations, which are practically inevitable and often anticipated in restrained conditions (see,

e.g. Mihashi & De Leite 2004). Cracks allow water and corrosives into the material, accelerating deterioration such as leeching, corrosion, sulfate attack and freezing-and-thawing damage. Current methods to increase durability of concrete structures include (a) densifying the microstructure of concrete material through well-graded particle size distribution to reduce transport of corrosives to the steel (see, e.g. Oh et al., 2002), (b) increasing concrete compressive strength, (c) modifying concrete through adding air entrainment, sulfate resistance cements etc. and (d) adding crack-control reinforcement. These approaches do not address the inherent brittleness of concrete, and most (a-c) rely upon the concrete remain uncracked within a structure throughout its service life. Since most of the concrete durability problems in the field start from concrete cracking, a fundamental solution that reduces the brittle nature of concrete is necessary and foremost effective.

A new class of tensile strain hardening materials, called Engineered Cementitious Composites (ECC), addresses the brittleness of concrete. This ductile material exhibits a metal-like ductility (Li 1993) under mechanical loading, including tensile and shear, and durability under severe environmental exposure. Table 1 shows a typical mix proportion of ECC. This mix contains cement, fly ash, fine silica sand, water, poly-vinyl-alcohol (PVA) fiber and a small amount of chemical admixtures. Through micromechanics

Table 1. Mixing proportion for ECC (M45).

Material	Cement	Sand	Fly Ash	Water	HRWR	Fiber (Vol.)
Proportion	1.0	0.8	1.2	0.54	0.013	0.02

based material design, ECC achieves over 3% tensile strain capacity under uniaxial tensile loading with only 2% fiber volume content. This high ductility effectively suppresses fracture and spalling tendencies, and significantly improves durability of new or repaired structures. This material meets nearly every characteristic sought by engineers for cement-based construction materials for safe, durable and sustainable infrastructure (Li, 2008).

2 FIELD PERFORMANCE OF ECC-CURTIS ROAD BRIDGE PATCH REPAIR

One of the earliest applications of ECC is a small patch repair on a bridge deck in the US. This application offers significant insights into ECC's long-term durability performance. In collaboration with the Michigan Department of Transportation (MDOT), this ECC patch repair was placed on the bridge deck of Curtis Road over M-14 in Southern Michigan in October 2002. For this project, one section of the deteriorated bridge deck was repaired with ECC while the remaining portion was repaired with a pre-packaged mixture of Portland cement and plaster of paris, a commercial concrete patching material (Figure 1). A complete summary of this work can be found in Li & Lepech (2004).

After placement, the ECC and concrete patching repairs were exposed to identical traffic and environmental loads, thereby allowing for a meaningful comparison of their long-term durability performance. Although the bridge has a relatively low average daily traffic of 3000 vehicles per day, it is used frequently by 11-axle trucks heavily loaded with aggregates. Hence, mechanical (traffic) loading on the patch repairs is significant. Potential environmental loading on the patch repairs includes shrinkage, temperature change, freezing and thawing, chloride penetration, salt-scaling and steel corrosion.

The performance of the ECC and adjacent concrete patch repairs have been assessed through site visits. Initial visits 2 days after construction showed no visible cracking in the ECC patch repair. However, a clearly visible crack, about 300 m wide, appeared in the concrete. A possible reason for the cracking was restrained shrinkage. After 4-months winter exposure, a number of microcracks with width around
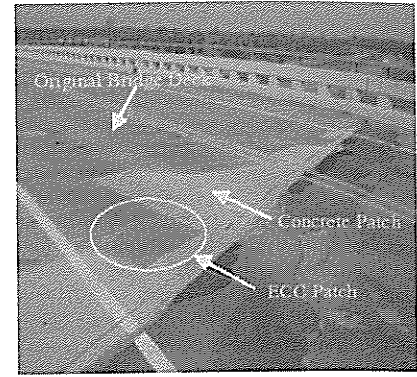

