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Behavior of ECC/Concrete Layered Repair System Under Drying Shrinkage Conditions

M. Li* and V. C. Li
The Advanced Civil Engineering Materials Research Laboratory (ACE-MRL), Department of Civil and Environmental Engineering, University of Michigan, USA

*corresponding author, e-mail: molz@umich.edu

Abstract

The lack of durability in concrete repairs induces premature repair deterioration and endless "repair of repairs". Most often drying shrinkage of "new" repair material restrained by "old" concrete substrate causes cracking in the repair material, and interface delamination between the repair and the concrete substrate, which may also introduce water and chemical agents in to the repaired system and accelerate further deterioration. This paper suggests a material solution to the described drying shrinkage induced concrete repair failures. Engineered Cementitious Composites (ECC) is a material micromechanically designed with high ductility and toughness indicated by multiple micro-cracking behavior under uniaxial tension. Its large tensile strain capacity can greatly reduce its cracking tendency under restrained drying condition. Experimental study on a layered repair system verified that when an adequate bond is provided, the high ductility of ECC could relieve shrinkage induced stresses in the ECC repair layer and at the ECC/concrete interface, thereby suppressing large surface cracks and interface delamination. The concept of translating ECC repair material ductility to the whole repair system durability can be widely applied to many concrete structures repair applications for developing cost-effective and durable concrete repairs.

Furthermore, the paper presents the effect of concrete substrate surface preparation on the performance of repaired system based on three different types of repair materials. It also discusses several improper understandings in common repair experiences, and brings forward the potential impact on the current ACI Repair Guide with the application of ECC as an innovative concrete repair material.

Keywords: Concrete repair, Surface Preparation, Bond, Durability, Drying shrinkage, Engineered Cementitious Composites (ECC), Ductility, Interface Delamination, Micro-cracking

Das Verhalten eines geschichteten Instandsetzungssystems aus ECC und Beton unter der Einwirkung von Trocknungsschwinden

Zusammenfassung

Mangelnde Beständigkeit von Betoninstandsetzungen führt zu frühzeitiger Zerstörung einer durchgeführten Instandsetzungsmaßnahme und einer endlosen Serie von „Instandsetzungen von Instandsetzungen". Meistens verursacht behindertes Trocknungsschwinden des neu aufgebrachten Reparaturmörtels auf dem alten Betonuntergrund die Bildung von Rissen im Reparaturmörtel und Ablösen einer Reparaturschicht vom Betonuntergrund. Dies kann dazu führen, dass Wasser und chemische Wirkstoffe in die instandgesetzte Schicht eindringen und beschleunigte Zerstörung bewirken. In diesem Beitrag wird eine werkstofftechnologische Lösung vorgeschlagen, um die gerade erwähnten Schäden zu vermeiden. ECC (Engineered Cementitious Composites; systematisch entwickelter Zement gebundener zusammen gesetzter Werkstoff) ist ein Gruppe von Werkstoffen mit hoher Duktilität, die auf der Basis der Mikromechanik zusammen gesetzter Werkstoffe entwickelt wurden. Bei einachsigem Zugversuch entsteht die hohe Duktilität durch Bildung von vielen Mikrorissen. Durch die hohe Dehnfähigkeit unter Zugbeanspruchung kann das Rissrisiko unter der Einwirkung von Trocknungsschwinden ganz wesentlich vermindert werden. Versuche an einem geschichteten Instandsetzungssystem haben gezeigt, dass die hohe Duktilität des ECC, die durch das Schwinden verursachten Spannungen in der ECC Schicht und in der Grenzfläche zwischen ECC und Beton ganz wesentlich vermindern und dadurch sowohl die Bildung weiter Oberflächenrisse als auch das Ablösen der Schicht vermeiden. Dabei muss aber sicher gestellt werden, dass eine hinreichende Haftfestigkeit zwischen der ECC Schicht und dem Beton erreicht wurde. Das Konzept, die hohe Duktilität von ECC für die Beständigkeit eines Instandsetzungssystems einzusetzen, kann weitgehend und bei vielen Betontragwerken angewendet werden, um preiswerte und dauerhafte Betoninstandsetzungen zu entwickeln.

Außerdem wird in diesem Beitrag der Einfluss der Oberflächenbehandlung des Betons auf die Eigenschaften des instandgesetzten Systems dargestellt. Bei diesen Untersuchungen wurden drei unterschiedliche Reparaturmörtel verwendet. Einige Missverständnisse im Zusammenhang mit gewöhnlichen Erfahrungen aus Instandsetzungen werden diskutiert. Mögliche Konsequenzen der Anwendung von ECC als ein innovativer Instandsetzungsmörtel für die ACI Richtlinien für das Instandsetzen (ACI Repair Guide) werden diskutiert.

Stichwörter: *Betoninstandsetzung, Oberflächenvorbereitung, Haftfestigkeit, Beständigkeit, Trocknungsschwinden, ECC (Engineered Cementitious Composites), Zähigkeit, Grenzflächenablösung, Mikrorissbildung.*

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 currently in urgent need of repair. While more and more "durable" repair materials have been developed recently in the market, current concrete repair experiences represent a mixed bag. It has been estimated that almost half of all concrete repairs fail in field [1]. Concrete repairs are often perceived to lack both early age performance and long-term durability. Therefore, it is of great research significance and challenge to develop effective and durable repairs, which should address underlying concrete deterioration problems and protect old concrete from aggressive environment in the long term.

Concrete repair failure results from a variety of physical, chemical and mechanical processes. It involves a series of causes and effects (Figure 1). Generally it is the restrained volume change due to drying shrinkage or difference in thermal coefficient that induces early age repair surface cracking, or interface delamination between the repair and the old concrete. Cracking and delamination are the insidious causes of many repair pathologies. They facilitate the ingress of chlorides, oxygen, moisture, alkali or sulphates into the repaired system and accelerate further deterioration. For example, water penetrating through cracks can contribute to reinforcement corrosion or freezing-and-thawing damage. In overlay repair applications, delamination of concrete bridge overlays from the substrate deck is one of the two primary causes of ultimate overlay failure [2]. Furthermore, the loss of structural integrity impairs load transfer between the repair and the old concrete structure. As a result, the repaired structure with unsatisfactory performance and unexpectedly short life must be repaired again, and consequently the significantly increased cost over the service life can be several times greater than the initial cost of structural design and construction.

The approach of this research is to utilize an ultra ductile concrete – an Engineered Cementitious Composites (ECC), as a repair material to improve durability of repaired concrete structures. By minimizing repair layer surface cracking and repair layer/old concrete substrate interface delamination due to restrained drying shrinkage, concrete repair deterioration process described in Figure 1 can be interrupted at the first stage or Phase 1. Experiments were carried out on simulated layered repair systems under controlled humidity, with variables of repair material type and surface preparation method. Measurements of surface cracking and interface delamination magnitude and extent confirm the effectiveness of simultaneously suppressing these two deterioration mechanisms when ECC is used as the repair material. Influence of concrete substrate surface preparation on the performance of layer repair systems based on different types of repair materials is also evaluated. The experimental results will further serve as a basis for discussion of potential differences in concrete repair design between using ECC repair material and using traditional repair materials.

1.2 Background

In concrete repair applications, the immediate shrinkage deformation of the "new" repair material after placement is restrained by the "old" concrete substrate which has already undergone shrinkage. Consequently, tensile stress is built up in the repair layer, and a combination of tensile and shear stress is developed along the interface between the repair and the concrete substrate. These stresses may cause repair surface cracking, and/or interface delamination (Figure 2). Crack width and delamination magnitude determine the transport properties through the repair system, so they are closely related to repair durability. The detailed discussion on stress distribution in a drying repair system and its failure mechanism can be found in [3].

