Proceedings of ICFRC International Conference on
Fibre Composites, High Performance Concretes and Smart Materials,
8-10 January 2004, Chennai, India pp. 57-74

High Performance Fiber Reinforced Cementitious Composites as Durable Material for Concrete Structure Repair

Victor C. Li
Professor and Director
Advanced Civil Engineering Materials Research Laboratory
Department of Civil and Environmental Engineering
University of Michigan, Ann Arbor, MI 48109-2125, USA
vcli@umich.edu

Abstract

This paper addresses the property requirements of repair materials for high durability performance for concrete structure repair. It is proposed that the high tensile strain capacity of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) makes such materials particularly suitable for repair applications, provided that the fresh properties are also adaptable to those required in placement techniques in typical repair applications. A specific version of HPFRCC, known as Engineered Cementitious Composites (ECC), is described. It is demonstrated that the fresh and hardened properties of ECC meet many of the requirements for durable repair performance. Recent experience in the use of this material in a bridge deck patch repair is highlighted. This article is a summary of a keynote lecture given at the Conference on Fiber Composites, High- Performance Concretes and Smart Materials, Chennai, India, Jan., 2004.

INTRODUCTION

In many industrialized countries, the outlay for infrastructure repair and retrofit is now approaching and is expected to exceed new construction outlay in the near future. In the US, the American Society of Civil Engineers (ASCE, 2003) recently reported that the condition of America's roads, bridges, drinking water systems and other public works has continued to deteriorate as a result of increasing use by a sprawling population and materials aging. Against this backdrop, there is an obvious need for increasing amounts of infrastructure repair, and that such repairs need to be durable. The demand for improvement in our understanding of the science, technology and method of durable repair is now greater than ever.

Concrete repairs often lack durability. It has been estimated that up to half of all concrete repairs fail (Mather and Warner, 2003). About three-fourths of the failures are attributed to the lack of durability, with the remaining attributed to structural failures. This inadequate performance is often ascribed to inappropriate material selection, poor application method, or a combination of both (Vaysburd et al, 1999; Warner, 1995). Failure of concrete repair typically manifests itself as cracking in the repair material and/or delamination from the substrate concrete, largely a consequence of non-uniform volume change under restrained conditions.

Investigations into the durability of concrete repair may be classified into three broad groups: 1) Numerical modeling of material and repaired system behavior; 2) Repair application methods; and 3) Repair materials development. Despite a large number of investigations, and plenty of new repair materials, durable concrete repair remains a challenge to the repair industry, owners of infrastructures, and researchers.

In recent years, rapid advances have been made in the development of high performance fiber reinforced cementitious materials (HPFRCCs). HPFRCCs are characterized by tensile strain-hardening after first cracking. Even though many of these materials are targeted for structures with high load or high deformation demands, it is proposed that the large ductility (in the form of *inelastic deformation capacity*) of HPFRCCs should make them excellent repair materials.

In this paper, the property demands for durability and the fresh property needs for different placement techniques of repair materials are briefly reviewed. A specific HPFRCC, known as Engineered Cementitious Composite (ECC), is proposed as having the fresh and hardened properties meeting performance requirements for durable repair of concrete structures. Experience in the use of this material in a bridge deck patch repair case study is highlighted. It is shown that high tensile strain capacity is one of the most important properties of a durable repair material to resist typical failures in repaired systems, and that such high tensile strain capacity can be achieved economically in ECC materials.

PROPERTY DEMANDS ON REPAIR MATERIAL

Requirements on the Hardened Properties of Repair Material

The concept of dimensional compatibility has been proposed by a number of authors (e.g. Emmons et al, 1993). This means that the mechanical and physical properties of the repair material should match those of the concrete substrate. The relevant properties include coefficient of thermal expansion and Young's modulus. The concept of dimensional compatibility ensures no excessive stress due to material property mismatch when the repaired system is subjected to thermal and/or mechanical loading.

Almost all repair materials experience some amount of autogenous shrinkage and drying shrinkage. Stresses resulting from restrained shrinkage may lead to failure in the repair material, and/or delamination failure at the interface between the repair material and concrete substrate.

To illustrate the different responses due to the presence or absence of inelastic deformation capacity in the repair material, we consider the simple case of a slab of repair material of length L under rigid end constraints (Fig. 1). For a quasi-brittle material with a simplified strain-softening curve shown in Fig. 2a, a single crack forms (Fig. 2b) when the stress exceeds the tensile strength of the material, or

$$E(\varepsilon_{sh} - \varepsilon_{cp}) \geq \sigma_t \qquad (1)$$

where ε_{sh} and ε_{cp} are the shrinkage strain and tensile creep strain respectively, E is the Young's modulus and σ_t is the tensile strength. Equation (1) can be re-written as

$$\varepsilon_{sh} \geq \varepsilon_e + \varepsilon_{cp} \qquad (2)$$

where $\varepsilon_e = \sigma_t / E$ is the elastic tensile strain capacity of the material. Equations (1) and (2) show the well known fact that high tensile strength and creep strain, low Young's modulus and shrinkage strain are conducive to resisting cracking due to shrinkage. The left hand side of (2) can be thought of as a strain demand due to shrinkage, while the right-hand side of (2) can be thought of as a strain supply. It should be noted that shrinkage and creep are time/stress dependent properties, thus complicating Eqs. (1) and (2).