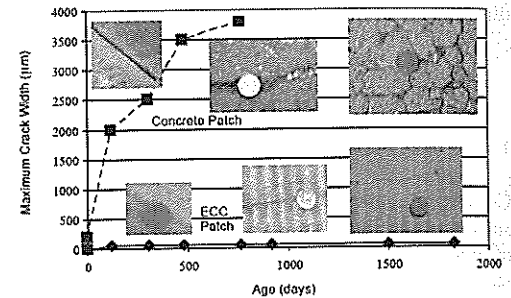Figure 1. ECC patch repair on Curtis Road Bridge, Michigan.

Figure 2. Crack width for ECC and concrete patch repairs.

50 µm had formed in the ECC patch repair. In contrast, the initial crack formed in the concrete repair widened to 2 mm and was surrounded by deteriorated and spalling concrete. In 2005, the concrete repair has severely deteriorated with cracks larger than 3.5 mm and had to be re-repaired. In 2007 when the complete bridge deck was reconstructed, the last available data point indicates that the ECC patch has survived the combined mechanical and environmental loading conditions with minor micro-cracking limited to less than 50 µm. No spalling or other deteriorations were found. The monitored crack width development is shown in Figure 2. This field performance data reveal promise of ECC as a durable construction material in the harsh environments of Michigan winters in addition to heavy traffic loads. The durability of ECC and ECC structures may be understood from an increasingly broad database of laboratory data some of which are summarized below.

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3 DURABILITY OF ECC UNDER MECHANICAL LOADING CONDITIONS

3.1 Tensile properties

The foremost important and unique property of ECC is its high tensile ductility and self-controlled crack width. These are intrinsic properties of ECC responsible for its durability performance under different loading conditions and environmental exposure. Figure 3 shows a typical uniaxial tensile stress-strain curve of ECC (M45) with tensile strain capacity of 500 times that of normal concrete and fiber reinforced concrete (FRC). The characteristic strain-hardening after first cracking is accompanied by formation of multiple micro-cracks. The typical crack width development is also shown in Figure 3. Up to the load when the material starts "softening", crack width of these micro-cracks remains lower than 60 μm. These micro-cracks are not "real" crack because their crack width is self-controlled and they carry increasing load after formation. The crack width of ECC is a material characteristic independent of steel reinforcement ratio and specimen size. In contrast, normal concrete and FRC rely on steel reinforcements to control crack width.

A series of uniaxial tensile tests carried out at ages up to 180 days validated that the high tensile ductility and controlled tight crack width of ECC is retained over time (Li & Lepech 2004). Test results show an initial reduction of strain capacity during the first 20 days after which it stabilizes to a long term value of 3%. While the long term tests have only been carried out to 180 days, micromechanical model predicts that the long-term strain capacity of ECC will remain at approximately 3%.

3.2 Compressive properties

Compressive properties of ECC are not significantly different from normal to high strength concrete. Its compressive strength ranges from 30–90 MPa. Elastic modulus at 20–25 GPa is lower than concrete due

to absence of coarse aggregates. This relatively low elastic modulus of ECC is desirable for concrete repair applications for limiting the tensile stress built up under restrained shrinkage. Compressive strain capacity of ECC at 0.45–0.65% is slightly higher than concrete. -
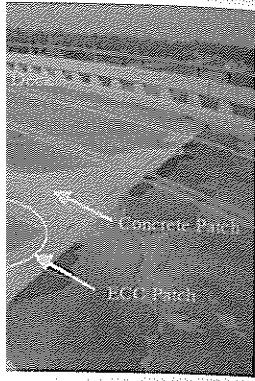
3.3 Fatigue behavior