Li [4] illustrated the effect of inelastic strain capacity of cementitious material on the deformation behavior of a 2-D slab geometry of length L restrained at its ends. For brittle or quasi-brittle repair material with tension softening behavior, the cracking potential under restrained shrinkage is defined as:

$$\mathrm{p} = (\varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp})) \tag{1}$$

where ε_{sh} is shrinkage strain, ε_e is elastic tensile strain capacity, and ε_{cp} is tensile creep strain. If $p \geq 0$, one single crack forms in the repair material with crack width proportional to the cracking potential p:

$$w = L((\varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp}))/(1 - L/2l_{ch}) \tag{2}$$

for $(\varepsilon_e + \varepsilon_{cp}) \leq \varepsilon_{sh} \leq w_c / L$

where w is crack width, l_{ch} is Hillerborg's material characteristic length:

$$l_{ch} = EG_f / \sigma_t^2 \tag{3}$$

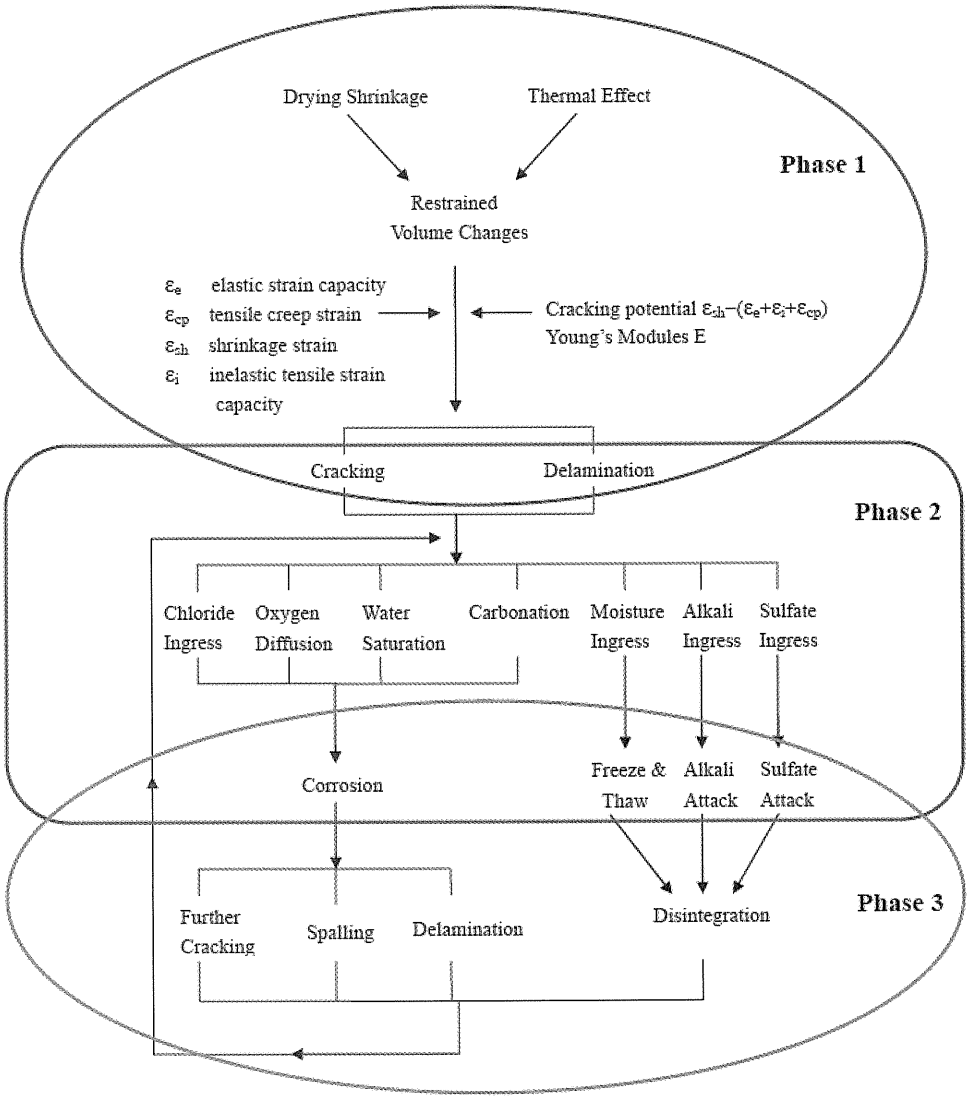


Figure 1: Repair failure causes and effects

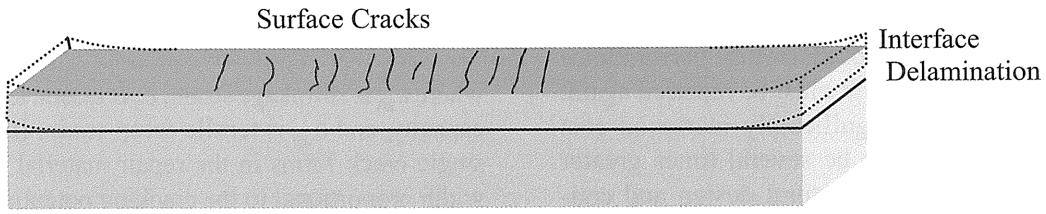


Figure 2: Layered repair system failure modes

E, G_f, σ_t, w_c are the material Young's modulus, fracture energy, tensile strength, and critical crack opening. A linear tension-softening law is assumed where strength retention decreases from σ_t to 0 as the crack width opens from zero to w_c. Equation (3) indicates that crack width w depends on the cracking potential p, the degree of brittleness L/2lch, and the repair dimension L[4]. For instance, highly brittle material with relatively small characteristic lengths, such as high strength concrete, is expected to exhibit more severe cracking with bigger crack width. Like other brittle or quasi-brittle materials, its crack width will increase with increasing structural dimensions.

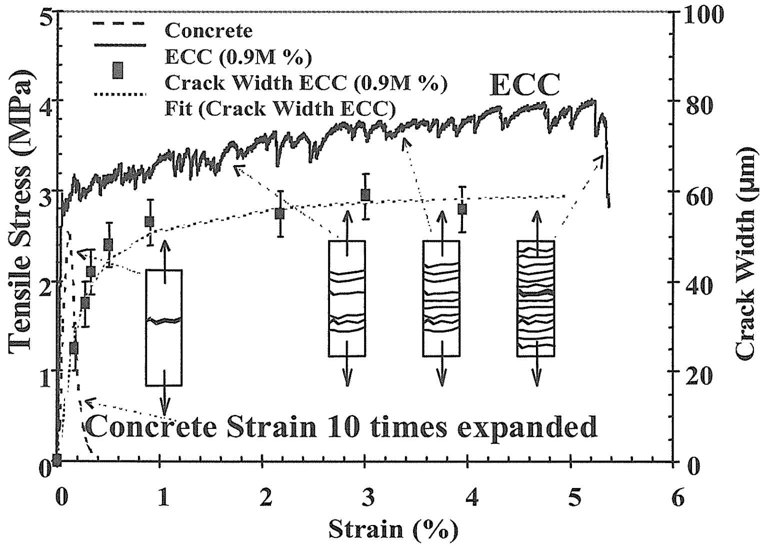


Figure 3: Typical tensile stress-strain curve and crack width development in ECC

In the case of a repair layer, the boundary conditions are different from the above. Restraint is applied at the base of the slab instead of its ends, leading to a number of distributed cracks along the repair layer. In repair materials which are mostly brittle, traction-free cracks will open with a crack width proportional to p. By this means, stresses built-up at the interface can be relaxed, and the delamination values are expected to be small.

