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

Mo Li and Victor C. Li
Advanced Civil Engineering Materials Research Laboratory, Department of Civil and Environmental Engineering, The University of Michigan, USA

Abstract
The lack of durability in concrete repairs induces repair failures in field and endless "repair of repairs". Most often drying shrinkage of "new" repair material restrained by "old" concrete substrate causes cracking in the repair material, combined with interface delamination between the repair and the concrete substrate, which may also introduce chlorides, oxygen, moisture, alkali or sulphate into the repaired concrete structure 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. Experimental study on a layered repair system verified that the high ductility of ECC can 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.

Keywords: Concrete repair, Durability, Drying shrinkage, Engineered Cementitous Composites (ECC), Ductility, Interface Delamination, Micro-cracking.

Mo Li
The University of Michigan
2350 Hayward, 1328 GG Brown
Ann Arbor, MI 48109-2125, USA

Email: molz@umich.edu
Tel: 734-763-1315

Prof. Dr. Victor C. Li
The University of Michigan
2350 Hayward, 2326 GG Brown
Ann Arbor, MI 48109-2125, USA

Email: vcli@umich.edu
Tel: 734-764-3368

1.0 Introduction

1.1 Motivation

A large number of existing concrete structures worldwide, including previously repaired ones, are presently suffering deterioration or distress [1]. These structures are currently in urgent need of repair, which should address underlying concrete deterioration problems and protect underlying concrete from aggressive environment in the long term. Therefore, concrete repairs need to be effective and durable.

While more and more "durable" repair materials have been developed recently in the market, current concrete repair experiences represent a mixed bag. Concrete structure repairs are often perceived to lack both early age performance and long-term durability. Some undesirable repair behaviors can be observed in the field in the forms of early age surface cracking, spalling, or interface delamination between the repair and the concrete substrate. Delamination and cracking may also introduce chlorides, oxygen, moisture, alkali or sulphates into the repaired system and accelerate further deterioration. Furthermore, the loss of structural integrity impairs load transfer between the repair and the concrete substrate. As a result, the repaired structure with unsatisfactory performance and unexpectedly short life must be further maintained or repaired again, which leads to significantly increased service life cost.

To achieve high durability of a repaired concrete structure, both durability of the repair material itself and the interaction between the repair and the concrete substrate need to be carefully evaluated. High strength concrete, for example, is believed to have good durability because of its low w/c ratio, 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 shrinkage restrained by the concrete substrate, 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, this high brittleness of repair material leads ultimately to a repaired structure with poor durability. 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 addition to the above consideration, it has been recognized that compatibility between repair material and the surrounding concrete is important for the durability of the repaired system. These include compatibility in the coefficient of thermal expansion and in the Young's Modulus [1]. A lower modulus in the repair material, in fact, could lead to lower stress build up due to restrained drying shrinkage, thus reducing the tendency to cracking in the repair material or at the interface between the repair material and the surrounding concrete.

In this paper, it is proposed to utilize Engineered Cementitious Composites (ECC) as the repair material to make durable concrete structure repairs. Experiments were carried out on simulated layered repair systems under controlled humidity. Measurements of time dependent surface cracking and interface delamination magnitude and extent confirm the effectiveness of simultaneously suppressing shrinkage induced repair surface cracking and delamination between the repair and the concrete substrate through the use of ECC as the repair material. Durability issues related to thermal expansion or contraction differences between the repair material and the concrete substrate can be addressed in a similar manner.

1.2 Background

In concrete repair applications, "new" repair materials are often bonded with "old" concrete substrates which have undergone shrinkage. After placement, the repair material will immediately begin shrinkage. However, the shrinkage deformation of the repair material is restrained by the concrete substrate, so that tensile stress will be developed in the repair layer, and both tensile stress and shear stress will be developed along the interface between the repair and the concrete substrate. The combination of these stresses is the reason to cause repair cracking and interface delamination.

Li (2004) [2] illustrated the effect of inelastic strain capacity of cementitious material on the deformation behavior of a 2-D slab geometry restrained at its ends. For brittle or quasi-brittle repair material with tension softening behavior, the cracking potential under restrained shrinkage is defined as:

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

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

In the case of a repair layer, the boundary conditions are different from the above, due to restraints applied at the base of the slab rather than at its ends. This type of restraint will lead to a number of distributed cracks along the repair layer. In the case of plain concrete, these traction-free cracks will again open with a crack width proportional to p, resulting in relaxation of most of the tensile stress built up, with little or no shear at the layer/substrate interface. As a result, delamination at the interface is expected to be small.

