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Durable Overlay Systems with Engineered Cementitious Composites (ECC)

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Abstract

This paper reviews recent research on the application of an engineered cementitious composite (ECC) as overlay in the repair of deteriorated concrete structures. ECC is an ultra-ductile fiber reinforced cement based composite, that has metal-like features when loaded in tension. The uniaxial tensile stress-strain curve shows a ‘yield’ point, followed by strain-hardening up to several percent strain, resulting in a material ductility of at least two orders of magnitude higher in comparison to normal concrete or standard fiber reinforced concrete. ECC also has unique cracking behavior. When loaded to beyond the elastic range, ECC maintains crack width to below 100 μm, even when deformed to several percent tensile strain.

Experimental testing of ECC overlay reveals significant improvements in load carrying capacity and in system ductility over conventional concrete or steel fiber reinforced concrete overlays. The commonly observed overlay system failures by delamination or by spalling are eliminated when ECC is applied. Numerical simulation of differential drying shrinkage also confirms the superior performance of ECC. In the presence of a vertical joint, large crack formation and/or delamination are observed in mortar and fiber reinforced concrete overlays. These failure modes are suppressed when ECC is used as the overlay material. The unique material behavior of ECC makes it an ideal candidate material for durable overlay applications.

Keywords: ECC, Repair Overlays, Ductility, Durability, Failure Mode.

Dauerhafte Beschichtungssysteme aus technisch entwickelten zementgebundenen zusammengesetzten Werkstoffen (ECC)

Zusammenfassung

In diesem Beitrag wird zunächst ein Überblick über neue Forschungsergebnisse zur Anwendung eines technisch entwickelten zementgebundenen zusammengesetzten Werkstoffes (ECC) als Beschichtung im Rahmen von Instandsetzungsmaßnahmen beschädigter Stahlbetontragwerke gegeben. ECC ist ein extrem duktiler faserbewehrter zementgebundener Werkstoff mit Eigenschaften unter Zugbelastung, die mit Metallen vergleichbar sind. Die Spannungs-Dehnungs-Linie dieser Werkstoffe weist eine „Fließgrenze" auf und nach Erreichen dieser Grenzdehnung nimmt die Dehnung bis zu einigen Prozenten bei steigender Belastung zu (Dehnungserhärtung). Die Duktilität dieser Werkstoffe ist mindestens zwei Größenordnungen höher, als die von normalem Beton oder von konventionell faserbewehrten Betonen. ECC weist auch eine einzigartige Rissbildung auf. Wenn der Werkstoff über die Elastizitätsgrenze hinaus belastet wird, bleibt die Rissweite unter 100 μm, selbst wenn die Verformung unter Zugspannung einige Prozent erreicht.

Ergebnisse von Versuchen mit ECC Reparaturschichten haben gezeigt, dass damit eine signifikante Verbesserung des Lasttragvermögens und der Duktilität erreicht werden kann, im Vergleich zum Verhalten von Bauteilen, die mit konventionellem Beton oder mit Stahlfaserbeton beschichtet wurden. Das häufig beobachtete Versagen von Beschichtungssystemen durch Ablösen oder Abplatzen kann durch die Verwendung von ECC vermieden werden. Das weitaus günstigere Verhalten von ECC kann auch durch die numerische Simulation des differentiellen Trocknungsschwindens bestätigt werden. Über vertikalen Rissen werden in Beschichtungen aus Mörtel oder faserbewehrtem Beton weit klaffende Risse und/oder Ablösen beobachtet. Diese Art des Versagens wird ausgeschlossen, wenn ECC zum Beschichten verwendet wird. ECC ist wegen seiner einzigartigen Werkstoffeigenschaften eine ideale Alternative für dauerhafte Reparaturbeschichtungen.

Stichwörter: *ECC, Reparaturbeschichtung, Duktilität, Dauerhaftigkeit, Versagensmodus.*

1 Introduction

Overlay is a common method of repairing deteriorated infrastructures, including pavements, bridge decks and parking garage decks. The overlay material may be asphalt, plain concrete, polymer concrete or fiber reinforced concrete. The concrete substrate may or may not have its steel reinforcements exposed when the overlay is placed.

The durability of the overlay system is a matter of significant interest, since their failure by delamination, spalling or restrained shrinkage cracking and subsequent reinforcement corrosion leads to repeated maintenance needs and loss of use. Increasingly, the design life of an overlay is expected to last over twenty years. The application of a very ductile fiber reinforced cementitious composite as the overlay material may overcome the commonly observed overlay durability problems. A series of experimental, analytical and numerical investigations carried out over the last several years point to a high potential of a much more durable repaired system when engineered cementitious composites (ECC) are used in place of normal concrete.

After a brief introduction to ECC, this paper first reviews research on the resistance to delamination and spalling of ECC overlay system under both monotonic and fatigue loading. The influence of ECC/concrete interface roughness is examined. A newly developed version of ECC, that can be sprayed to form the overlay (or for general repair), is presented. Resistance to drying induced damage in such repaired systems is also discussed.

2 Engineered Cementitious Composites

ECC is a special class of high performance fiber reinforced concrete with extreme tensile ductility, typically in the 3-5 % range (about 300-500 times that of normal concrete and fiber reinforced concrete (FRC)) [1,2]. ECC attains high ductility with relatively low fiber content (typically less than 2-3 %) via microstructural control. Micromechanics provides guidelines on tailoring of the fiber, matrix and interface properties. A typical tensile stress-strain curve is shown in Figure 1, for an ECC reinforced with 2.5 % PVA (REC 15) fibers.