Steel fibers have been used recently in concrete repairs to control drying shrinkage and service-related cracking. For common tension-softening FRC material, shrinkage induced stresses are expected to induce surface cracking similar to normal concrete. However, since the cracks are bridged by fibers, some amount of tensile stress is still maintained in the layer. Therefore, tensile and shear stresses at the interface cannot be released by freely opening of cracks. As a result, interface delamination can be more prominent than the case of brittle repair material such as concrete and mortar.

In order to suppress both surface cracking of the repair layer and interface delamination, the repair material need to exhibit "plastic straining" in order to accommodate its shrinkage deformation, and thus relieve the stresses built-up under restrained drying shrinkage conditions. By this means, repair cracking and interface delamination can be minimized. Plasticity in the form of microcrack damage has been demonstrated in high performance fiber reinforced cementitious composites (HPFRCC). These materials exhibit an ultimate strength higher than the first crack strength, and accompanied by a large strain capacity ε_i at ultimate strength. For such materials, the cracking potential [4] is modified as

$$p = (\varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})) \tag{4}$$

Engineered Cementitious Composites (ECC) [5] represents a class of HPRFCC which has been optimized to have large values of ε_i and tight micro-crack width at minimum fiber content. This is accomplished by engineering the microstructure of the composite so that the fiber, matrix and their interface interact mechanically in such a way that flat steady state micro-cracking will take place, instead of the common form of localized fracture due to Griffith crack propagation. The micromechanics theory behind the conditions for multiple cracking has been used to tailor the three phases of the composite systematically [6].

Figure 3 shows a typical uniaxial tensile stress-strain curve of ECC with a strain capacity of 5 %, about 500 times of that of normal concrete [7]. This high ductility of ECC is achieved by formation of many closely spaced microcracks. These microcracks are not "real cracks" since they carry increasing load after formation, therefore allowing ECC to exhibit strain-hardening behavior similar to ductile metals. For this reason, the microcracking in ECC may be referred to as "damage", distinguished from real cracks which open with decreasing traction, or localized fracture. Figure 3 also shows the development of crack width with increasing straining. After a strain of about 1 %, the early cracks stopped widening and maintain more or less constant width less than 60 μm. This steady state crack width can be tailored to have different values. Further deformation will be accommodated by additional microcracks till the material was saturated with these microcracks. ECC with less than 60 μm crack width has low permeability similar to uncracked concrete [8]. ECC's large value of ε_i gives a highly negative cracking potential p, indicating that localized fracture due to restrained shrinkage will never occur. The high tensile ductility of ECC material, together with its tight crack width during strain hardening stage, suggests ECC as a promising material for durable repair jobs.

2 Experimental Program

2.1 Materials

Three different repair materials — concrete, steel fiber reinforced concrete (SFRC) with tension softening stress-strain curve and ECC were investigated in this study (Table 1). Concrete and SFRC were employed as controls since they have been used in repair applications and included in ACI Concrete Repair Guide ACI 546R-04 [9]. Xx specimens were tested for each material. 6 specimens were tested for each material to measure properties listed in Table 1.

Both the concrete repair and the concrete substrate in this test had the same material composition. Concrete mixture, as shown in Table 1, consisted of coarse aggregate (CA) with 14 mm nominal grain size, Portland type I cement (C), sand (S) and water (W). Superplasticizer (SP) was used to achieve sound workability. Concrete specimens were tested to have averaged compressive strength (f_c') of 60 MPa, and Young's modulus (E) of 26 GPa. Under tensile loading, concrete is a brittle material with sudden fracture failure.

Steel fiber reinforced concrete (SFRC) mixture had the same composition with concrete mixture, except that it contained 1 % (V_f, volume fraction) steel fibers. The steel fibers with smooth surface and hooked ends had length of 30 mm and diameter of 500 μm. The averaged compressive strength of this SFRC was 63 MPa, slightly higher than that of the concrete mixture. Its compressive Young's Modulus was measured to be almost the same as concrete. Under tensile loading, SFRC is a quasi-brittle material with tension softening stress-strain curve as a result of the fiber bridging effect. Both concrete and SFRC have around 0.01 % ultimate tensile strain capacity (ε_u).

The ECC mixture is comprised of Type I Portland cement (C), water (W), silica sand (S) with 0.1mm nominal grain size, type F fly ash (FA), and 2 % (V_f) polyvinyl-alcohol (PVA) fibers. These PVA fibers (PVA-REC 15) had length of 12 mm and diameter of 39 μm. The ECC mixture has averaged compressive strength of 62 MPa. Its Young's modulus was lower (20 GPa) than concrete and SFRC due to the absence of coarse aggregate (CA) in its composition. A lower modulus repair material is actually desirable to in limiting the tensile stress induced by restrained drying shrinkage.

Since drying shrinkage is a time-dependent process, it is necessary to evaluate the development of ECC tensile strain capacity at different ages. Direct tensile test conducted in this study (Figure 4), together with a long term test up to 200 days [10], show that ECC tensile strain capacity changes with age as a result of the subtle competition between the time dependent changes of the matrix toughness and the fiber/matrix interface bond properties. However, tensile strain hardening behavior of ECC with a strain capacity larger than 2.5 % can be guaranteed at all ages.

2.2 Specimen Configuration and Surface Preparation

Wittmann and Martinola [3] conducted an experimental study on a 1500 mm-long layered system, with a 40 mm-thick layer of fresh mortar cast on top of an old concrete beam. Delamination height around 0.7 mm and delamination length around 600 mm at age of 28 days were measured. In this

Table 1: Repair materials composition and properties at 28 days

Material	C	W	S	FA	CA	SP	V_f	ε_u %	f_c' (MPa)	E (GPa)	Tensile Behavior
Concrete	1.0	0.4	1.3	--	1.3	0.01	--	0.01	60±1	26±1	brittle
SFRC	1.0	0.4	1.3	--	1.3	0.01	0.01	0.01	63±2	26±1	quasi-brittle
ECC	1.0	0.53	0.8	1.2	0	0.03	0.02	3~5	62±2	20±1	ductile