Once condition (1) or (2) is satisfied, a single crack is formed in the slab, with crack width w governed by the degree of brittleness ($1/l_{ch}$) of the slab material (Stang and Li, 2004):

$$w = L(\varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp}))/(1 - L/2l_{ch}) \quad \text{for} \quad (\varepsilon_e + \varepsilon_{cp}) \le \varepsilon_{sh} \le w_c/L \qquad (3)$$

where the material characteristic length $l_{ch} \equiv EG_F/\sigma_t^2$ and G_F, f_t, w_c are the fracture energy, tensile strength and critical crack opening (when traction drops to zero in Fig. 2b), respectively. Equation (3) is illustrated in Fig. 3 as the linear line with slope $S = L/(1 - L/2l_{ch})$.

Figure 3 suggests that the crack width will grow from zero linearly proportional to the restrained shrinkage cracking potential, defined as the excess of strain demand over strain supply $(\varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp}))$. This slope has two limits. When l_{ch} drops to L/2, the slope becomes infinity, and the material behaves like an ideally brittle material. When l_{ch} increases to infinity, the slope approaches L. The ratio $L/2l_{ch}$ is the brittleness number introduced by Hillerborg (1983). Figure 3 demonstrates that even for the same cracking potential, a material with low l_{ch} will have larger crack width (e.g. Point A) and the crack development tends to be unstable. A material with high l_{ch} will have the lowest crack width (e.g. Point C) and the crack development tends to be stable. For material with intermediate l_{ch}, the crack width development (Point B) will behave somewhere in between these two limits.

From the above analysis, it is clear that the restrained shrinkage crack width w depends on the cracking potential, the degree of brittleness, and the slab dimension. It explains that fiber reinforced concrete (FRC) will have smaller crack width than a plain concrete due to a higher value of l_{ch}, assuming all other properties the same. However, both concrete and FRC, or more generally, all quasi-brittle materials, will have crack width dependent on the repair dimensions (L in this example).

For a ductile repair material with inelastic tensile strain capacity ε_i, Eq. (2) modifies to

$$\varepsilon_{sh} \ge \varepsilon_e + \varepsilon_i + \varepsilon_{cp} \qquad (4)$$

For HPFRCC with high ε_i, by definition much larger than ε_e (Naaman and Reinhardt, 1996), Eq. (4) suggests that the cracking potential $(\varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp}))$ will be small, or even negative. Hence it is likely that HPFRCC will suppress fracture induced by restrained shrinkage. However, as discussed below, it is a well known fact that in the inelastic strain-hardening stage, HPFRCC will undergo a multiple micro-cracking phenomenon (Fig. 4). The issue then becomes one of how large the width of these micro-cracks is, i.e. whether such microcracks could compromise the durability of the repair material over time.

Requirements on the Interface Property of the Repaired System

The bond between the repair material and the concrete substrate is often considered important because of potential failure of the repaired system by delamination. Repaired systems subjected to drying shrinkage were investigated numerically by Kabele (2001) and by Wittmann & Martinola (2003) who demonstrated significant benefits of the inelastic deformation capacity of the repair material to the durability of the repaired system.

Figure 5 shows the simulated behavior of a thin overlay repaired system in the presence of a joint (Kabele, 2001). The deformation modes are contrasted for three repair materials: brittle mortar, quasi-brittle steel fiber reinforced concrete (SFRC) and ductile HPFRCC with $\varepsilon_i = 5\%$. In all cases, vertical cracking begins at the top surface of the overlays. In the case of mortar overlay, through thickness cracks in the overlay relieve the tensile stress, limiting the delamination to near the joint. In the case of the SFRC overlay, delamination is severe since the horizontal stress induced by the differential drying cannot be relieved due to crack bridging by fibers. In the case of the HPFRCC overlay, neither large cracks nor delamination occurs even after prolonged drying. This numerical experiment demonstrates that the potentially high interfacial shear stress in repaired systems can be minimized by the large inelastic tensile strain capacity of HPFRCCs.

Requirements on Fresh Properties of Repair Material

Various placement techniques are used for repair material applications, depending on the type of structure and repair conditions. The fresh property requirements are expected to be different for different placement techniques, including form and cast-in-place, full depth repair, overlay, overhead repair, form and pump, and shotcreting. For example, self-consolidating behavior can be beneficial in many of these techniques, but a rheology with initially low but rapidly rising viscosity is needed for shotcreting.