After first cracking, tensile load capacity continues to increase, resulting in a macroscopic strain-hardening phenomenon accompanied by multiple microcracking. The crack width development is also shown in Figure 1. It is clear, that the crack width increases steadily up to about 60 μm, at about 1 % strain. Thereafter, the crack width stabilizes and tends to remain constant at a steady state crack width even as the composite strain reaches 4 %.

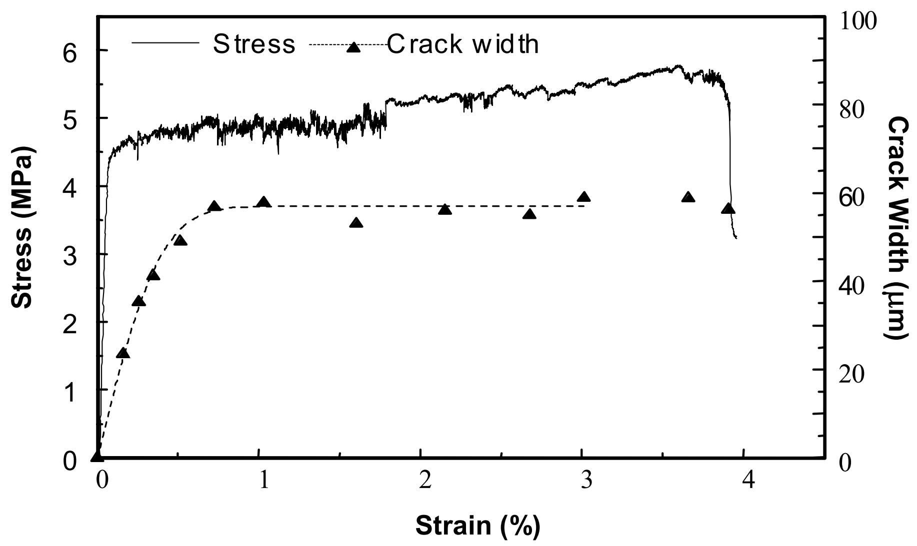


Figure 1: A typical stress-strain curve of ECC, showing high tensile strain capacity, and tight crack width control.

The steady state crack width is governed by the fiber bridging property, and is related to the fiber modulus, diameter, and interface chemical and frictional bonds. Lower fiber content leads to larger crack width and vise versa. For example, we have observed, that a 2 % volume fraction of the same composite produces a steady state crack width of about 80 µm. Note that this steady state crack width is an intrinsic material property. It is independent of the applied load, and size and geometry of the ECC overlay.

The small crack width at the material composite level described above has been observed in an increasingly large database of experiments of reinforced ECC (or R/ECC) at the structural element scale, (see e.g. [3,4]).

3 Overlay Specimen Configuration and Materials

In order to simulate the most adverse loading situation on an overlay, Lim and Li [5] proposed the specimen and loading configuration shown in Figure 2. The base concrete has a joint, above which a 50.8 mm delaminated interface (labeled as ‘initial unbonded zone’) is artificially introduced, simulating the presence of a defect at the interface between the repair material and the base concrete. The four point bending setup creates a mixed mode loading condition for this interfacial

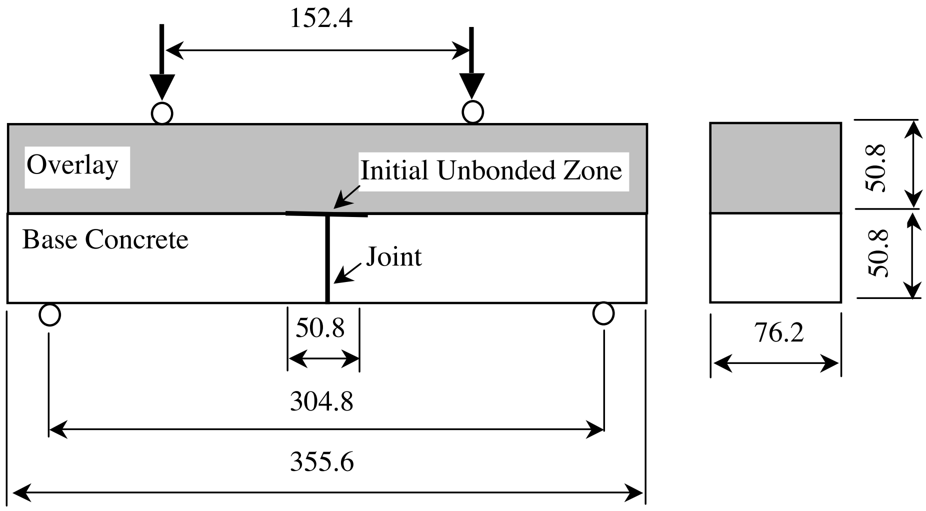


Figure 2: Dimension of simulated overlay system and loading configuration.

Table 1: Mix Proportions of PC, SFRC and ECCs

Material	Cement	Water	FA	CA	SF	SP*	MC	Fiber †
PC	1.0	0.5	2.27	1.8	-	-	-	-
SFRC	1.0	0.5	2.27	1.8	-	-	-	0.01
PE-ECC	1.0	0.35	0.5	-	0.1	0.01	-	0.02
PVA-ECC	1.0	0.43	1.0	-	-	0.025	0.002	0.02
(FA: Fine Aggregate, CA: Coarse Aggregate (maximum size<9.5 mm), SF: Silica Fume, SP: Superplasticizer, MC: Methyl Cellulose † Volume fraction *Water content in superplasticizer is 66 %)								

crack. The two base concrete blocks were diamond saw cut from a larger piece of concrete, with the cut surface in contact with the repair material. The repair material was cast on top of the concrete blocks after four weeks of water curing. Details of the specimen preparation process can be found in [5].