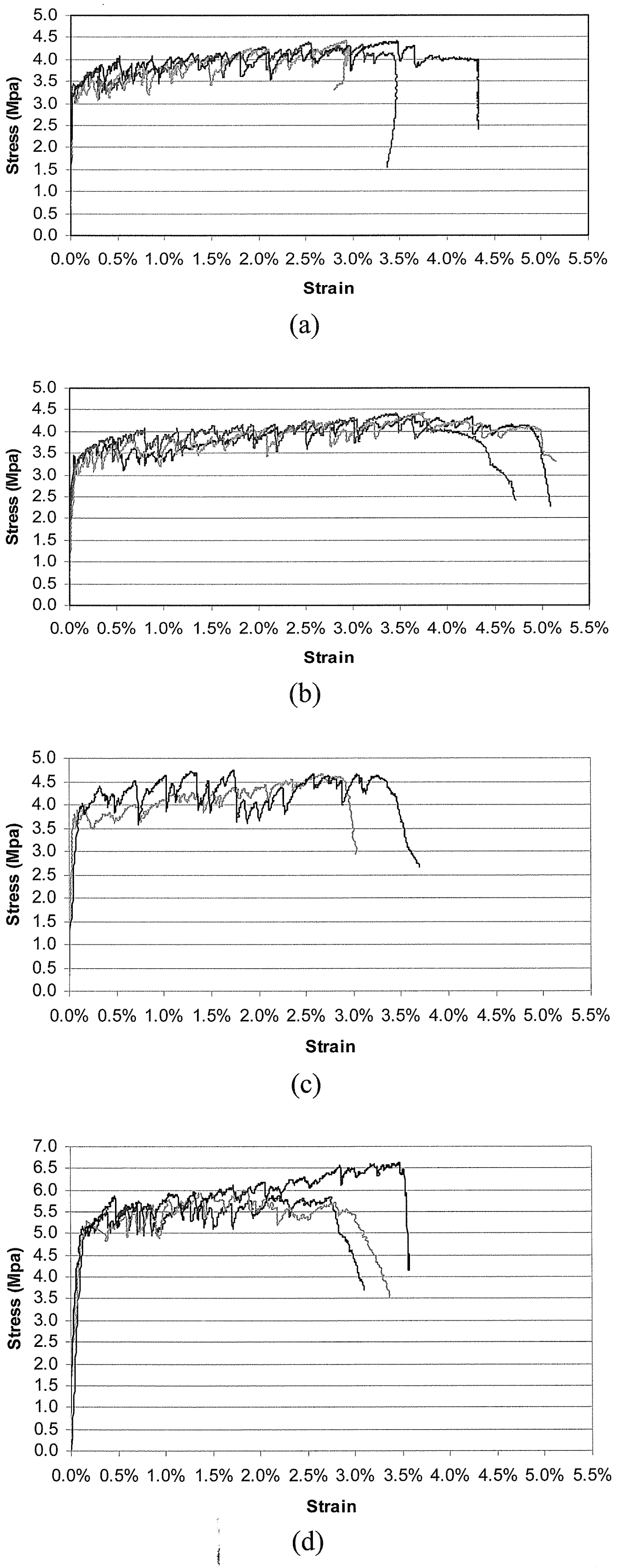


Figure 4: Stress-strain curves of ECC repair material measured at ages of (a) 3 days; (b) 7 days; (c) 14 days; (d) 28 days

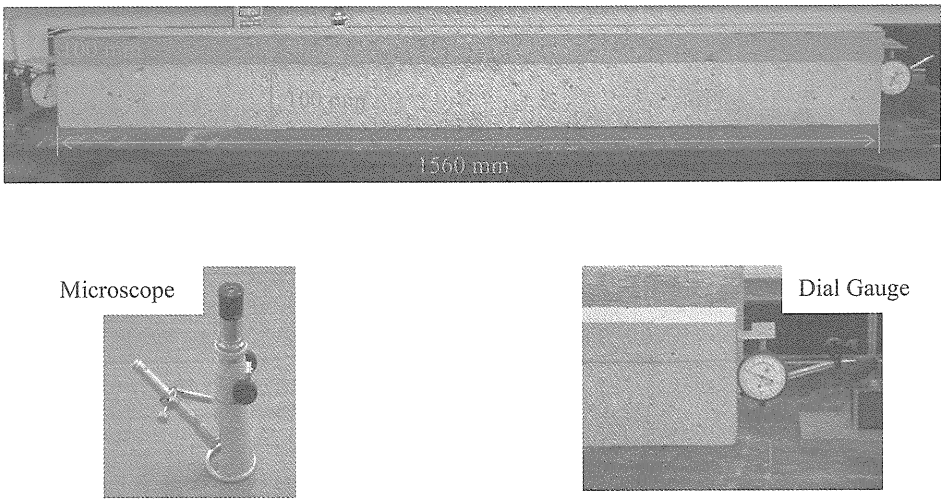


Figure 5: Layered repair system test set-up

study, layered repair systems were experimentally investigated with each of the three repair materials – concrete, SFRC and ECC. Concrete substrates were cast with dimensions of 1560 mm×100 mm×100 mm, as shown in Figure 5. They were moisture cured until the age of 28 days, and then left to dry in ambient condition for an additional 60 days before the repair layers were placed. The additional 60 days were for the purpose of allowing any potential shrinkage in the substrates to occur before bonding the repairs with layer thickness of 50 mm.

The contact surfaces of the concrete substrates were prepared in four different ways: (a) normally cast (smooth); (b) roughened to 4~5 mm; (c) roughened to 7~8 mm (Figure 6); and (d) roughened to 7~8 mm + cement bonding slurry. For case (b), (c) and (d), the substrate surfaces were roughened in fresh state using a chisel to remove slurry cement from external surfaces of coarse aggregates. Before placing the repair layers, the substrate surfaces were recleaned with a brush and high-pressure air to ensure a clean bonding surface, and then they were damped to an adequate moisture level. After that, repair layers made of each of the three repair materials were cast on top of the concrete substrates. If cement bonding slurry was used, a thin coating of "creamy" grout was vigorously and thoroughly brushed into the prepared surface immediately before placing the repair material.

The repair layers were moisture cured for 24 hours and then demolded. After demolding, the layered specimens were moved into a room with ambient conditions of 20-30 °C, and 35-55% RH. For each specimen, two dial gauges (Figure 5) were used to record interface vertical separation distance at end locations of the specimens as a function of drying time after delamination begins. In addition, a portable microscope (Figure 5) was used to measure the delamination data at 20 different locations along the interface, from which the delamination crack profile was derived. The microscope was also employed to observe crack pattern, crack number and crack width of the top surface of the repair layer, as a function of age. Both the delamination and the surface cracking were measured on a daily basis.

Free shrinkage tests were also carried out to characterize free shrinkage properties of concrete, SFRC

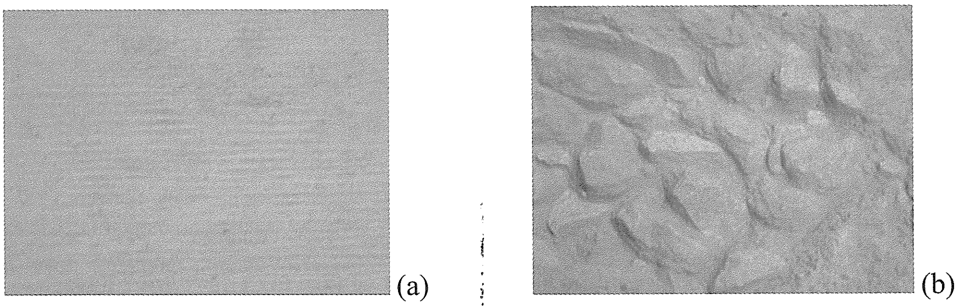


Figure 6: Concrete substrate surface preparation: (a) normally cast (smooth); (b) roughened to 7~8 mm

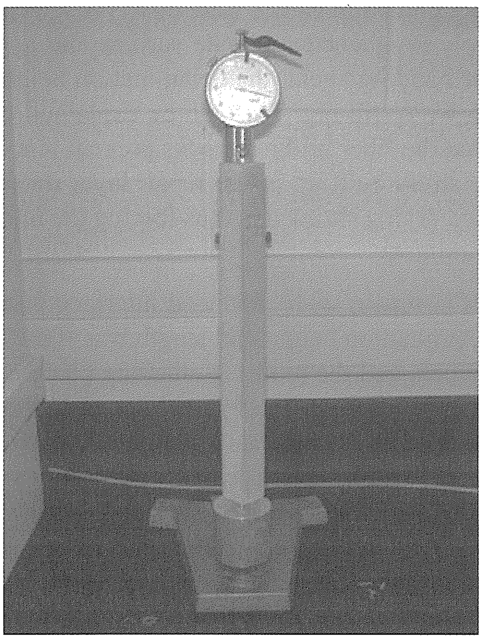


Figure 7: Free drying shrinkage test on repair materials

and ECC mixtures (Figure 7). The free shrinkage tests specimens were from the same batch as the repair layer mix for each of the three repair materials. The tests were conducted according to ASTM C157/C157-99 and ASTM C596-01 [11] standards, except that the storing and testing environments of the specimens were modified to be exactly the same as the layered specimens, with ambient condition of 20-30 °C and 35-55 % RH. It is for the purpose of relating the free shrinkage tests results to behavior of the layered specimens.