ENGINEERED CEMENTITIOUS COMPOSITES AS A REPAIR MATERIAL

From the discussions in the previous section, it appears that the following properties are highly desirable of a repair material:

- Low cracking potential $(\varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp}))$, low Young's modulus E, tight crack width w and low permeability k in cracked state;
- High delamination resistance in repaired system; and
- Adaptable rheology for different placement techniques.

Naturally, the repair material must also be durable under expected service conditions, including environmental loads (e.g. freeze-thaw), and mechanical loads (e.g. fatigue loading, and abrasion loading in the case of riding surfaces such as bridge decks or pavements). It is proposed that some HPFRCC materials, such as ECC, may meet many of these demands for high performance repair.

ECC is a special family of HPFRCC with microstructures tailored according to micromechanics theory (Li, 1998; Li et al, 2001). The most notable features of ECC are its high tensile ductility, characterized by a high value of ε_i, and tight crack width control (Fig. 6). The composition of a typical PVA fiber reinforced ECC is given in Table 1. Very fine sand with maximum particle size of 150 μm, and Type F fly ash was adopted in this mix. The PVA-REC 15 fiber has length and diameter of 12 mm and 39 μm, respectively. Other properties of this fiber can be found in Li et al (2001).

Table 2 summarizes experimental data of ECC in light of property requirements discussed above. Typical properties of normal concrete are also included for comparison purpose. The data shown in Table 2 indicate that ECC has a negative cracking potential, implying that it is unlikely to experience localized fracture due to restrained shrinkage. This is because of the very large value of the inelastic strain capacity ε_i, despite the higher drying shrinkage of ECC resulting from the high cement content and without coarse aggregates. The relatively low E value, also resulting from not using coarse aggregates in the mix, further limits the restrained shrinkage stress build up. Indeed, when the material is in the inelastic strain-hardening range, the effective tensile modulus is less than 1 GPa, making it a material (Fig. 6) with large deformability.

The restrained shrinkage crack width w shown in Table 2 is derived from a ring test in which both the concrete and the ECC were dried to 50% RH (Weimann and Li, 2003). As expected, there was only one crack in the concrete (1 mm crack width), while the ECC developed 10 cracks of much smaller width (.03 mm) (Fig. 7). Preliminary permeability tests of ECC and reinforced concrete specimens deformed to 1.5% revealed a coefficient of permeability about five orders of magnitude lower than that of the cracked concrete (Lepech et al, 2003).

The bond behavior of ECC with concrete has been examined using an ECC overlay on a concrete substrate (Lim and Li, 1997; Li, 2003). The specimens contained a vertical joint in the concrete substrate and a horizontal interfacial crack (forming a T-shaped discontinuity) and were subjected to four point bend loading. In the case of concrete and tension-softening FRC overlays, the interfacial crack always kinked out into the concrete repair material. In the case of ECC overlays, the interfacial crack kinked but was immediately trapped inside the ECC. Further load increase caused the interfacial crack to grow slightly, but returned to the kink-trap mechanism again (Fig. 8). This kink-trap process continued until the ECC overlay failed by exhausting the flexural strength, at load levels nearly twice that of the concrete/concrete repaired system, and with higher deformation capacity. Thus in an ECC repaired system, both spalling and delamination failure appeared to be suppressed.

The bond behavior of ECC/concrete repaired system subjected to drying shrinkage loading has not been examined experimentally. However, the failure mode of ECC overlay on a concrete substrate has been investigated numerically by Kabele (2001). Indeed, the simulated deformation mode shown in Figure 5c for the HPFRCC/concrete repaired system assumed properties of ECC material. Kabele reported that the tensile stress was relieved by the inelastic deformation of ECC, and very little interfacial shear stress could be built up even at the joint location.

The fatigue response of repaired systems was investigated by Zhang and Li (2002) using the same overlay test configuration as described above for the tests under monotonic loading. They found that the ECC/concrete repaired system possesses fatigue life several orders of magnitude higher than a concrete/concrete repaired system.

Resistance to freeze-thaw deterioration is essential for repair materials exposed to cold climates. ECC specimens tested under ASTM C666A were found to exhibit a durability factor of 100 with no degradation of dynamic modulus after 300 freeze-thaw cycles (Li and Lepech, 2004).

For roadway surface repairs, ECC must provide an adequate surface for driving and breaking, while withstanding traffic abrasion. Surface friction and wear track tests conducted by the Michigan Department of Transportation (MDOT) indicated Aggregate Wear Index (AWI) values for textured ECC samples (Li and Lepech, 2004) exceeding the established minimum AWI for Michigan trunkline road surfaces, despite the absence of coarse aggregates. ECC was deemed suitable for roadway surface repairs.