ECC has greatly improved fatigue response compared with normal concrete and FRC. Suthiwarapirak et al., (2002) conducted flexural fatigue test on ECC and demonstrated higher ductility and fatigue life compared with polymer cement mortars commonly used in repair applications. Furthermore, fatigue loading does not seem to increase the crack width. Kim et al., (2004) experimentally validated that after 100,000 cycles of fatigue loading, the crack width in the reference concrete link-slab specimen increases from 50 μm to over 0.6 mm, while the crack width in the ECC link-slab remains close to 50 μm.
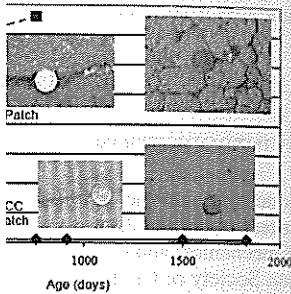
3.4 Abrasion and wear resistance

To evaluate ECC's abrasion and wear resistance for roadway applications, surface friction and wear track testing according to Michigan Test Method 111 was conducted in conjunction with MDOT (Li & Lepech 2004) using a static friction tester. These tests were conducted on a wet pavement surface with vehicle tires operated at 65kph. Initial friction forces between the tire and the ECC surfaces were determined. Then ECC specimens were subjected to 4 million tire passes to simulate long term wear. After wearing, friction forces were again determined to evaluate deterioration or surface polishing during wearing. The final friction forces are called the Aggregate Wear Index (AWI). AWI values for the textured ECC samples range from 1.6 kN to 2.3 kN, which are higher than the required minimum AWI of 1.2 kN for Michigan trunkline road surfaces. The test results show that ECC has good abrasion and wear resistance to heavy traffic.

3.5 Simulated layered repair system under mono-tonic and fatigue loading

Traffic loading can cause repair cracking and interface delamination between the repair layer and the concrete substrate. In addition, reflective cracking can be suppressed when ECC is used as the repair material (Zhang & Li, 2002). A layered repair system was investigated for resistance to reflective cracking and delamination under four-point monotonic and fatigue bending loading (Li & Li 2007). This system (Li & Co-workers 1997, 2000) contains a layer of repair material made of high early strength HES-ECC or concrete
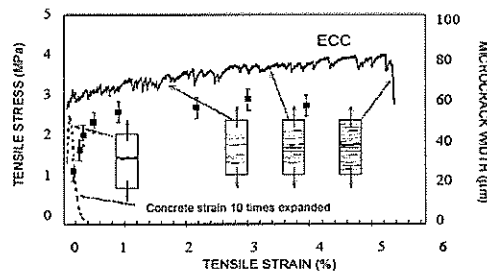
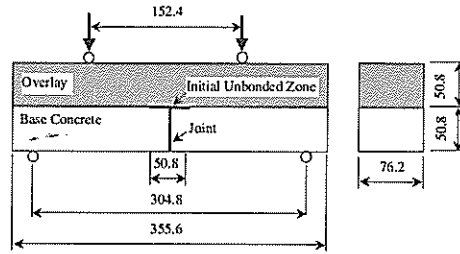Figure 3. Tensile stress-strain curve and crack width development of a typical version of ECC.

Figure 4. Dimensions (mm) of layered repair system under four-point monotonic/fatigue bending.
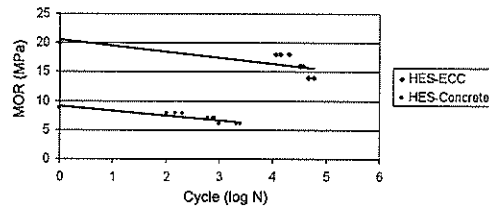

Figure 5. Fatigue life of ECC and concrete overlay repair.

cast on a substrate layer of old concrete with an initial vertical crack and interfacial delamination (Figure 4).

When subject to monotonic loading, the ECC layered repair system exhibited 100% increased load carrying capacity, and 5–10 times the deformation capacity of concrete layered repair system. Instead of forming one single crack in the concrete repair layer, the initial interfacial crack would kink into the ECC repair layer, and then trapped there. Upon additional loading, delamination resumes at the interface. The unique kink-trap-cracking behavior repeated itself with increasing loading till the flexuralstrength of HES-ECC was exhausted. In this way, repair spalling was successfully suppressed by using ECC.