For common tension-softening Fiber Reinforced Concrete (FRC) materials, shrinkage induced stresses is expected to induce surface cracking similar to normal concrete. However, since the cracks are bridged by fibers, the width may be expected to be smaller, and some amount of tensile stress is maintained in the layer. As a result, the interface shear stress is not relieved, so that delamination may be more prominent than normal concrete.

In order to suppress both surface cracking of the repair layer and interface delamination, the repair material will need to exhibit "plastic straining" in order to relieve the tensile stress built up by restrained shrinkage. Once plastic straining occurs, the interfacial shear stress will also be relaxed, and interface delamination may 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 [2] is modified as

$$p = (\varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})) \qquad (2)$$

Engineered Cementitous Composites (ECC) [3] represents a class of High Performance Fiber Reinforced Cementitous Composites (HPRFCC), which has been optimized to have large values of ε_i 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 as to suppress the common form of localized fracture due to Griffith crack propagation, in favor of flat steady state micro-cracking. The micromechanics theory behind the conditions for multiple cracking has been used to tailor the three phases of the composite systematically [4]. Figure 1 shows a typical uniaxial tensile stress strain curve of ECC with a strain capacity of 5%, which is about 500 times of that of normal concrete [5]. This high ductility of ECC is achieved by formation of many closely spaced microcracks. These microcracks are not "real cracks" since they keep carrying 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", distinguishing it from real cracks which open with decreasing traction, or localized fracture. Figure 1 also shows the development of crack width with increasing straining. After a strain of about 1%, the early cracks stopped widening and remained more or less constant, with crack width less than 60μm. 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. The less than 60μm crack width has very low permeability similar to uncracked concrete [6]. The cracking potential p of this ECC material is highly negative, suggesting that localized fracture due to restrained shrinkage will never occur in such a material [2]. The high tensile ductility of ECC material, together with its tight crack width during strain hardening, suggests that ECC can be a promising material for durable repair jobs.

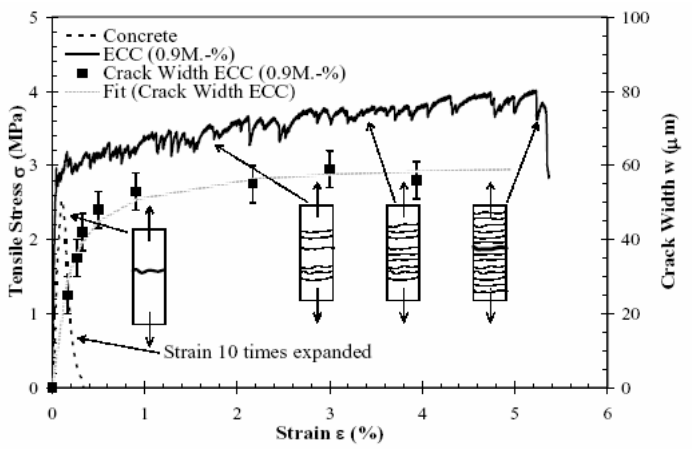


Figure 1. ECC typical tensile stress-strain curve and crack width development

2.0 Experimental Program

2.1 Materials

Three different repair materials, concrete, a tension softening steel fiber reinforced concrete (SFRC) and ECC were used in this study (Table 1). Concrete and SFRC were employed as controls since they have been used in repair applications.

Both concrete repair and concrete substrate in this test had the same material composition. Concrete mixture, as shown in Table 1, consisted of coarse aggregate (CA) with 10mm 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 under compressive loading, having strength (f_c') of around 60MPa, and Young's modulus (E) of around 26GPa. Under tensile loading, concrete is a brittle material with sudden fracture failure.

Table 1: Repair materials composition and properties

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

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 had length of 30mm and diameter of 500µm, with smooth surface and hooked ends. SFRC mixture's compressive strength was higher than concrete mixture because of reinforcing fibers, which is around 63MPa. Its compressive Young's Modulus was almost the same with concrete. Under tensile loading, SFRC is a quasi brittle material with tension softening stress strain curve due to the fiber bridging effect. Generally both concrete and SFRC have about 0.01% tensile strain capacity (ε_u).