For repair applications, two versions of ECC have been designed. One version exhibits self-consolidation (Kong et al, 2002; Fischer et al, 2003), thus making it suitable for placement techniques such as form and pump. Another version of ECC designed for shotcreting application allows the material to pump through a hose and then sprayed onto a concrete surface. A thickness of 45 mm and 25 mm of this material can be built up for a vertical and overhead surface spray (Kim et al, 2003) with minimal rebound.

PERFORMANCE OF ECC IN BRIDGE DECK PATCH REPAIR

To evaluate the performance of ECC in realistic field conditions, a recently completed ECC repair project (Li and Lepech, 2004) is briefly summarized below. An MDOT owned two-lane bridge which required limited shallow patching of a deteriorated concrete deck was selected. This bridge, constructed in 1976 and having been repeated repaired, is a four span, simply supported, steel girder bridge with a nine inch thick reinforced concrete deck. While traffic frequency is relatively low, a large number of 11-axle gravel trucks use this structure as a truck route, greatly increasing loads on the bridge.

In order to compare the performance of ECC to more conventional repair material, only a section of the 7m x 9m patch was repaired with ECC, while the remaining portion was repaired with a concrete patching material commonly used by MDOT maintenance crews. This repair scenario allowed for a unique comparison between ECC and concrete materials subjected to identical environmental and traffic loads. One day after concrete patching, the ECC patch was cast. Using a 340L drum mixer, pre-batched ECC components were mixed onsite. The self-consolidating ECC was cast without vibration applied.

Long term performance of both the ECC patch and adjacent concrete patch has been recorded through a series of site visits. Initial visits conducted two days after patching showed no visible cracking in the ECC, while a clearly visible crack, approximately 300μm wide, had appeared in the concrete patch, most likely due to a positive cracking potential. The development of crack width over time in both ECC and concrete patches is shown in Figure 9. From this unique comparison of adjacent patch sites subjected to identical mechanical and environmental loading, ECC was shown to be far superior to the concrete repair material.

CONCLUDING REMARKS

This paper attempts to lay out the property requirements, both for the repair material itself, as well as for the repaired system, which are pertinent to enhancing repair durability performance. It is suggested that the high ductility of HPFRCC can serve as a driver of the cracking potential into the negative regime, thus preventing any fracture failure as a result of restrained shrinkage deformation of the repair material.

Engineered Cementitious Composites (ECC) have been designed with extreme ductility at several hundred times that of most current repair materials. In addition, the low Young's modulus and the unique high delamination and spall resistance make ECC an ideal material for concrete structure repair. Long term durability, in terms of freeze-thaw resistance and fatigue load resistance, has been demonstrated experimentally. Other properties of ECC are generally compatible with normal concrete. Recent experience of ECC used for a concrete bridge deck patch repair further supports the contention that ECC can be a very durable repair material.

Special versions of ECC, with self-consolidating property or with sprayable properties, have been developed and made suitable for various types of repaired material placement techniques. The cost of ECC (dominated by fiber cost) is about two to three times that of normal concrete, but far below the cost of a large number of currently marketed repair materials, especially some polymer concrete used for repair applications.

Despite a rapidly increasing knowledge base of ECC material, there is need for further systematic studies of ECC in repair applications subjected to severe service environments, especially when the material is used in the strain-hardening state when microcracks will be present. Special functionalities, such as high early strength important to repair applications in transportation structures, also need to be added to ECC.

ACKNOWLEDGEMENTS

Research grant support from the US National Science Foundation and helpful inputs from M. Lepech and S. Wang are acknowledged.

REFERENCES

1. ASCE (2003). "Report Card for America's Infrastructures," <http://www.asce.org/reportcard/index.cfm?reaction=full&page=6>, Accessed, Nov., 2003.
2. Billington, S., and Rouse, J.M., "Time-dependent Response of Highly Ductile Fiber-Reinforced Cement Based Composites," in *Proc., BMC-7*, Warsaw, Poland, Eds. A.M. Brandt, V.C. Li, and I.H. Marshall, 47-56.
3. Emmons, P.H., McDonald, J.E., and Vaysburd, A.M., (1993). "Some Compatibility Problems in Repair of Concrete Structures," *Proc., 3rd Int. Colloquium on Mat. Sci. and Restoration, Vol. 1, Expert Verlag*, 836-857.
4. Fischer, G., Wang, S. and Li, V.C., (2003). "Design of Engineered Cementitious Composites (ECC) for processing and workability requirements," in *Proceedings, BMC-7*, Warsaw, Poland, Eds. A.M. Brandt, V.C. Li, and I.H. Marshall, 29-36.
5. Hillerborg, A., (1983). "Analysis of One Single Crack," in *Fracture Mechanics of Concrete*, Ed. F.H. Wittmann, 223-249, Elsevier Science Publishers B.V., Amsterdam, the Netherlands.
6. Kabele, P., (2001). Assessment of Structural Performance of Engineered Cementitious Composites by Computer Simulation, CTU Reports 5(4), Czech Technical University in Prague.