When subject to the same level of fatigue loading, ECC layered repair system showed significantly longer service life than concrete layered repair system (Figure 5).

4 DURABILITY OF ECC UNDER ENVIRONMENTAL LOADING CONDITIONS

4.1 Freezing and thawing

Based on ASTM C666A, freeze and thaw testing was conducted on ECC and normal concrete specimens (Li et al., 2003). In addition, a series of ECC tensile specimens were also subjected to freeze thaw exposure to evaluate its effect on ECC's tensile strain capacity. Testing of the non-air-entrained ECC and concrete prisms was conducted concurrently over 14 weeks. After 5 weeks (110 cycles), the concrete specimens had severely deteriorated, requiring removal from the test. However, ECC specimens survived 300 cycles with no degradation of dynamic modulus. The computed durability factor of ECC was 100, far larger than 10 for the non-air-entrained concrete. The uniaxial tension tests performed on freeze and thaw exposed ECC coupons after 200 cycles showed no significant drop in strain capacity (3%).

4.2 Accelerated weather testing

Hot water immersion tests, performed on single fibers embedded in ECC matrix, and composite ECC material specimens, were conducted to simulate hot and humid environments (Li et al., 2004). After immersion in hot water at 60°C for 26 weeks, little change was seen in fiber properties. Interfacial properties, however, experienced significant changes particularly between 13 and 26 weeks of immersion, resulting in a drop of ultimate composite strain capacity from 4.5% at early age to 2.8% after 26 weeks of hot water immersion. The residue strain capacity of ECC, after this accelerated weather environment (equivalent to more than 70 years of natural weathering), is still over 250 times that of normal concrete.

4.3 Salt-scaling resistance

Sahmaran & Li (2007a) studied the durability performance of non-air-entrained ECC subjected to mechanical loading and freezing and thawing cycles in the presence of de-icing salts. After 50 exposure cycles, the surface condition visual rating and total mass of the scaling residue of ECC remained within acceptable limits according to ASTM C 672 (Figure 6). This level of durability held true even for specimens pre-loaded to cracking at high deformation levels. Non-air-entrained mortar specimens used as reference specimens deteriorated severely under identical testing conditions. Pre-loaded and virgin (non-pre-loaded) ECC coupon specimens were also exposed to freezing and thawing cycles in the presence of de-icing salts for 25 and 50 cycles to determine their residual tensile behavior. The reloaded specimens showed negligible loss of ductility, but retained multiple micro-cracking behavior and a tensile strain capacity over 3%. These results confirm that ECC, both virgin and micro-cracked, remains durable despite exposure to freezing and thawing cycles in the presence of de-icing salts.

4.4 Transport properties

The transport properties of concrete cover determine the time needed for the penetration of aggressive agents to reach the steel reinforcements. Transport

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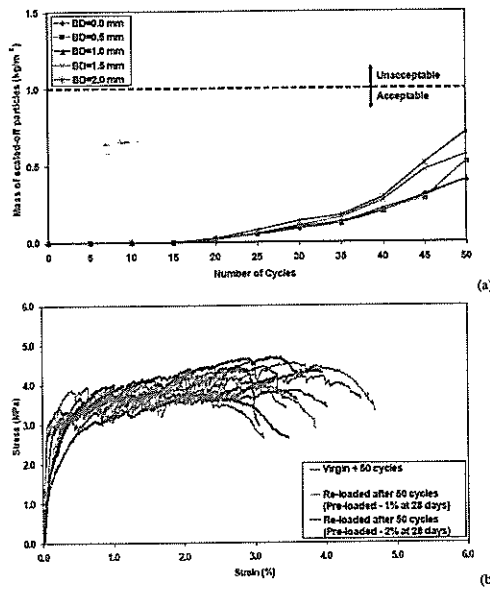

(a)

(b)

Figure 6. Effect of freeze and thaw cycles in the presence of de-icing salts for beams preloaded to different bend- ing deformation (BD) levels, showing mass of scaled-off particles.