The base material is a plain concrete. For the repair material, the same plain concrete (PC), steel fiber reinforced concrete (SFRC) and two types of ECC are used. The material composition is given in Table 1. The major difference between these

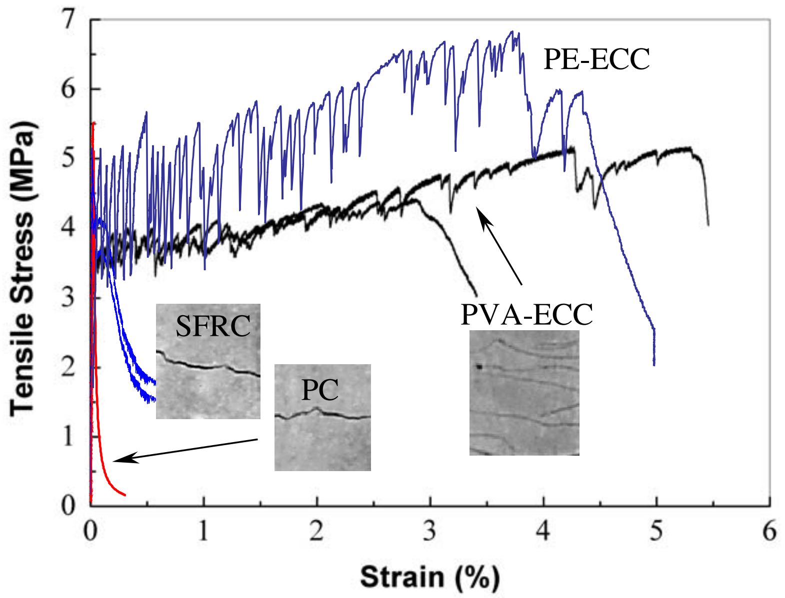


Figure 3: Tensile stress-strain curves of PC, SFRC, PVA-ECC and PE-ECC.

four materials is their tensile behavior, shown in Figure 3. The PC is brittle. The SFRC is quasi-brittle, meaning that a bridged crack will continue to open with decreasing load-carrying capacity. The PE-ECC was designed with high modulus polyethylene fiber, while the PVA-ECC was designed with a Poly-vinyl Alcohol fiber especially developed for ECC reinforcement [6]. Clearly, the ECC materials have tensile strain capacity about two orders of magnitude higher than the PC or SFRC (about 0.01 %).

4 Resistance to Delamination and Spalling

Figure 4 shows the failure behavior of the three overlay systems PC/PC, SFRC/PC and PE-ECC/PC. The corresponding load-deflection curves are shown in Figure 5. In the case of PC/PC, the interfacial defect propagated a small amount along the interface, but kinked and immediately formed a spall going through the thickness of the PC overlay. In the case of SFRC/PC, the kinked crack was bridged by the steel fiber, allowing load, albeit decreasing, to be transmitted across this crack. This too formed a spall cutting through the full thickness of the overlay. In the case of the system repaired with the PE-ECC material, the failure pattern is much more complex. It appeared that the initial horizontal defect propagated slightly

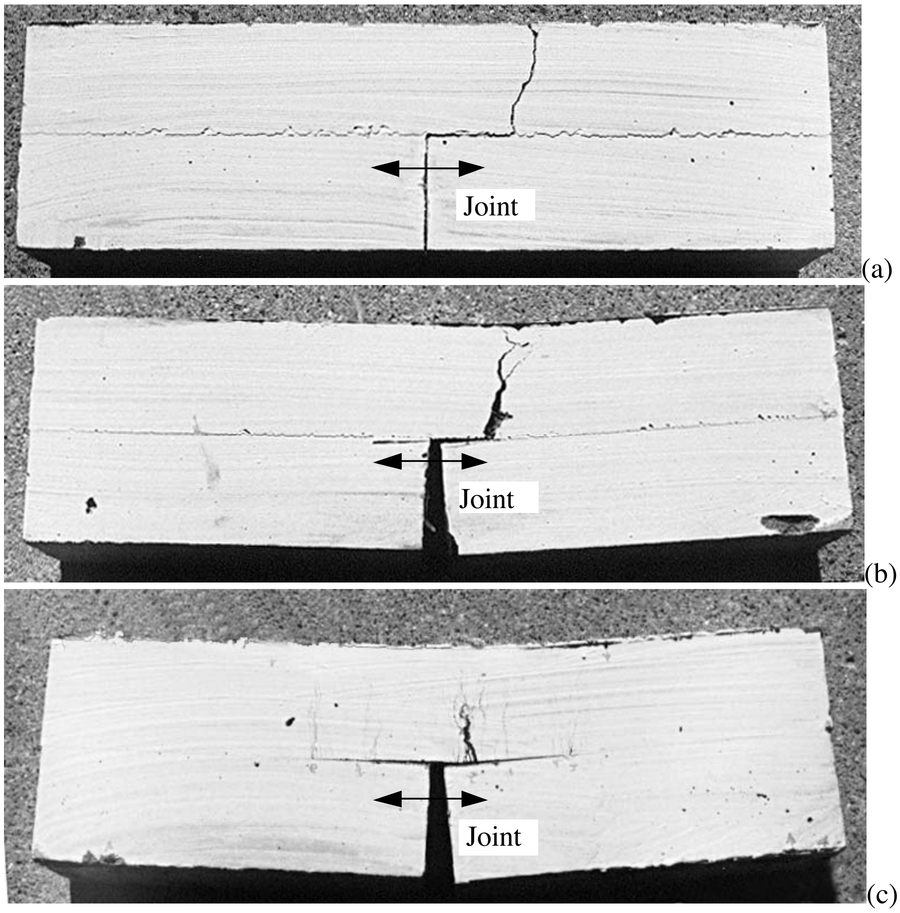


Figure 4: Failure modes of (a) PC/PC, (b) SFRC/PC and (c) PE-ECC/PC overlay systems.