The ECC mix used in this study comprised Portland Type I cement (C), water (W), silica sand (S) with 0.1mm nominal grain size, type F fly ash (FA), and 2% (V_f) poly-vinyl-alcohol (PVA) fibers. These PVA fibers (PVA-REC 15) had length and diameter of 12mm and 39µm. ECC mixture's compressive strength was measured to be 62±2 MPa. Its Young's modulus was lower (20±1 GPa) than concrete and SFRC due to lack of coarse aggregate in its composition. Uniaxial tensile tests were conducted to measure ECC mix's strain capacity at different ages (Figure 2).

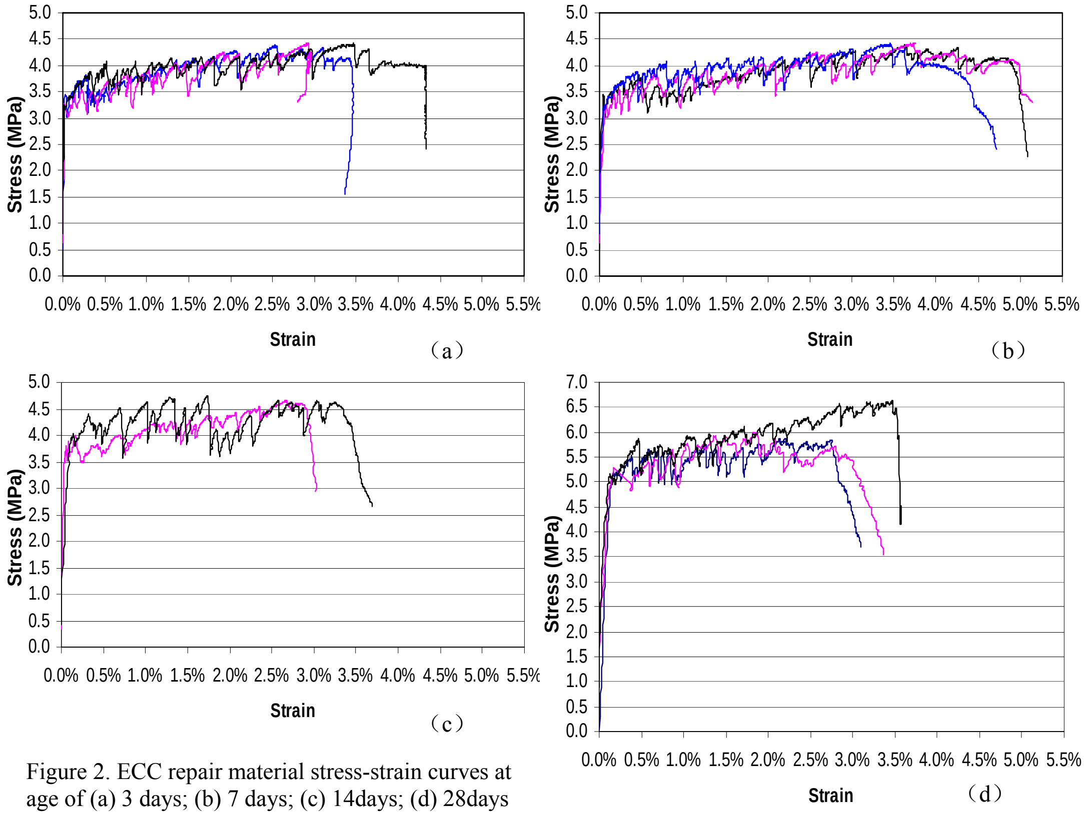


Figure 2. ECC repair material stress-strain curves at age of (a) 3 days; (b) 7 days; (c) 14days; (d) 28days

Figure 2 shows that ECC mix always had strain hardening behaviour at different ages. Its tensile strength ranged from 4MPa to 7MPa, increasing with ages. Its tensile strain capacity changed with age due to the subtle competition between the time dependent changes of the matrix toughness and the fiber/matrix interface bond properties. However, based on long term test up to 200 days [7], it still guaranteed a tensile strain capacity more than 2.5% in the long term, indicating that ECC is a ductile material at both early and late ages. The ductility of ECC was crucial for achieving durability of repaired structures, as we will show in the later sections.

2.2 Specimen Configuration

Layered repair systems were experimentally investigated with each of the three repair materials – concrete, SFRC and ECC. Concrete substrates were cast initially with dimensions of 1560mm×10mm×10mm, as shown in Figure 3. The concrete substrates were moisture cured until 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. The contact surfaces of the substrates were roughened in fresh state using chisel to remove slurry cement from external surfaces of coarse aggregates. The estimated roughness amplitude was 7~8mm, as shown in Figure 4. Before placing the repair layers, the contact surfaces of concrete substrates were recleaned with a brush and high-pressure air to ensure a clean bonding surface, and then they were adequately damped. The moisture level of contact surfaces was critical to achieve bond. Excessive moisture in a contact surface may clog the pores and prevent absorption of the repair material. On the other hand, an excessively dry substrate contact surface may absorb too much water from the repair material, resulting in undesirable excessive shrinkage [8].