7. Kim, Y.Y., Kong, H.J. and Li, V.C., (2003). "Design of an Engineered Cementitious Composite (ECC) Suitable for Wet-mix Shotcreting," Accepted, *ACI Materials J.*
8. Kong, H.J., Bike, S. & Li, V.C., (2003). "Development of a Self-Compacting Engineered Cementitious Composite Employing Electrosteric Dispersion/Stabilization," *J. Cement & Concrete Comp.*, 25(3), 301-309.
9. Lepech, M., Weimann, M., and Li, V.C. (2003). "Permeability of ECC in Strain-Hardening State," in preparation.
10. Li, V.C., (1998). "Engineered Cementitious Composites – Tailored Composites Through Micromechanical Modeling," in *Fiber Reinforced Concrete: Present and the Future* edited by N. Banthia, A. Bentur, and A. Mufti, Canadian Society for Civil Engineering, Montreal, 64-97.
11. Li, V.C., (2003). "Durable Overlay Systems with Engineered Cementitious Composites (ECC)," *Int'l J. for Restoration of Buildings and Monuments*, 9(2), 215-234.
12. Li, V.C., and Lepech, M. (2004). "Crack Resistant Concrete Material for Transportation Construction," in *Proc. CD of TRB Meeting*, Jan., 2004.
13. Li, V.C., Wang, S., and Wu, C., (2001). "Tensile Strain-Hardening Behavior of PVA-ECC," *ACI Materials J.*, 98(6) 483-492.
14. Lim, Y.M. and Li, V.C., (1997). "Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites" *J. Cement and Concrete Composites*, 19(4) 373-385.
15. Naaman, A.E., and Reinhardt, H.W., (1996). "Characterization of High Performance Fiber Reinforced Cement Composites HPFRCC," in *High Performance Fiber Reinforced Cementitious Composites, RILEM Proceedings* 31, Eds. A.E. Naaman and H.W. Reinhardt, 1-23.
16. Mather, B., and Warner, J., (2003). "Why do Concrete Repairs Fail," Interview held at Univ. of Wisconsin, Dept. of Engrg. Professional Development, MD, WI, <http://aec.engr.wisc.edu/resources/rsrc07.html>. Accessed, Nov., 2003.
17. Qian, S., Kim, Y.Y. and Li, V.C., (2004). "Influence of Concrete Material Ductility on the Behavior of Stud Shear Connection," in *Proceedings, FRAMCOS-5*, Vail, Colorado.

18. Stang, H. and Li, V.C., (2004). *Mechanics of Fiber Reinforced Concrete – Materials Design for Structural Engineering*, in preparation.
19. Vaysburd, A.M., Carino, N.J. and Bissonette, B., (1999). "Predicting the Performance of Concrete Repair Materials," NISTIR 6402, NIST.
20. Warner, J., (1995). "Concrete Durability – Lessons Learned from Past Performance," *Proc., Concrete 95 – Towards Better Concrete Structures*, Federation Int'l de la Precontrainte, Brisbane, Australia, Sept., 1995.
21. Weimann, M.B. and Li, V.C. (2003). "Hygral Behavior of Engineered Cementitious Composite (ECC)," *Int'l J. Restoration of Buildings and Monuments*, 9(5), 1-22.
22. Wittmann, F.H. and Martinola, G., (2003). Decisive Properties of Durable Cement-Based Coatings for Reinforced Concrete Structures. *Int'l J. Restoration of Buildings and Monuments*, 9(3), 235-264.
23. Zhang, J. and Li, V.C., (2002). "Monotonic and Fatigue Performance in Bending of Fiber Reinforced Engineered Cementitious Composite in Overlay System," *J. of Cement and Concrete Research*, 32(3), 415-423.

Table 1 Composition of a Typical ECC

Cement	Water	Sand	Fly Ash	SP	V_f (%)
1.0	0.53	0.8	1.2	0.03	2.0

SP = superplasticizer; proportion by weight except for fiber

Table 2 Typical properties of ECC and normal concrete

Properties	Concrete Mat'l	ECC	Reference
ε_{sh} (%)	0.04 – 0.1	0.1 – 0.15	Weimann and Li, 2003
ε_e (%)	0.01	0.015	Li et al, 2001
ε_i (%)	0	2-5	Li et al, 2001
ε_{cp} (%)	0.02-0.06	0.07[*1]	Billington and Rouse, 2003
$\varepsilon_{sh}-(\varepsilon_e+\varepsilon_i+\varepsilon_{cp})$ (%)	(-0.03) to 0.07	(-4.99) to (-1.94)	This study
E (GPa)	25-30	20	Qian et al, 2004
f_c' (MPa)	30-60	60-70	Qian et al, 2004
Restrained shrinkage[*2] w (mm)	1	.03	Weimann and Li, 2003
k (m/s)[*3]	1.7×10^{-5}	2.5×10^{-10}	Lepech et al, 2003
Delamination resistance	Kink-spall	Kink-trap	Lim and Li, 1997; Li, 2003
Constructability		Self-consolidating Sprayable	Kong et al, 2003; Fischer et al, 2003 Kim et al, 2003