along the interface, then kinked, but was immediately trapped inside the ECC repair material. Trapping means, that the kinked crack was arrested, so that additional load was needed to drive the interface crack to propagate again along the interface of the bi-material system. Then the kink-trap phenomenon repeated itself a number of times, resulting in a pattern of kinked-trapped cracks. This process finally stopped, when the mid-section of the overlay acts like a beam, and the flexural strength of the ECC beam was exceeded. The final failure occurred, when a flexural fracture formed close to the top of the joint. Unlike the PC/PC and SFRC/PC overlay systems, the final failure of the ECC/PC system had nothing to

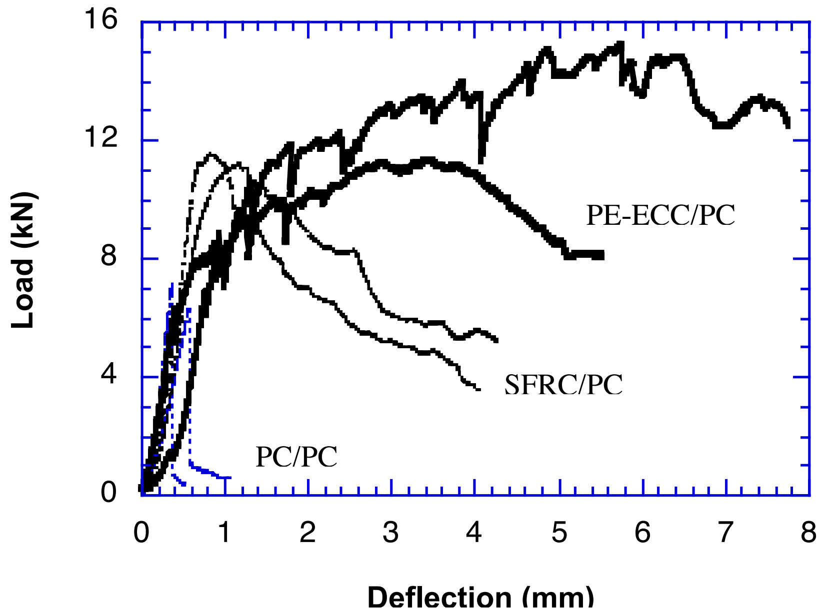


Figure 5: Load-deflection curves of the PC/PC, SFRC/PC and the PE-ECC/PC overlay systems.

do with the position of the interfacial crack-tip at failure. A close-up of the multiple kink-trap phenomenon is shown in Figure 6.

As indicated in Figure 5, the peak load and the deflection magnitude at peak load are both higher for the ECC overlay system, compared to the PC and SFRC overlay systems. This suggests, that by eliminating the delamination and spall processes, the ECC overlay provides both higher load carrying capacity and energy absorption capacity to the repaired system. It is interesting to note, that the "structural" strength of the ECC overlay system is more than double that of the PC overlay system, despite the fact, that the ECC and the PC both had about the same cracking strength (approximately 4 MPa, Figure 3). By trapping the microcracks inside the overlay, it may be expected, that water penetration from the top surface will be minimized in the ECC overlay, leading to improved durability of the ECC overlay system.

The kink-trap phenomenon occurs only when ECC is used as the overlay. A fracture mechanics theory based on the energetics of crack propagation along the interface and crack kinking into the repair material, as well as the fracture resistance in these two crack paths, was proposed to explain the kink-trap phenomenon. The rapidly