3 Experimental Results

3.1 Shrinkage of Repair Materials

Three specimens were tested for each material and the average free shrinkage strain (ε_{sh}) values were plotted in Figure 8. It should be noted that ECC mixture had the highest shrinkage strain value, due to higher cement content and absence of coarse aggregates; SFRC mixture had the lowest shrinkage strain value due to the contribution of steel fibers.

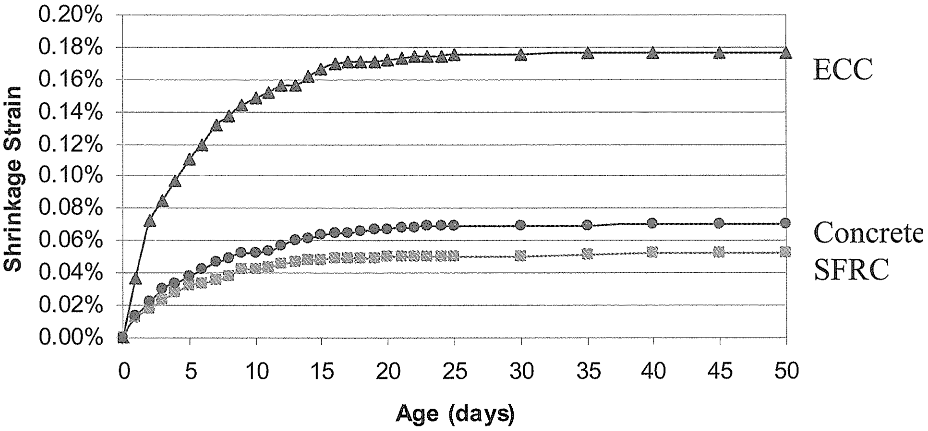


Figure 8: Shrinkage strain of repair materials as function of drying time

Table 2: Concrete, SFRC and ECC cracking potential estimation (properties measured at specimen's age of 28 days)

Properties	ε_{sh} (%)	ε_e (%)	ε_i (%)	ε_{cp} (%)	$p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$ (%)
Concrete	0.07	0.01	0	0.02 ~ 0.06	0 ~ 0.04
SFRC	0.053	0.01	0	0.02 ~ 0.06	(-0.017) ~ 0.023
ECC	0.177	0.015	2.5 ~ 5	0.07	(-4.908) ~ (-2.408)

The cracking potential p for concrete, SFRC, and ECC can be estimated (Table 2), based on measured values of ε_{sh} and ε_i, and other parametric values (ε_e and ε_{cp}) from [4]. Although ECC had the highest shrinkage strain due to higher cement content and absence of coarse aggregates, its negative p-value verifies that under restrained drying shrinkage ECC will experience microcrack damage in the inelastic straining stage, while concrete and SFRC are subjected to tensile fracturing due to their positive p-values.

3.2 Surface Cracking of Repair Layers and Interface Delamination

Surface cracking and interface delamination of the three types of repair systems are summarized in Table 3. The experimental results show that with a normally cast (smooth) substrate surface, concrete, SFRC and ECC repair all exhibited relatively large delamination heights and lengths. It should be noted that the delamination values (height and length) of ECC repair were significantly higher than the other two repair materials, as expected, because of the large fly ash content in its mix and its relative low chemical bond with the concrete substrate.

For concrete repair, enhancing interface bonding by roughening methods and/or adding bonding agent (cement-based slurry) did reduce the delamination values. However, the crack pattern and width did not change a lot. Concrete repair always exhibited several localized cracks with large crack width (>100 μm), as suggested by its high cracking potential p. Furthermore, stronger interface bonding actually led to larger surface cracking width, since the shrinkage deformation of the repair layer had to be released by surface crack opening instead of interface delaminating. With the deeply roughened interface and bonding agent, the concrete repaired system had several localized fractures with much bigger crack width (>200 μm).

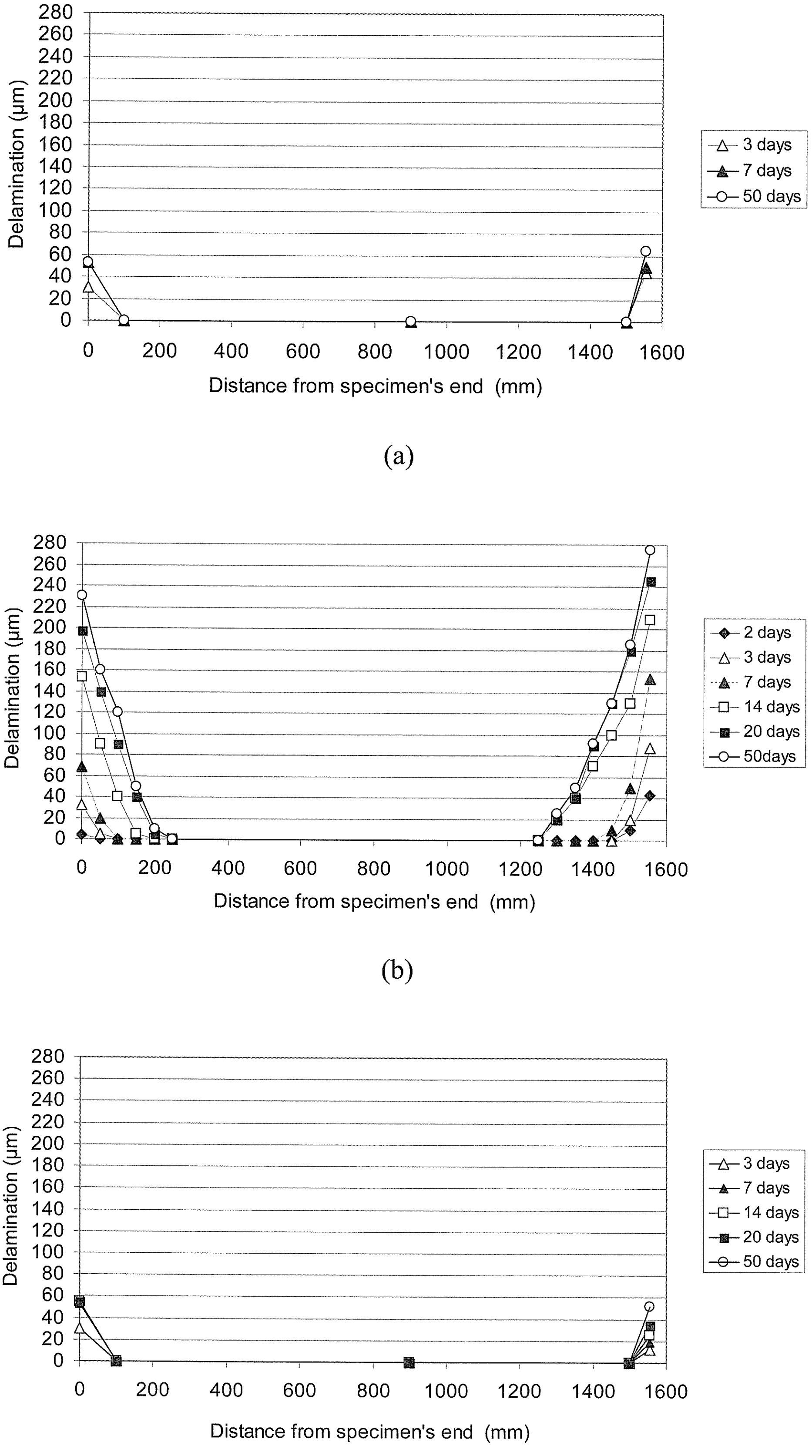
For SFRC repair, no significant changes in interface delamination values were observed. Even with a deeply roughened substrate surface and application of bonding agent, the delamination height and length were still big. This can be explained by the fact that the fiber bridged cracks prevent relaxation of the stress built up in the repair layer due to restrained drying shrinkage, thus forcing the interface to delaminate.