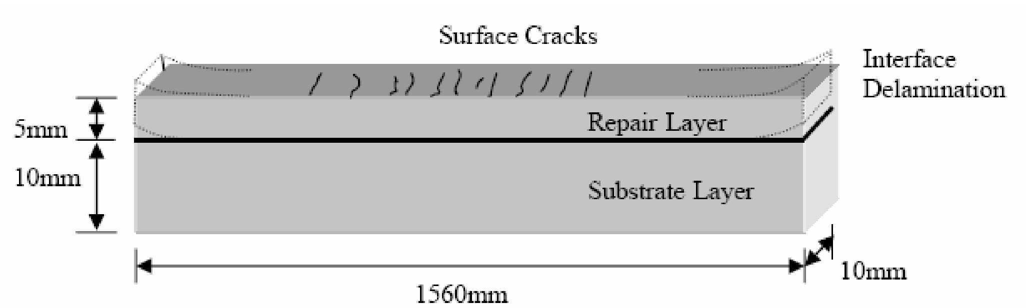


Figure 3. Layered repair system configuration and potential failure modes

 (a)  (b)

Figure 4. Concrete substrate surface preparation: (a) before roughened; (b) roughened (to 7~8mm)

After achieving a clean bonding surface with appropriate moisture level, 5-cm-thick repair layers were cast on the top of the concrete substrates, using each of the three repair materials. The repair layers were moisture cured for 24 hours and then demolded. After demolding, the layered specimens were moved into a room which has ambient conditions of 20-30℃, and 25-55% RH. For each specimen, two dial gauges fixed on steel holders were used, which allow for recording interface vertical separation distance at end locations of the specimens as a function of drying time after delamination begins. In addition, a portable microscope was used to measure the delamination data at 20 different locations along the specimen, which gave the delamination crack profile. 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 and ECC mixtures. 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 [9] 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℃ and 25-55% RH. It is for the purpose of using free shrinkage tests results to describe the shrinkage of repair layers of the layered specimens.

3.0 Experimental Results

3.1 Shrinkage of Repair Materials

Figure 5 shows the shrinkage strain of concrete, SFRC, and ECC mixtures obtained from free shrinkage tests. 4 specimens were tested for each material and the average data were plotted on this figure. It can be seen 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 because of contribution of steel fibers.

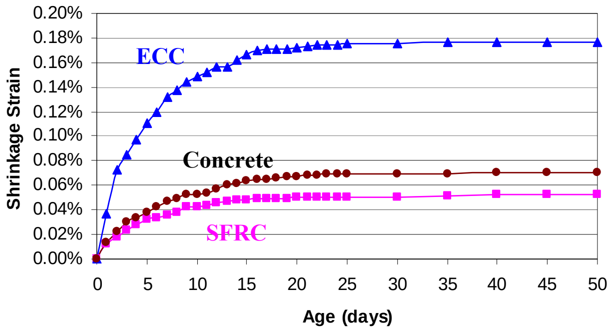


Figure 5. Shrinkage strain of repair materials at different ages

The cracking potential p for concrete, SFRC, and ECC can be estimated, as shown in Table 2. (Parametric values other than ε_{sh} discussed in this paper are from [2].) The p-values for the three materials confirm that concrete and SFRC are subjected to tensile fracturing due to restrained drying shrinkage, while ECC will experience microcrack damage in the inelastic straining range.