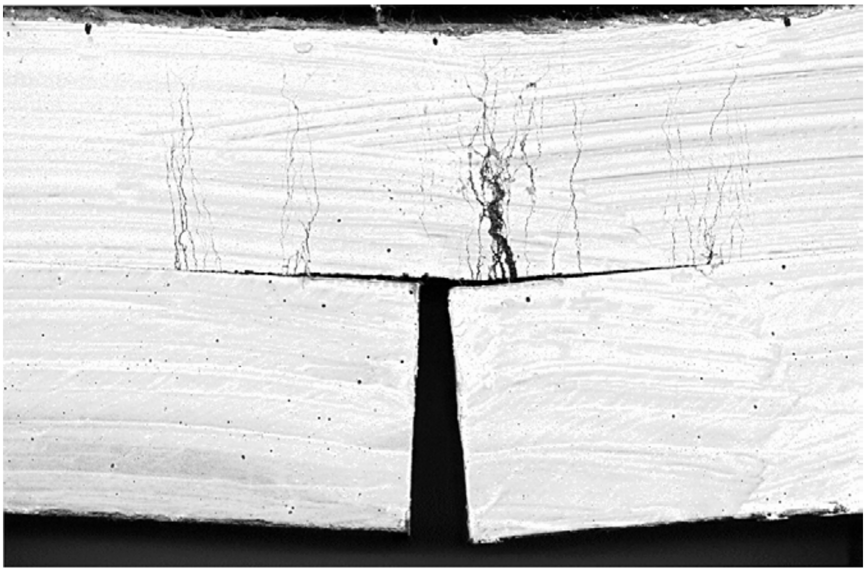


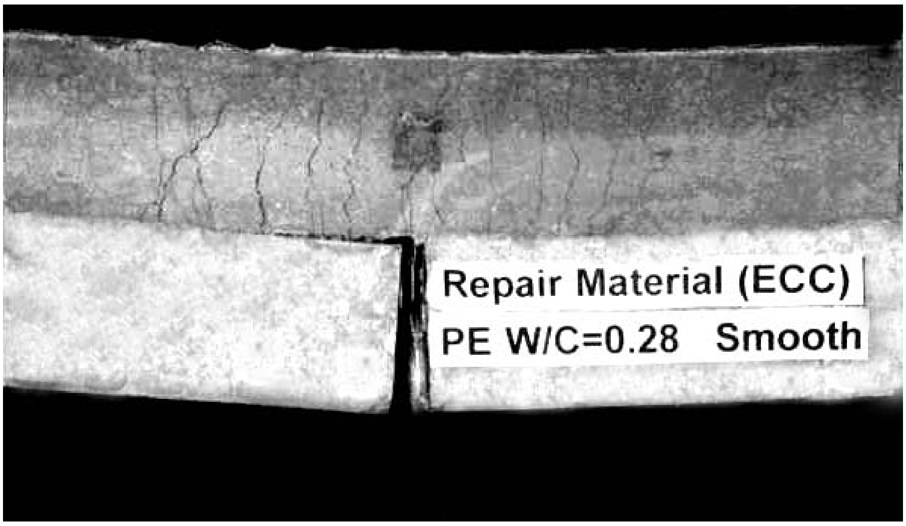
Figure 6: Close-up view of the kink-trap mechanism in the PE-ECC/PC overlay system.

rising toughness of ECC as the kink crack grows in length is considered important. More details can be found in [5]. Numerical modeling by Kabele [7] successfully reproduced this kink-trap phenomenon.

5 Influence of Surface Preparation

The interface fracture toughness of a bi-material system is known to depend on the roughness of the interface. This in turn could influence the kink-trap phenomenon. The influence of interface roughness on the kink-trap phenomenon was examined by Kamada and Li [8]. In their study, some specimens were prepared with the top of the base concrete roughened by a scarifier, prior to the casting of the ECC overlay. The PE-ECCs employed in this study have compositions slightly different than that listed in Table 1, but these differences (mainly in the fiber content and the w/c ratio) are not expected to change the conclusions.

The failure pattern is indeed affected by the smoothness of the interface. Figure 7 shows the contrast. When the interface is rough, the kinked crack cannot return to the interface. Instead, it developed into a fan-like “plastic zone” with many microcrack branches inside. Increasing load is needed in order to develop this “plastic zone”. In fact, the load deformation curves between the two sets of test are difficult to distinguish, given the variability from specimen to specimen. (Additional tests by



(a)

(b)

Figure 7: (a) The kink-trap mechanism associated with a smooth interface is replaced by (b) a plastic-zone formation when the ECC/PC interface is roughened.

Zhang and Li [9] do show, that the deformability of the smooth interface overlay system is higher than that of the rough interface overlay system). In both cases, however, the peak load and the corresponding load-point displacement reached are much higher than those when PC or SFRC are used as the overlay material. Thus while the kink-crack mechanism prevalent in the smooth interface case gives way to the "plastic zone" formation, the macroscopic behavior remains similar. The benefits of using ECC over PC or regular FRC seem to be independent of interface roughness or surface preparation.

6 Durability Under Fatigue Loading

Because overlay systems are often subjected to repeated loading, the fatigue durability performance is of interest. The fatigue performance of ECC overlay system was examined by Zhang and Li [9], using the same test set-up as described above for monotonic loading. The PVA-ECC material with composition detailed in Table 1 was used as the repair material. The control test was carried out with a PC overlay.

Figure 8 summarizes the fatigue test data obtained, in the standard S-N curve format. The equivalent flexural stress σ plotted on the vertical axis has been calculated from the applied moment M:

$$\sigma = \frac{M}{\frac{1}{6}Bh^2} \tag{1}$$

where B and h are the width and depth of the overlay. It appears that there is little difference in the fatigue performance whether the interface is smooth or rough. In both cases, the fatigue life for the ECC overlay system is significantly higher than that of the PC overlay system.

In terms of crack pattern, there is no observable difference between tests carried out under monotonic and fatigue loading.

7 Repairing with Sprayed ECC

A special version of ECC was developed recently for spray repair operation [10]. For this processing route, the fresh mix must be deformable enough during the mixing and pumping process, but must stiffen up rapidly after the sprayed ECC reaches the concrete substrate. This was attained by controlling the rheology of the cement paste through optimal combinations of a superplasticizer, a viscosity agent, and the addition of calcium aluminate cement particles. The strategy of using the