mechanisms include permeation, diffusion and cap- illary suction. It is known that the permeability of cracked concrete scales with the third power of crack width (Tsukamoto 1990, Wang et al., 1997), and that a crack with width below 100 μm (50 μm for gas permeability) tends to behave like sound concrete. Wang et al., (1997) and Lepech & Li (2005) found that cracked ECC exhibits nearly the same permeabil- ity as sound concrete, even when strained in tension to several percent (Figure 7). Within this study, both ECC and reinforced mortar specimens were stretched in ten- sion to 1.5%, 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 a 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 is apparent.

Chloride diffusion coefficients for ECC were exam- ined by Sahmaran et al., (2007). Beam specimens were ponded in saltwater solution with 3% NaCl, according to AASHTO T259–80. For uncracked beams, the chloride diffusion coefficient for ECC was found to be $6.7510 \times 10^{-12} m^2/s$, compared with $10.58 \times 10^{-12} m^2/s$ for mortar beams used as control. Under high imposed bending deformation, preloaded ECC beam specimens revealed micro-cracks less than
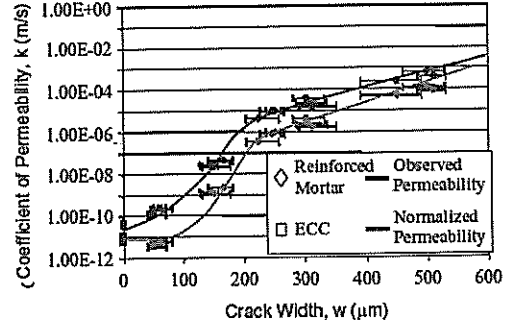

Figure 7. Permeability of precracked ECC and reinforced mortar measured as a function of crack width.
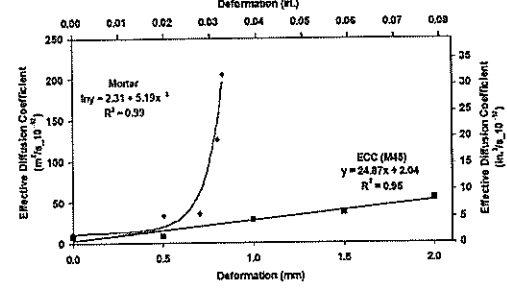

Figure 8. Diffusion coefficient versus pre-loading defor- mation level for reinforced ECC and reinforced mortar.

50 μm and an effective diffusion coefficient signif- icantly lower than that of similarly preloaded rein- forced mortar control beams due to the tight crack widths inherent in ECC. In contrast, cracks larger than 150 μm were often produced under the same imposed deformation levels for the reinforced mortar beams. Figure 8 shows the effective diffusion coeffi- cient versus pre-loading deformation level for ECC and mortar. It is revealed that the diffusion coeffi- cient of ECC varies linearly with the number of cracks, whereas the diffusion coefficient of reinforced mortar is proportional to the square of the crack width.

4.5 Corrosion resistance

The high tensile ductility of ECC leads to high cor- rosion-induced-spalling resistance and further pro- longed service life of R/ECC structures. Sahmaran et al., (2008) conducted an experimental investigation on R/ECC cylinder with a single steel rebar embedded and subjected to accelerated corrosion by electro- chemical method. Corrosion-induced crack width of mortar specimens increased with time as corrosion activity progressed. Larger crack widths, up to 2 mm wide, were obtained at higher levels of corrosion.

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On the other hand, crack widths of ECC remained nearly constant (~ 0.1 mm) with time as corrosion activity progressed, while the number of cracks on the surface of the specimen increased. The results of this study also showed that ECC has significant anti-spalling capability as compared to conventional mortar (Figure 9). If 0.3 mm maximum crack width limit for outdoor exposures as specified by AASHTO (2004) were used to represent the serviceability limit of reinforced concrete structures, the service life of reinforced ECC would be at least 15 times that of the reinforced mortar.