[*1] Measured as compressive creep; tensile creep likely higher
[*2] Measured by ring test at 50%RH
[*3] Measured at cracked state under imposed 1.5% tensile strain

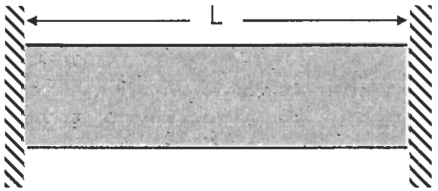


Fig.1 Simple Slab of Repair Material Under End Constraints

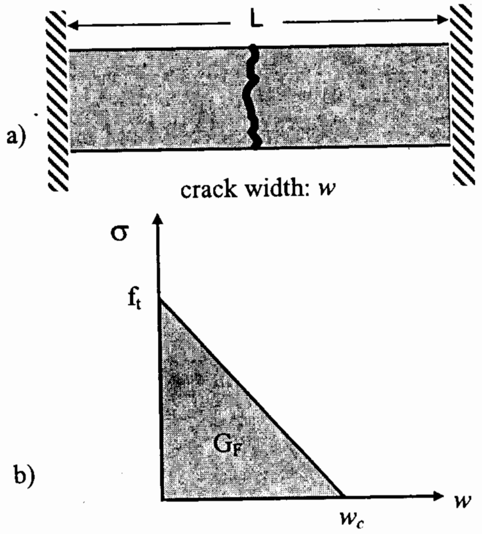


Fig.2 **(a) Formation of a Single Crack of Width w Controlled in a Quasi-Brittle Material by (b) The Post-Cracking Tension-Softening Curve**

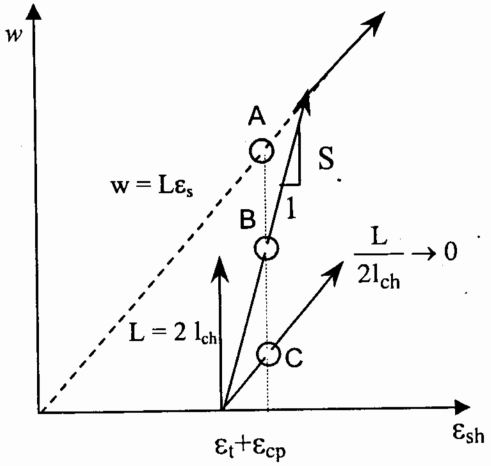
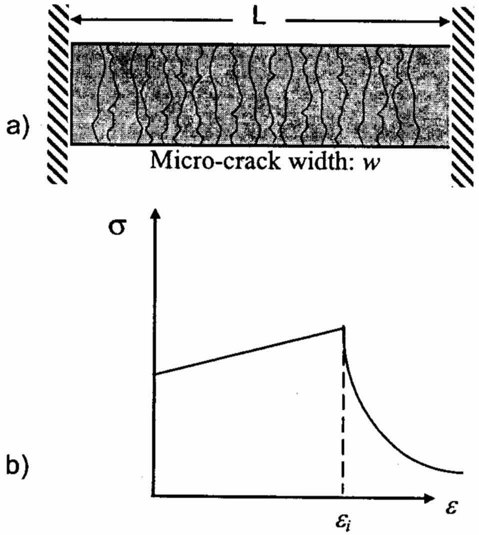


Fig.3 Schematic Plot of Crack Width w as a Function of Shrinkage Strain ε_{sh}. The Crack Width Development is Shown for Three Materials with Different Degrees of Brittleness A, B, or C



[illegible] (a) Formation of Multiple Cracking of Width w Controlled in HPFRCC by (b) the Tensile Stress-Strain Curve for $\varepsilon < \varepsilon_i$.