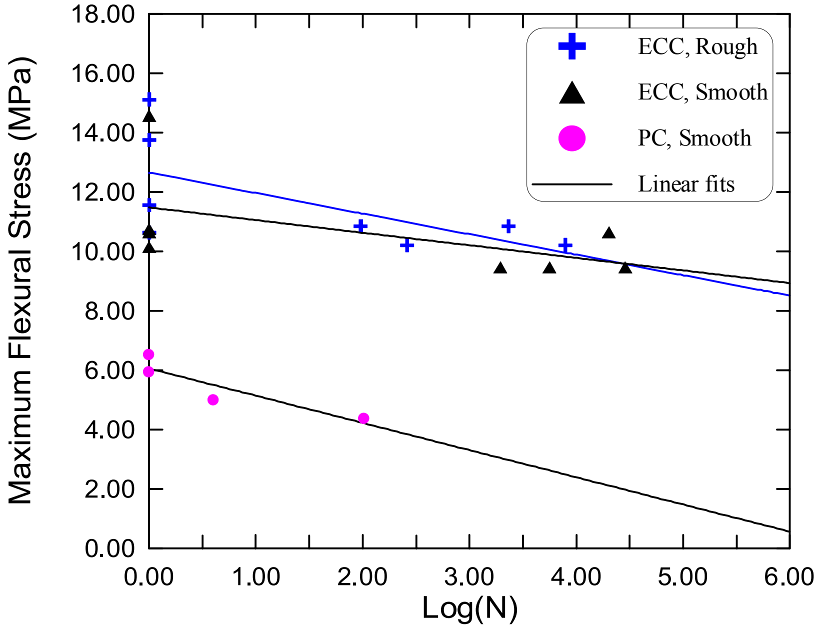


Figure 8: S-N curves of PVA-ECC/PC and PC/PC overlay systems tested under flexural fatigue loading.

rheology of the paste to drive the flow of the ECC while keeping other ingredients similar to that shown for PVA-ECC in Table 1 makes it possible to satisfy the fresh property requirement for spraying, while adhering to the micromechanics criteria for tensile strain-hardening.

A test set up similar to that shown in Figure 1 was used. The specimen was fabricated by spraying ECC onto a panel and then saw cut to the required testing dimensions as shown in Figure 9. Control tests were carried out with standard pre-packaged mortar mixes commercially designed for repair jobs. The test specimens were identical to those shown in Figure 1 except that the layer thicknesses were reduced by 50 %. The test result (Figure 10) shows, that the specimen using the sprayed ECC is more than 100 % stronger and several times more ductile than those repaired with standard repair mortar mixes.

8 Resistance to Drying Induced Damage

After an overlay is placed, drying shrinkage of the overlay may result in cracks as the overlay is restrained from deforming by the substrate concrete. The restrained shrinkage cracks could increase the flow of water and aggressive agents into the

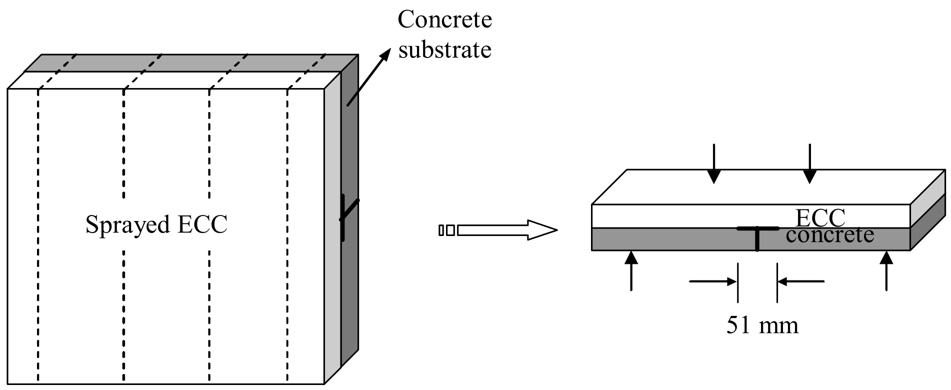


Figure 9: Spray PVA-ECC/PC overlay specimen.

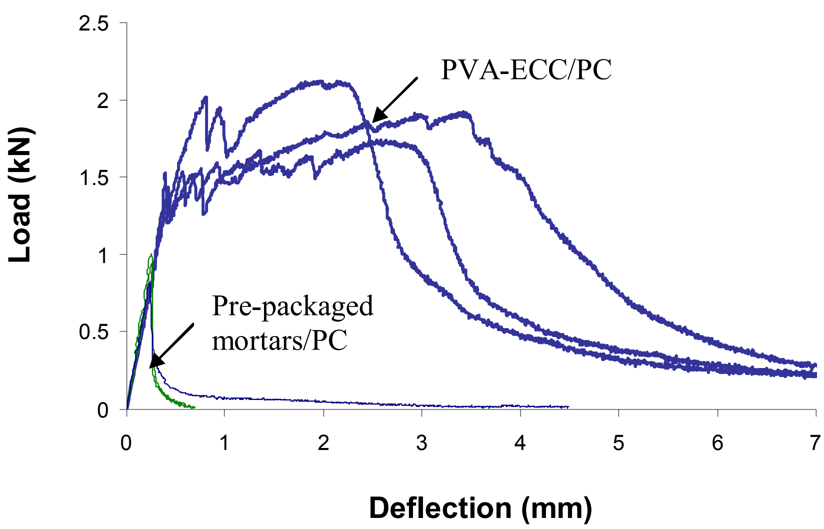


Figure 10: Load-deflection curves of sprayed PVA-ECC/PC overlay systems, showing much higher peak load and deformation capacity in comparison to spray pre-packaged mortars commonly used in concrete structure repair.