Reinforcement corrosion in mortar specimens resulted in a marked reduction in stiffness and flexural load capacity, as a result of mass loss of steel (Sah-maran et al., 2008). After 25 hours of accelerated corrosion exposure, the flexural strength reduced to about 34% of the original flexural capacity of the control mortar beam. In contrast, the ECC specimens after 50 hours of accelerated corrosion exposure retained almost 100% of the original flexural capacity. Beyond 50 hours, the flexural capacity decreased, but retained over 45% that of the original capacity even after 300 hours of accelerated corrosion exposure. Longitudinal cracks due to expansion of the corrosion products also affected the failure mode of the reinforced mortar under four-point bend load. However ECC deterioration due to the corrosion of reinforcement did not modify the ductile failure mode in ECC beams. Overall, the experimental results from this study suggest that the propagation period of corrosion could be safely included in estimating service life of a structure when concrete is replaced by ECC.

4.6 Repair system under restrained drying shrinkage

Shrinkage induced repair cracking and repair/old interface delamination are common phenomena in repaired
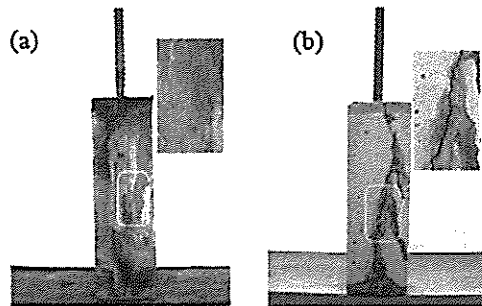

Figure 9. (a) R/ECC specimen after 300 hours accelerated corrosion, (b) R/mortar specimen after 75 hours accelerated corrosion.
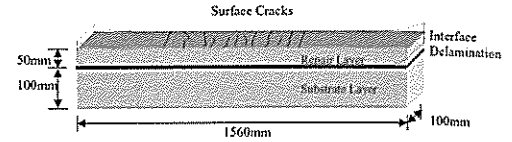

Figure 10. Layered repair specimen dimensions and potential failure modes.

concrete structures. Because shrinkage deformation of the repair layer is restrained by surrounding concrete that has undergone most of its shrinkage, tensile stress can build up in the repair layer and cause cracking, and a combination of tensile and shear stress can build up at the repair/old interface and cause interface delamination. Cracking and delamination are main reason to initiate many durability problems in concrete repairs.

Li & Li (2006) experimentally (Figure 10) and numerically validated that the high tensile ductility of ECC can accommodate shrinkage deformation of the repair layer by forming multiple micro-cracks with tight crack width below 60 μm. By this means, tensile and shear stresses at the interface were relieved, so that both repair cracking and interface delamination were limited to below 70 μm. It was also found that for normal concrete repair, several localized cracks over 450 μm in width formed in the repair layer. For normal FRC repair, several localized cracks formed with width larger than 120 μm. Since the cracks were bridged by steel fibers and could not open freely to accommodate the repair layer's shrinkage deformation, the interface delamination was much larger (280 μm) than concrete and ECC repairs.

5 CONCLUSIONS

ECC is emerging in full-scale infrastructure applications. Among a number of attractive properties, the most unique ones include its high tensile ductility and self-controlled crack width of its micro-cracks. These properties lead to superior durability under a wide variety of mechanical and environmental loading conditions commonly encountered by transportation infrastructure. Failure modes such as tensile fracture, fatigue, surface spalling, reflective cracking, freeze and thaw damage, chloride and water penetration, corrosion, salt-scaling, restrained-shrinkage-induced cracking and delamination were shown to be suppressed. These laboratory findings corroborate with the durable field performance of an ECC patch repair on a bridge deck in Michigan, USA constructed in 2002 and monitored for six years. The concept of translating ECC materialductility to structural durability can be widely applied to both new construction
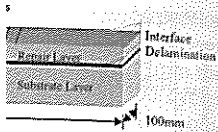
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