Table 2: Concrete, SFRC and ECC cracking potential estimation

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

3.2 Cracking of Repairs

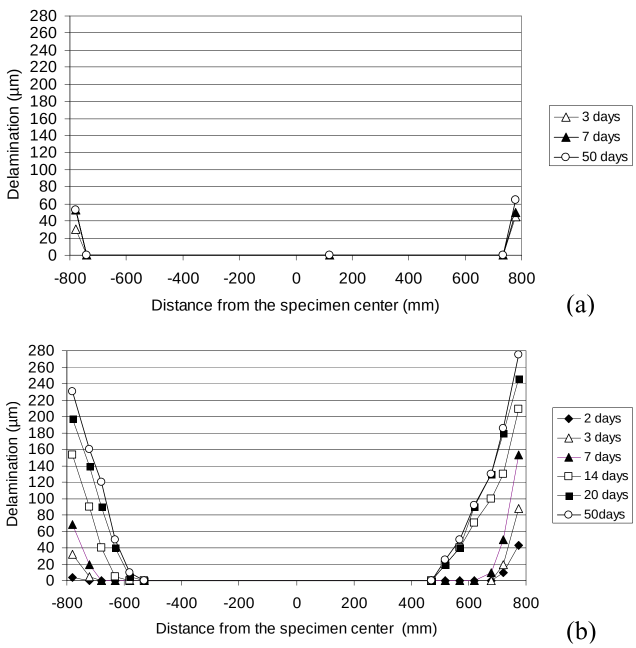
Table 3 shows surface crack pattern, crack number and crack width of the three repaired systems respectively. When concrete was used as the repair material, 4 cracks localized at age of 50 days. The maximum crack width was 270µm. When Steel Fiber Reinforced Concrete (SFRC) was used as the repair material, 3 cracks localized, and the maximum crack width was 140µm, which was smaller than that of concrete due to fiber bridging effect, as discussed in section 1.2. The restrained shrinkage induced crack width for concrete or SFRC repair is a structural property, which is dimensional dependent.

In contrast, when ECC was used as the repair material, 76 microcracks were formed with the maximum crack width of 60µm, which was much smaller than that of concrete or SFRC repair. The average value of ECC repair's crack widths was 35µm or so. Since shrinkage strain of ECC was less than 0.2 % (Figure 5), it was much below ECC's tensile strain capacity of 2.5~5 %. Therefore, the restrained shrinkage cracking of ECC was occurring in the strain-hardening stage. This indicates that the restrained shrinkage crack width of ECC repair is a material property, which is independent of structural dimensions. Even for larger scale repair applications with different types of restrained conditions, ECC repair is expected to still exhibit tight crack width below 60µm, similar to uncracked concrete in terms of water permeability [6].

Table 3: Crack type, number and width of concrete/SFRC/ECC repaired systems at age 50 days

Repair Material	Crack Type	Number	Width
Concrete	Localized fractures	4	220-270µ
SFRC	Localized fractures	3	120-140µ
ECC	Multiple microcracks	76	10-60µ

3.3 Interface Delamination



(a)

(b)

Figure 6 shows the interface delamination profiles of the three layer repair systems at different ages. These profiles are approximately symmetric about the mid-point of the specimen, as would be expected. At the age of 50 days, both the ECC and the concrete repaired systems exhibited low delamination heights at the specimen ends, which were 53µm for the former and 65µm for the latter. The delaminated length was around 50mm, as shown in Figure 6. In contrast, the SFRC repaired system had much larger delamination height (275µm) than ECC or concrete repaired system at the age of 50 days. Its delamination length was also

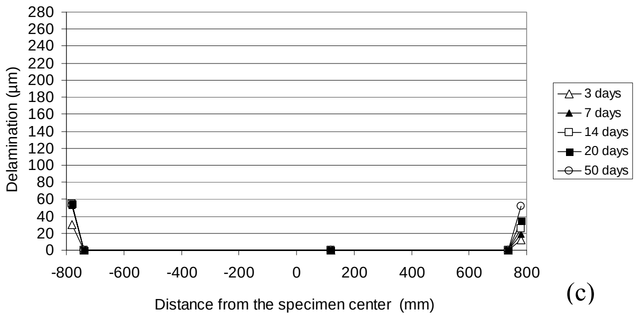


Figure 6. Interface delamination profile of (a) concrete (b) SFRC (c) ECC repaired systems

long, around 350mm. The interface delamination developments as a function of time are shown in Figure 7. It can be seen that ECC and concrete repaired systems completed their interface delamination at very early ages – within 10 days. However for SFRC repaired system, delamination continued to evolve up to 20 days, at which time the SFRC repair material had undergone most of its shrinkage (Figure 5).