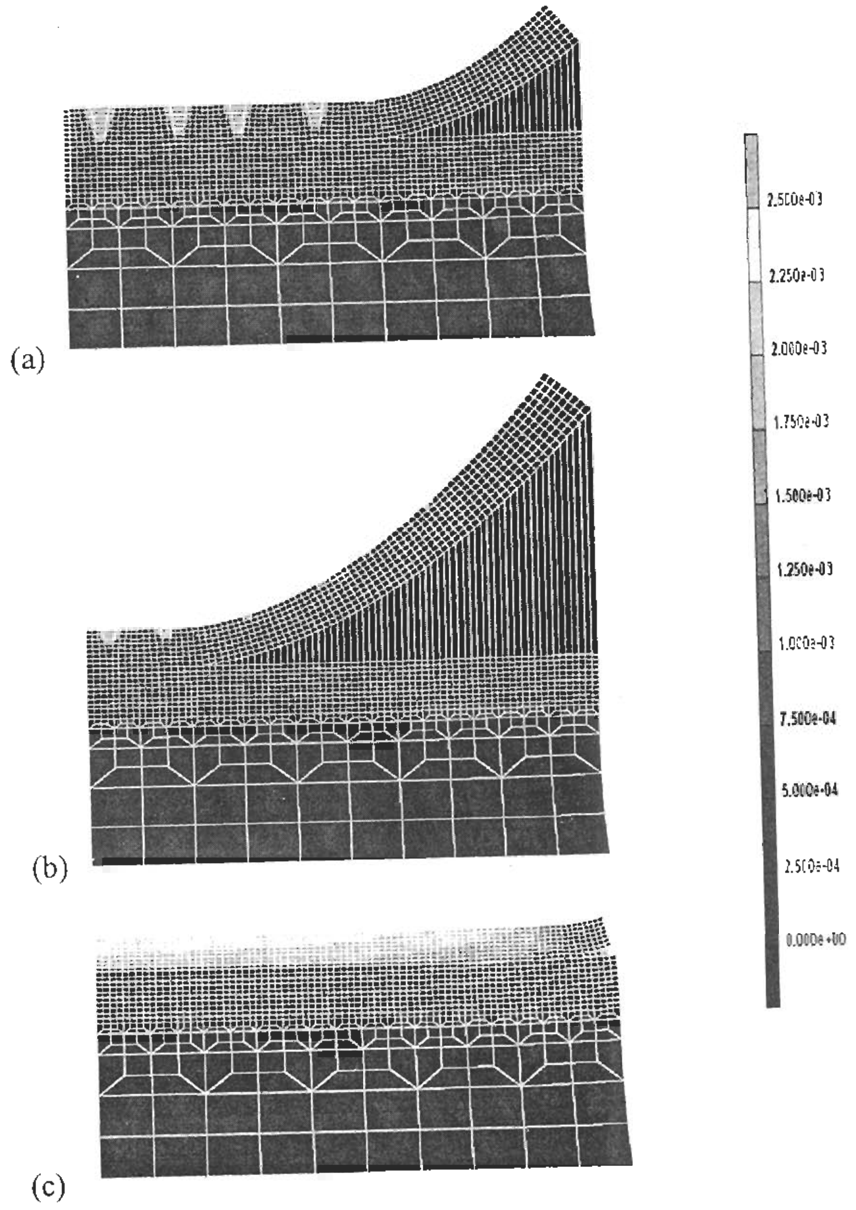


Fig.5 Contour Bands of Normal Cracking Strain (%) on Deformed FEM Mesh (Magnification 100x) for (a) Mortar Overlay at 16 days, (b) SFRC Overlay at 10 days, and (c) HPFRCC Overlay at 100 days. Joint is at Right Hand Edge of Repaired Systems (adapted from Kabele, 2001)