For ECC repair, with enhanced interface bonding, the delamination height and length was significantly reduced, and the multiple cracking phenomenon became more and more predominant. For the "roughened to 7-8 mm" and "roughened to 7-8 mm + cement bonding slurry" cases, under environment with the same relative humidity and temperature, the ECC repaired system exhibited the most desirable performance. The crack width of the ECC repair and the interface delamination were both very small (<60 μm), which was ideal for achieving durability. No localized fracture was observed in the ECC repair layer.

Surprisingly, although SFRC repair had the smallest shrinkage strain, the SFRC repaired system exhibited both large crack width (120-140 μm) and large interface delamination height (>275 μm) and

Table 3: Interface delamination and surface cracking of different layer repair systems

Repair Material	Surface Preparation	Delamination		Cracking	
		Height (μm)	Length (mm)	Number	Width (μm)
Concrete	Smooth	410	320	2	120-130
	4-5mm roughened	190	172	3	130-190
	7-8mm roughened	65	50	4	220-270
	7-8 mm roughened + bonding slurry	32	23	4	210-360
SFRC	Smooth	550	397	2	90-120
	4-5mm roughened	370	375	5	70-110
	7-8mm roughened	275	350	3	120-140
	7-8 mm roughened + bonding slurry	310	354	4	90-150
ECC	Smooth	1225	722	0	--
	4-5mm roughened	425	402	21	10-60
	7-8mm roughened	53	50	76	10-60
	7-8mm roughened + bonding slurry	40	31	103	10-60



(a)

(b)

(c)

Figure 9: Interface delamination profile of (a) concrete (b) SFRC (c) ECC repaired systems when the concrete substrate surfaces were roughened to 7~8mm

length (>350 mm) (Figure 9), which are severe enough for introducing undesirable agents into the repaired system, resulting in a lost of durability. As pointed out before, the large interface delamination in SFRC was associated with the prevention of stress relaxation in the repair layer by the bridging fibers. Although fibers also bridge across the microcracks in ECC, ECC was able to relax the stress in the repair layer by forming a large number of surface cracks through its unique multiple cracking behavior. The contrast of repaired system behavior with SFRC and ECC as repair material is a direct consequence of the tension-softening vs strain-hardening properties of these two materials. These experimentally revealed effects of repair material tensile properties on the repair layer surface cracking and interface delamination behavior are consistent with those numerically predicted by Kabele (2001) [12].

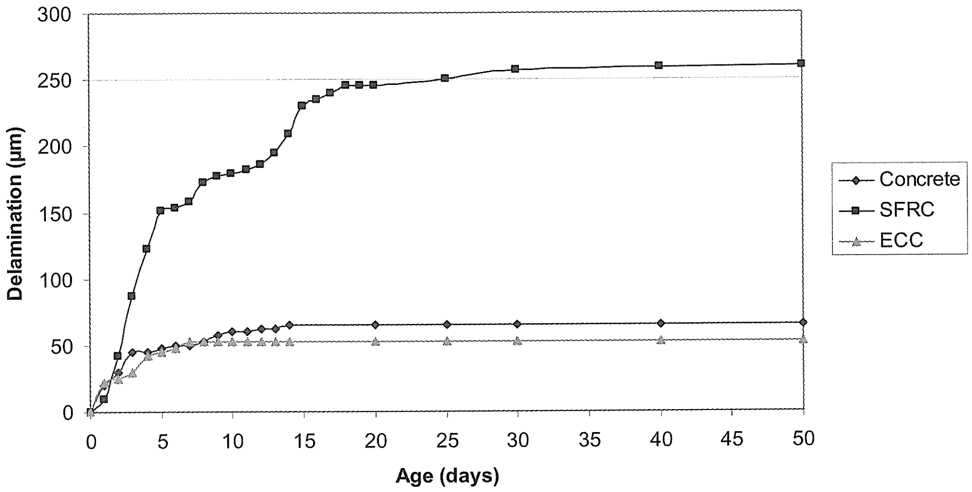


Figure 10: Specimen end delamination height of repaired systems at different ages (concrete substrate surfaces roughened to 7~8mm)

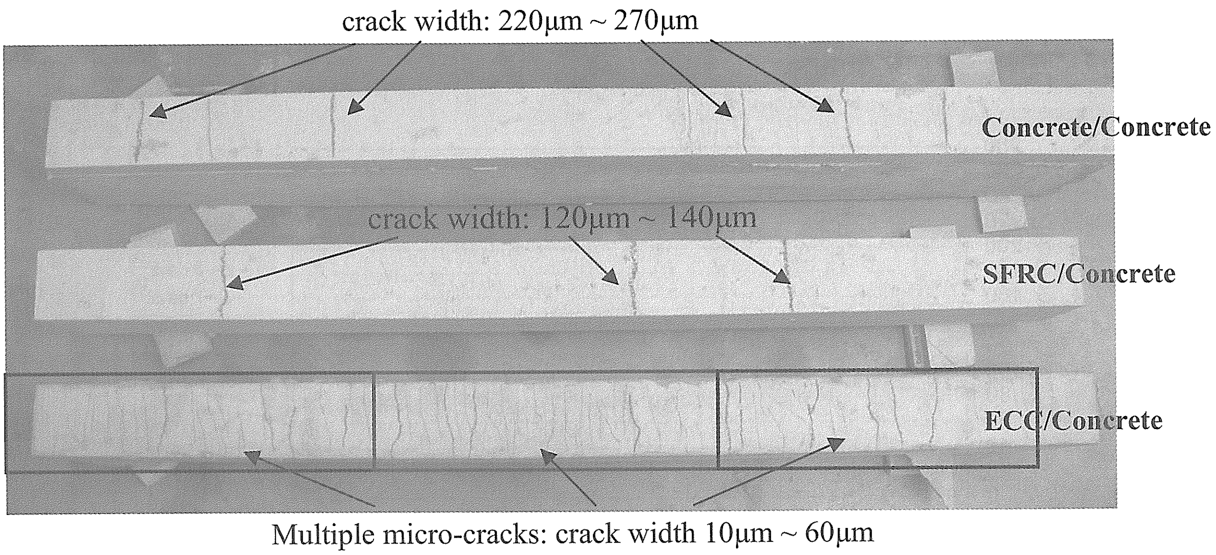


Figure 11: Surface crack pattern of different layered repair systems based on concrete, SFRC and ECC (concrete substrate surfaces roughened to 7~8mm)