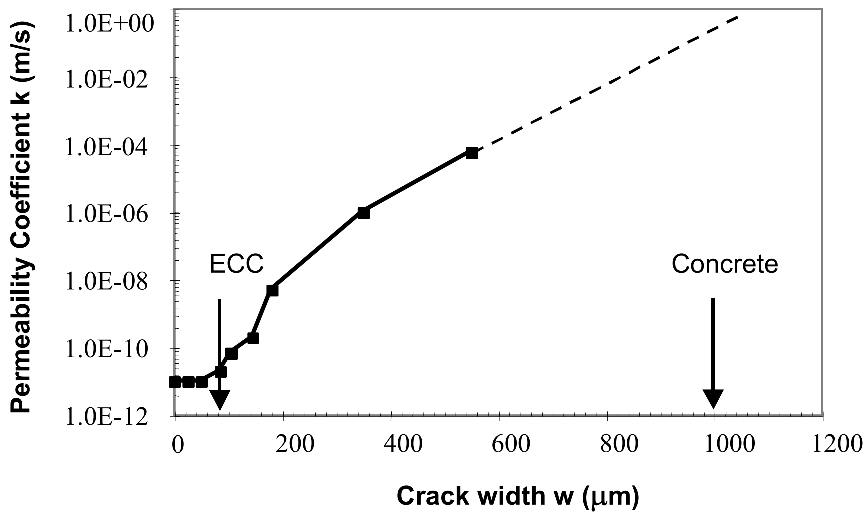


Figure 11: Experimentally measured permeability coefficient as a function of crack width in plain concrete (adapted from [11]). The dashed part of the curve is extrapolated from the experimental data (solid curve).

overlay system, and may reach the steel reinforcement in the substrate concrete, resulting in reduction in the durability of the overlay system.

The water transport properties, including the permeability coefficient, flow rate and absorption, have been studied (see, e.g. [11-13]) in various cracked cementitious materials. Wang et al [11] demonstrated the significance of crack width in controlling the permeability coefficient of cracked concrete. The permeability coefficient was shown to increase by seven orders of magnitude (from 10^{-11} to 10^{-4} m/s) as the crack opens from zero to 500 μm (Figure 11). Of particular interest is that the curve becomes noticeably flat when the crack width drops to below 100 μm.

Tsukamoto [12] studied the flow rate of water through a crack, and found a general relationship that the flow rate scales as the third power of crack width. This relationship holds for both plain concrete and fiber reinforced concrete, although the FRC generally suppresses the flow rate further compared to plain concrete, for a given crack width. This was attributed to the increased tortuosity of the cracks in the presence of fiber bridging. In all cases, the flow rate becomes negligible when the crack width falls below 100 μm.

Reinforcement corrosion in cracked R/C specimens was studied by Ramm and Biscoing [14]. They found, that "with a crack width of 0.1 mm, corrosion was not to be observed in any case."

These experimental data suggest, that the 100 µm crack width define a threshold above which significant increase in transport properties is observed. An effective means of minimizing the transport of harmful ingredients via water movement through cracks is to control crack width to below 100 µm.

Restrained shrinkage tests were carried out with ECC and standard concrete using the technique introduced by Grzybowski and Shah [15]. Cementitious materials were cast around a steel ring and the development of the crack width as a function of time was monitored. Figure 12 shows, that the crack width of the ECC material is less than 80 µm, more than an order of magnitude lower than that for normal concrete (about 1 mm) for the specimen dimensions used. These test results suggest, that while ECC has higher shrinkage due to the higher cement content, the shrinkage deformation is accommodated by a larger number of cracks each with a much smaller crack width in comparison to normal concrete.

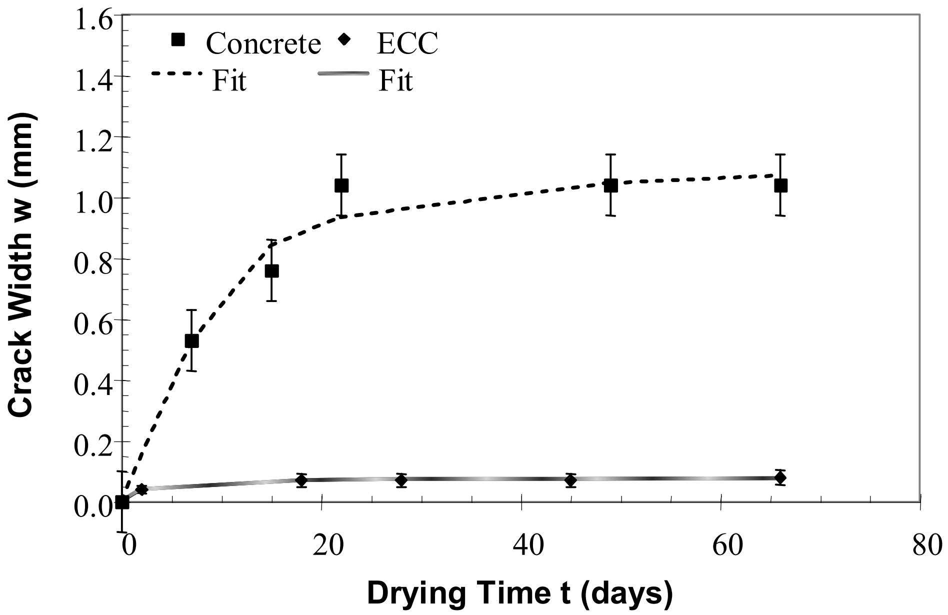


Figure 12: Crack width development for PVA-ECC and normal concrete in restrained drying shrinkage test.