4.0 Discussion and Conclusions

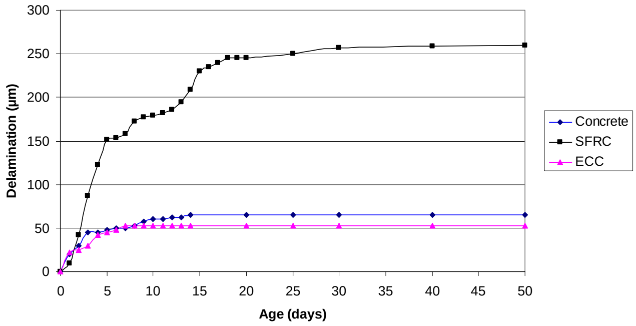


Figure 7. Specimen end delamination height of repaired systems at different ages

Under environment with the same relative humidity and temperature, the ECC repaired system exhibited the most desirable performance despite the fact that the ECC's drying shrinkage strain was higher than the other two repair materials. The crack width of the ECC repair and the interface delamination were both very small (<60µm), which was ideal for achieving durability. Conversely, the concrete repaired system had several localized fractures with much bigger crack width (220-270µm). Surprisingly, although SFRC repair had the smallest shrinkage strain, the SFRC repaired system exhibited both large crack width (120-140µm) and large interface delamination height (275µm) and length (350mm), which could be severe enough for introducing undesirable agents into the repaired system, resulting in a lost of durability.

The experimental results proved the concept that ductility of repair material is essential for achieving durability of repaired structures. With a negative cracking potential p=(-4.908)~(-2.408), localized fracture was suppressed in the ECC. 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. In contrast, for brittle or quasi brittle repair materials like concrete and SFRC, the way to accommodate the material's shrinkage deformation is either to crack or to delaminate, or both. In this test, the concrete repair had strain capacity of ~0.01% (Table 1) and shrinkage strain of 0.07% (Figure 5), indicating that its cracking potential could be large. As a result, the shrinkage deformation of the concrete repair was accommodated by forming localized cracks and opening them. Similarly for the SFRC repair, the cracking potential was also high so that localized fractures formed. However, these cracks were bridged by steel fibers so that they could not open freely. Therefore, the SFRC repair could not accommodate all of its shrinkage deformation by only forming and opening cracks. The only other way to accommodate the shrinkage deformation was by delamination. This explains the reason why the SFRC repaired system had the most severe delamination among the three, and why the delamination continued to later ages, in contrast to concrete or the ECC repaired system. The above scenarios were predicted numerically by Kabele (2001) [10]. This paper provides experimental confirmation and also illustrates the realization of translating repair material ductility into repair system durability.

The interaction between the repair and the concrete structure can be a very complicated process. When shrinkage of "new" repaired material is restrained by "old" concrete substrate, there will be delicate time dependent competition between forming surface cracking and interface delamination. Research need to be further conducted to investigate time dependent properties of many variables, including repair material shrinkage, first cracking strength and strain capacity development, and interface bond development.

This study verified the outstanding performance of ECC repaired system under restrained drying shrinkage, suggesting ECC as a promising material to make durable concrete structure repairs. Under restrained shrinkage, ECC developed multiple microcracks rather than several localized cracks. 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.

5.0 References

1. Vaysburd, A. M., Brown, C. D., Bissonnette, B, and Emmons, P. H., ""Realcrete" versus "Labcrete"", *Concrete International,* Vol. 26 No.2, pp 90-94 , 2004

2. Li, V. C., "High Performance Fiber Reinforced Cementitious Composites as Durable Material for Concrete Structure Repair," *Int'l J. for Restoration of Buildings and Monuments*, Vol. 10, No 2, pp 163–180, 2004

3. Li, V. C., "From Micromechanics to Structural Engineering--the Design of Cementitous Composites for Civil Engineering Applications", *JSCE J. of Struc. mechanics and Earthquake Engineering,* Vol. 10, No.2, pp 37-48, 1993

4. Li, V.C., "On Engineered Cementitious Composites (ECC) – A Review of the Material and its Applications," *J. Advanced Concrete Technology*, Vol. 1, No. 3, pp.215-230, 2003

5. Weimann, M. B. and Li, V. C., "Hygral Behavior of Engineered Cementitious Composites (ECC)", *International Journal for Restoration of Buildings and Monuments*, Vol. 9, No 5, pp 513-534, 2003

6. Wang, K., Jansen, D. C. and Shah, S. P., "Permeability Study of Cracked Concrete", *Cement and Concrete Research*, **27**, 3, pp. 381-393, 1997

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

8. Emmons, P. H., "Concrete Repair and Maintenance Illustrated", pp. 155-164, 1994,

9. **A**merican **S**ociety for **T**esting and **M**aterials (U.S. Code Organization)

10. Kabele, P., "Assessment of Structural Performance of Engineered Cementitious Composites by Computer Simulation", CTU Report 4, V.5, Czech Technical University, Prague, 2001