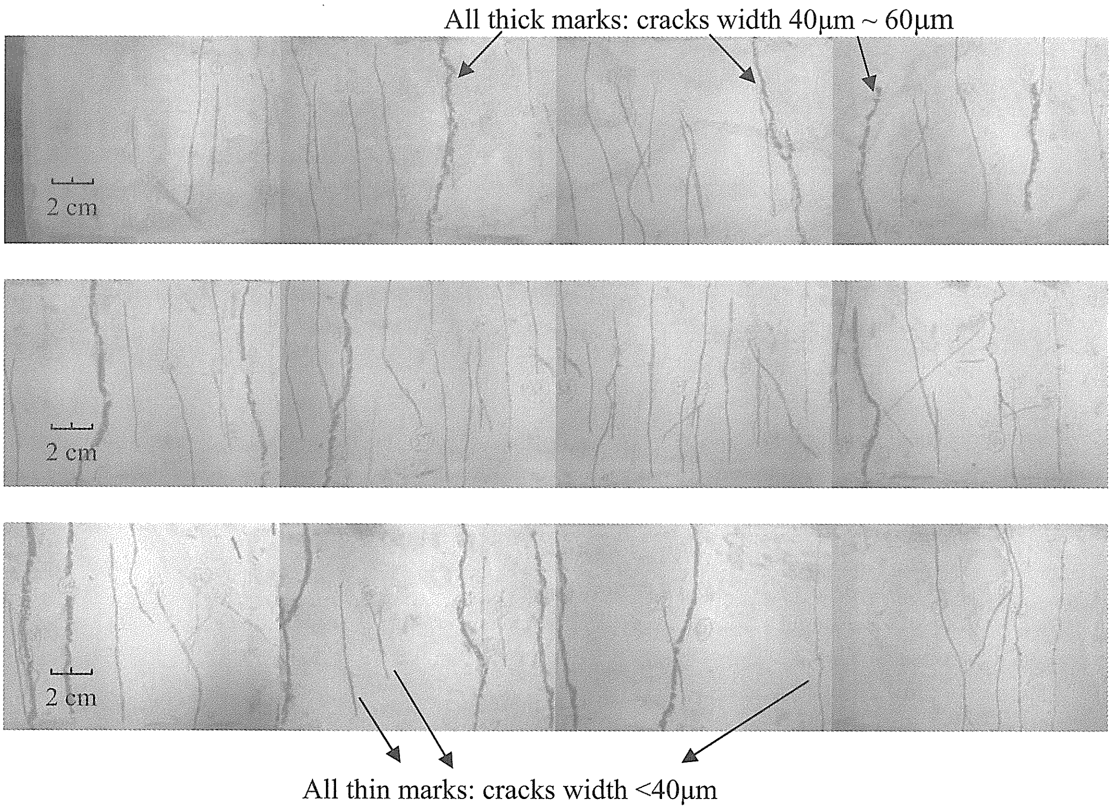


Figure 12: Expanded view of surface microcracking for ECC repair, from left to right rectangular areas marked in Fig. 11 for ECC/concrete specimen.

4 Implications for Repair Applications

For successful repairs with maximum life, the ACI Concrete Repair Guide ACI 546R-04 [9] provides guidance on repair material selection, concrete substrate surface preparation and bonding methods. It also refers to ACI Concrete Building Code ACI 318-02 [13] which recommends using shrinkage and temperature reinforcement to control cracking. These ACI recommendations or stipulations may need to be reconsidered in light of the unique properties of ECC.

This study verified the outstanding performance of ECC repaired system under restrained drying shrinkage conditions, suggesting ECC as a promising material to make durable concrete structure repairs. When an adequate bond was provided, ECC repair developed multiple microcracks rather than several localized cracks, consequently suppressed interface delamination under restrained drying shrinkage. Unlike other brittle or quasi brittle materials, the tight crack width of ECC is a material property, which is independent of structural dimensions. This implies that with increasing structural scale, the advantage of using ECC as the repair material will be even more important.

Surface preparation is one of those basic conditions provided by ACI 546R-04 [9], which should be met before repair material placement. Section 2.7 within ACI 546R-04 [9] recommends using in-place tensile pull-off tests to evaluate whether the surface preparation and the bonding of repair materials are adequate. Failure in substrate is preferred, which means that materials having high bonding strength with the old concrete are more likely able to make repairs with sound performance and durability. Experimental results from this study show that sufficient bonding strength is necessary for ECC repair material to perform well. However, for brittle or quasi brittle repair materials with high cracking potential, enhancing interface bonding strength should have very limited aid in achieving durability of the repaired structure. Once sufficient stresses have been built up in the repaired system due to restrained repair volume change, stronger bond does reduce the trend of interface delamination, but promotes the tendency of surface cracking and potentially increases cracking number or width. Therefore, special attention needs to be paid to the intent

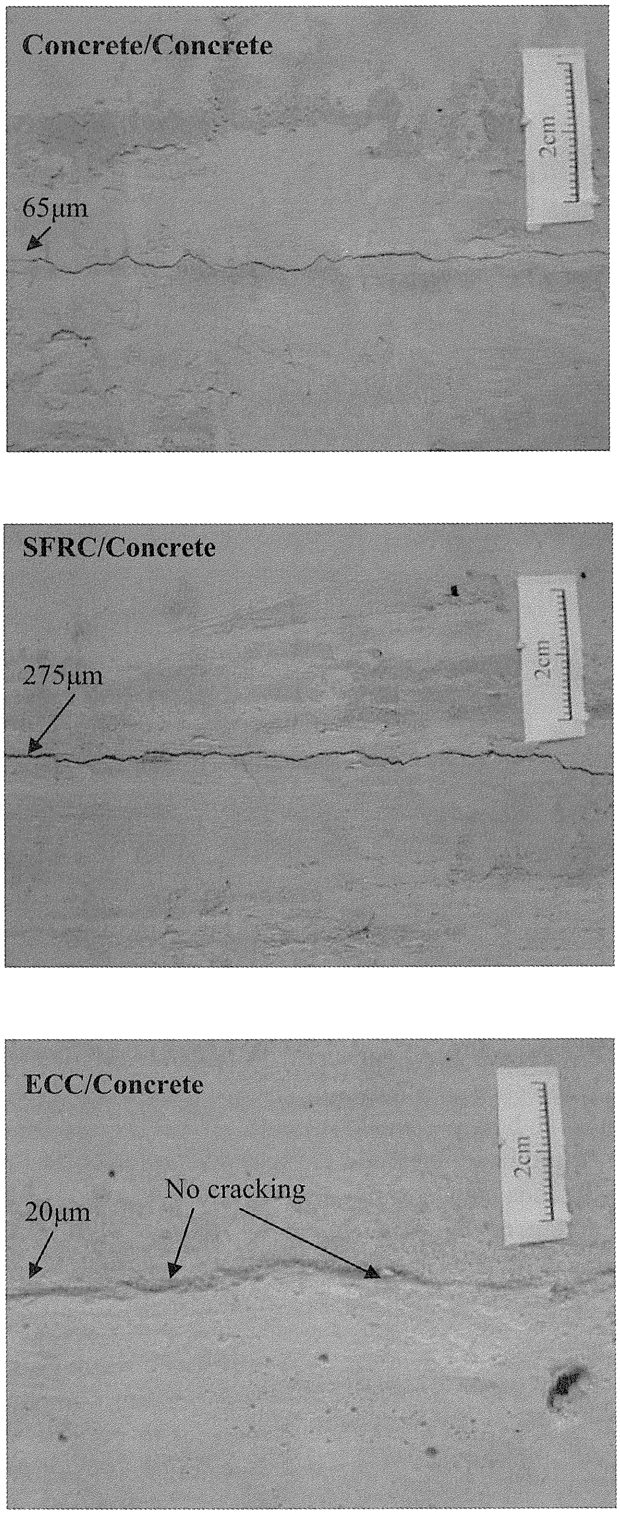


Figure 13: Interface delamination and delamination height of layered repair systems based on concrete, SFRC and ECC (concrete substrate surfaces roughened to 7~8mm)

of the pull-off test because it over-simplifies the interaction between the repair and the concrete substrate, and neglects the delicate competition between the formation of surface cracks and delamination. Simply seeking strong bond but ignoring repair material tensile ductility cannot ensure durable repairs.