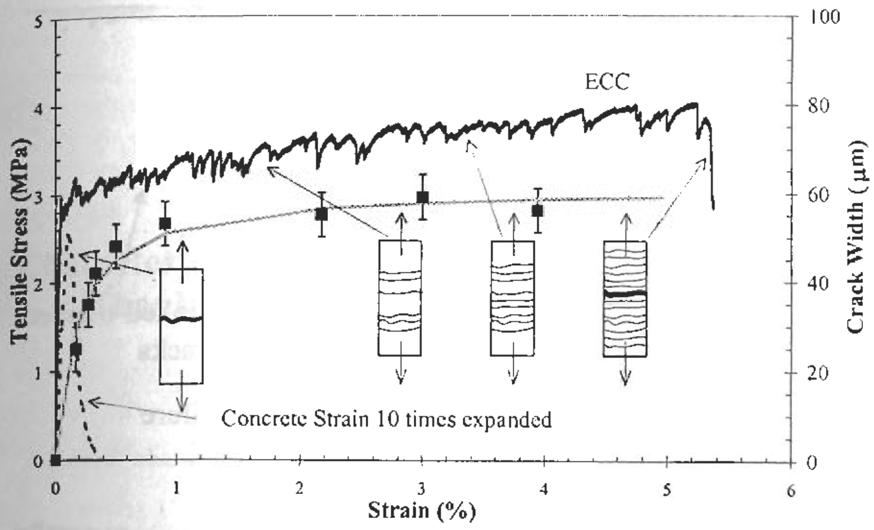


Fig.6 Stress-Strain Relation & Crack Width Development of a Typical ECC

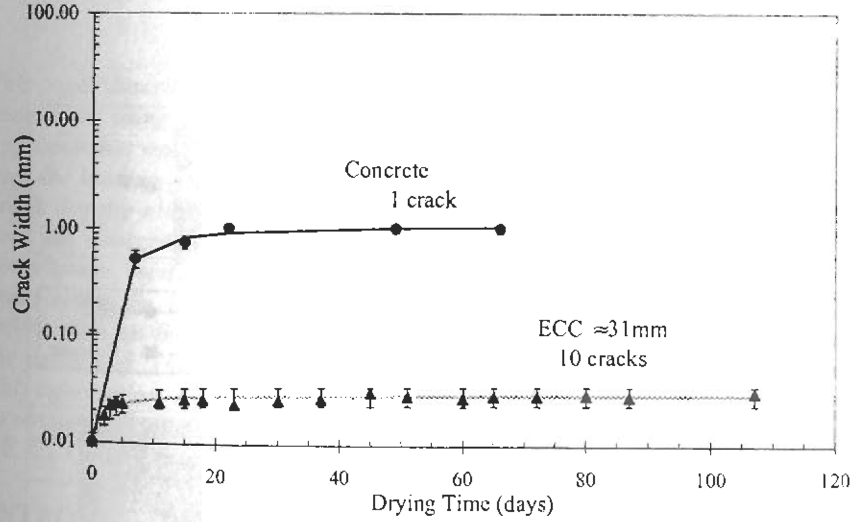


Fig.7 Crack Width Development in Ring Test with Specimens Dried to 50%RH

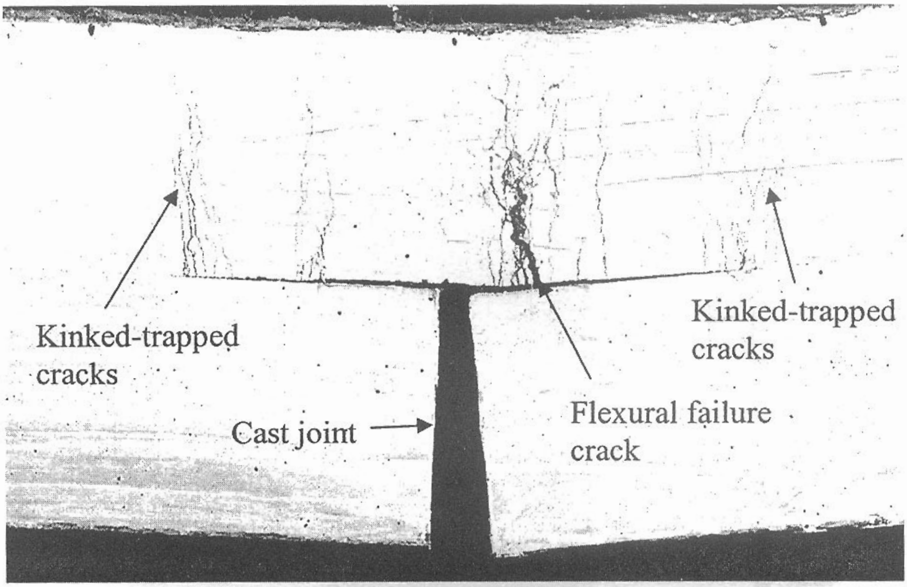


Fig.8 Close-up View Of the Kink-Trap Mechanism in the ECC/Concrete Overlay System, Showing the Kinked-Out Microcracks from the Interface Trapped in the ECC Repair Material

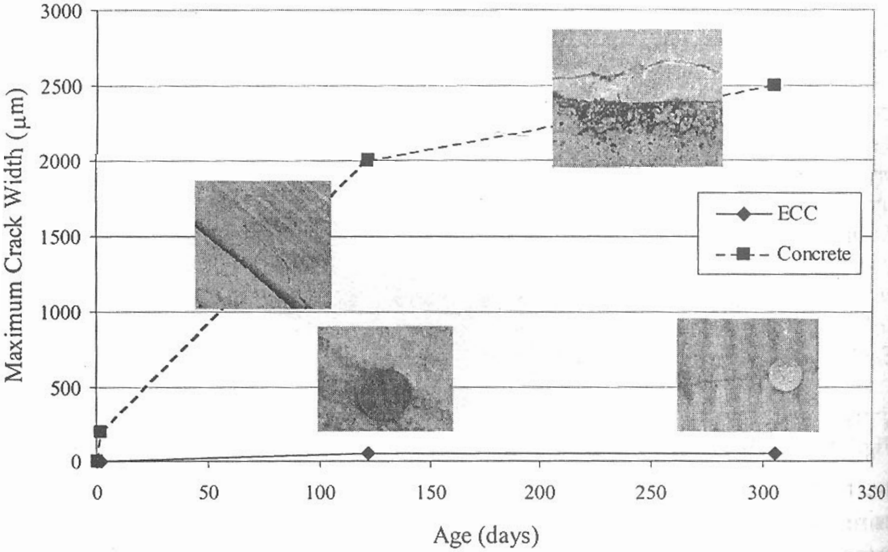


Fig.9 Development of Crack Width over Time in ECC and Concrete Patch