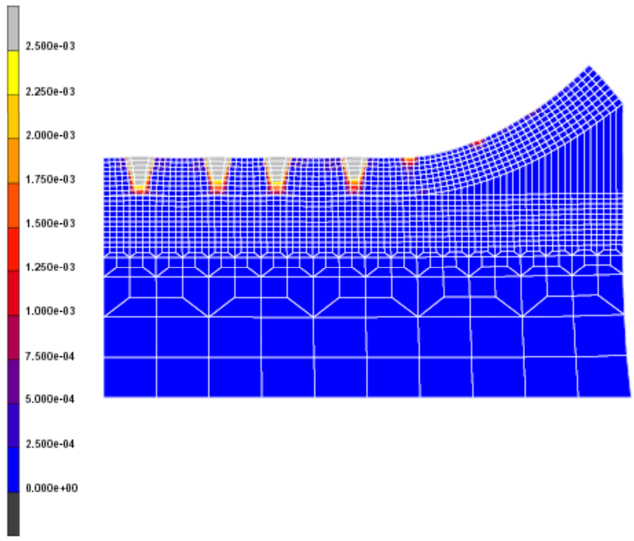


Figure 13 a): Contour bands of normal cracking strain (%) on deformed mesh (magnification 100x) for mortar overlay at 16 days

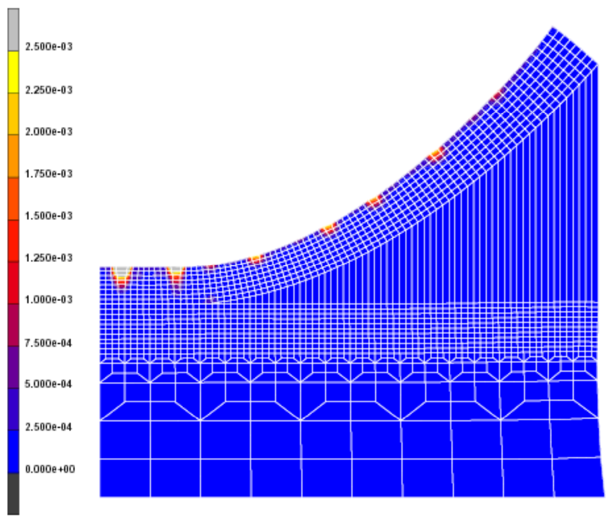


Figure 13 b): Contour bands of normal cracking strain (%) on deformed mesh (magnification 100x) for SFRC overlay at 10 days

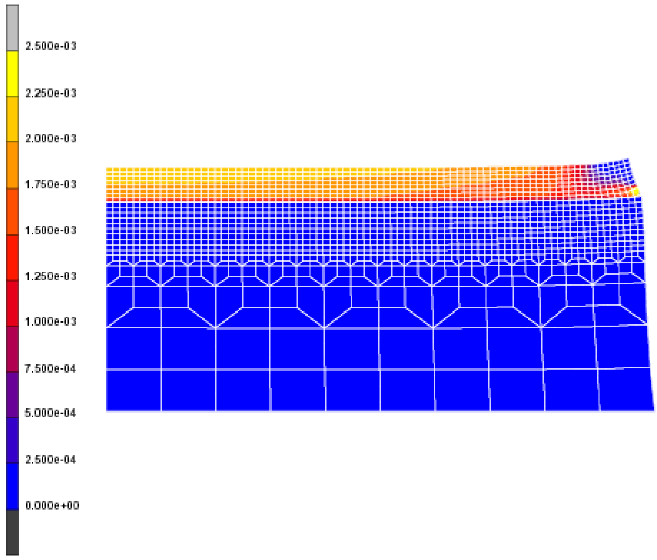


Figure 13 c): Contour bands of normal cracking strain (%) on deformed mesh (magnification 100x) for ECC overlay at 100 days (adapted from [7]).

These shrinkage crack width are also shown in Figure 11, which once again suggest that after cracking, the rate of water transport through the ECC overlay (at $3x10^{-11}$ m/s) can be many orders of magnitude lower than that in normal concrete (at $8x10^{-1}$ m/s). The transport rate does not depend on the number of cracks, but depends non-linearly on the crack width.

Differential drying through the thickness of an overlay may lead to cracking of the overlay and delamination at the interface starting at a through thickness vertical joint. This problem for mortar overlay has been carefully analyzed numerically by Martinola and Wittmann [15]. The same problem was analyzed by Kabele [7] contrasting the failure behavior of mortar, SFRC and ECC overlays. The numerical results are shown in Figure 13. 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 in this manner, as the cracks are bridged by the steel fibers. In the case of the ECC overlay, neither large cracks nor delamination occurs even after a long term drying. The horizontal stress is relieved by the large inelastic tensile strain capacity of the ECC. In addition, eventual interface crack propagation is inhibited by the kink-trapping mechanism described earlier.

9 Conclusions

Severe mechanical loading in the presence of a joint in the concrete substrate and a defect on the horizontal interface between the concrete substrate and the repair material shows, that ECC overlay systems outperform SFRC or PC overlay systems. Delamination and spalling are both prevented by either development of the kink-crack trapping mechanism, or the formation of a large plastic zone in the ECC layer. The kink-crack trapping mechanism prevails when the ECC/PC interface is smooth, while the plastic zone mechanism prevails when the ECC/PC interface is rough. In either case, the macroscopic system behavior in terms of load-deflection response is similar, and shows much higher peak load and corresponding deflection value at failure. These observations appear to hold for both monotonic and fatigue loading. Fatigue tests reveal significantly improved fatigue life at any stress level in the ECC/PC overlay system in comparison to PC/PC overlay system.

Despite the higher amount of cement in ECC in comparison to normal concrete, and a higher free shrinkage, restrained shrinkage cracks in ECC are at least an order of magnitude lower than normal concrete, suggesting improved durability against the ingress of water and aggressive agents migrating into the repair layer. Numerical simulation of differential drying also suggests, that ECC/PC overlay outperform other overlay systems in preventing large crack formation in the overlay and delamination from the edge of a through-thickness joint.

From both the mechanical loading and the environmental loading point of view, there is substantial evidence, that ECC can serve as a durable overlay material. The unique tensile strain-hardening behavior and the tight crack width control of ECC are responsible for the ECC overlay system performance described in this paper. ECC can be applied by the regular casting technique, or by means of spraying, a process similar to that of shotcreting.

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