In Section 3.7 of ACI 546R-04 [9], repair material with minimal shrinkage is recommended for interface integrity. Ultimate drying shrinkage of cement-based repair material is limited to below 0.1 %. However, experimental results from this study reflects that cracking potential p is much more related to repair behavior under restrained drying shrinkage rather than the free drying shrinkage value. Even with ε_{sh} less than 0.1 % (0.07 % for concrete and 0.053 % for SFRC), repairs made of concrete or SFRC in this study all exhibited cracking or interface delamination to various degrees. This is because of their low strain capacity (~0.01 %) and consequent large value of cracking potential. In contrast, although ECC has ε_{sh} more than 0.1 % (0.177 % in this case), with a negative cracking potential $p = (-4.908)\sim(-2.408)$, it suppressed localized fracture. Simultaneously, the large tensile ductility of this material relaxes any potential stress build-up in the repair layer, thus minimizing the delamination of the interface. Tensile deformation of the repair layer was accomplished by multiple microcrack damage. The experimental results validate the concept that ductility of repair material is essential for achieving durability of repaired structures.

In addition to the above, ACI 546R-04 [9] refers to ACI 318-02 [3], which recommends using shrinkage and temperature reinforcement to control cracking in Section 7.12 [13]. A minimum reinforcement ratio of 0.0014 ~ 0.002 is specified depending on steel grade. The shrinkage and temperature reinforcement is required to be spaced not farther apart than 5 times the slab thickness, nor farther apart than 18 in. By virtue of the tight crack width control of ECC at strain-hardening stage, which is normally below 60 μm, these cracking control reinforcement may not be needed at all. The potential elimination of cracking control reinforcement removes the risks of steel corrosion and cover spalling, which are very common repair pathologies in the field. The reduction in steel reinforcement amount and repair thickness also makes the repair jobs simpler. Consequently, both construction cost and maintenance cost can be greatly reduced.

5 Discussion and Conclusion

To make effective and durable concrete repairs, we need (a) verified understanding of causes and effects of concrete repair failures; (b) proper evaluation of repair material properties and its interaction with surrounding concrete; (c) adequate design of short-term laboratory experiments which closely simulate long-term field conditions; and (d) novel method of developing new materials which are suitable for repair applications. The unsuccessful repair experiences are often manifestation of the improper understanding of repair approaches such as follows:

1) Basis of material and repair system "durability"

It is often believed that improving the compressive strength of the repair material or accelerating its strength gain would lead to improved durability of a repaired system. This misconception encourages people to seek various expensive high strength repair materials that do not behave as expected or sometimes even worse in field conditions. High strength concrete, for example, is often believed to have good durability because of its low w/c ratio [14], which makes this material stronger and less impermeable compared with normal concrete. However, high strength concrete tends to fracture due to its high brittleness when undergoing restrained shrinkage, despite its high compressive strength. Once cracked, the repaired system will be in danger of losing durability when exposed to an aggressive environment; no matter the repair material has "low permeability" in the absence of cracking. In general, it is the inherent brittleness and susceptibility to fracture of most of repair materials that ultimately lead to premature deterioration of the repaired concrete structure. In this sense, material durability should be more related to its fracture toughness than its strength; the former is the material's resistance to cracking. A repair material with tensile ductility for suppression of fracture should behave even better.

In this experiment, ECC is demonstrated to control the width of surface crack and interface delamination to below 60 μm. Wang et al (1997) [8] demonstrated the significance of crack width in controlling the permeability coefficient of cracked concrete. The permeability coefficient of cracked concrete was shown to decrease by seven orders of magnitude (from 10^{-4} to 10^{-11} m/s) as crack widths decrease from 550 μm to 0 μm. When crack width falls below 100 μm, the flow rate is similar to uncracked concrete. Hence even with a large number of surface cracks, ECC may behave like sound concrete with no cracks, by virtue of its tight crack width control.

2) Interaction between the repair material and its surrounding concrete

It has been recognized that compatibility between the repair material and the surrounding concrete is important for the durability of the repaired system [15]. Incompatibility may come from shrinkage of the repair material relative to the old concrete substrate, difference in material thermal coefficient, creep properties and Young's modulus. All of these may result in unequal load sharing and interface stresses. Current research often place emphasize on the isolated properties of repair materials, while neglecting the more important properties of the composite system. For example, free drying shrinkage deformation is an important material property, but restrained drying shrinkage properties are more related to the repair durability because there is always "new bonded to old" in various repair applications. The restrained drying shrinkage properties should be evaluated, which include material cracking pattern, crack number, crack width, and interface delamination magnitude. These properties are manifestation of a very complex process which involves a number of parameters, such as repair material shrinkage deformation, tensile strain capacity, creep strain and interface bonding strength. It should be noted that all of these parameters change with material ages, and as a result there will be delicate time dependent competition between forming surface cracking and interface delamination. In this sense, the defined repair material shrinkage cracking potential p [4], and its bonding strength with old concrete, should be combined to predict durability of repaired concrete structures. Merely reducing repair material free shrinkage or simply pursuing a strong interface bonding may not achieve improved repair durability.

In this study the layered repair system was experimentally investigated under drying shrinkage conditions. However, its behavior under thermal effect can also be predicted based on the gained knowledge. Note that equation (1) can be modified as

$$p = (\Delta\varepsilon_{ther} - (\varepsilon_e + \varepsilon_{cp})) = (\Delta\alpha \cdot \Delta T - (\varepsilon_e + \varepsilon_{cp})) \quad (5)$$

And equation (4) can be modified as

$$p = (\Delta\varepsilon_{ther} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})) = (\Delta\alpha \cdot \Delta T - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})) \quad (6)$$

where $\Delta\varepsilon_{ther}$ is difference between the strain of the repair and the concrete substrate under thermal effect, $\Delta\alpha$ is the difference between the thermal coefficients of the repair material and the concrete substrate, and ΔT is the temperature change. All the same, inelastic strain capacity of ductile material can greatly reduce cracking potential p to a negative value under thermal effect.

In summary, a material based methodology, by using ductile ECC material, is proposed and experimentally validated in this study for surface crack and interface delamination control in a layered repair system. Repair material tensile ductility is closely related to cracking potential under restrained volume change such as drying shrinkage or thermal effect. In this sense, repair material ductility should be given great importance in future concrete repair design guides. When repair material ductility requirement is satisfied, crack control reinforcement and material free drying shrinkage limit become less important, while surface preparation methods to enhance interface bond will be more meaningful on achieving durability of repaired concrete structures.

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Mo Li is a doctoral student of Civil and Environmental Engineering at the University of Michigan. Her research interests include concrete repair durability, composite materials development for sustainable infrastructure, reinforced concrete structure corrosion, and using material methodology for improving durability of civil infrastructure.
E-mail: molz@umich.edu

Professor Dr. Victor C. Li is a Professor of Civil and Environmental Engineering at the University of Michigan. His research interests include micromechanics based composite materials design and engineering, innovative structures design based on advanced materials technology and sustainable infrastructure engineering.

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