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The effects of surface preparation on the fracture behavior of ECC/concrete repair system

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Abstract

This paper presents the influence of surface preparation on the kink-crack trapping mechanism of engineered cementitious composite (ECC)/concrete repair system. In general, surface preparation of the substrate concrete is considered essential to achieve a durable repair. In this experiment, the "smooth surface" system showed more desirable behavior in the crack pattern and the crack widths than the "rough surface" system. This demonstrates that the smooth surface system is preferable to the rough surface system, from the view point of obtaining durable repair structure. The special phenomenon of kink-crack trapping which prevents the typical failure modes of delamination or spalling in repaired systems is best revealed when the substrate concrete is prepared to have a smooth surface prior to repair. This is in contrast to the standard approach when the substrate concrete is deliberately roughened to create better bonding to the new concrete. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: ECC repair system; Kink-crack trapping mechanism; Surface preparation; Durable repair

1. Introduction

Engineered cementitious composites (ECCs) [1,2] are high performance fiber-reinforced cement based composite materials designed with micromechanical principles. Micromechanical parameters associated with fiber, matrix and interface are combined to satisfy a pair of criteria, the first crack stress criterion and steady state cracking criterion [3] to achieve the strain hardening behavior. Micromechanics allows optimization of the composite for high performance while minimizing the amount of reinforcing fibers (generally less than 2–3%).

ECC has a tensile strain capacity of up to 6% and exhibits pseudo-strain hardening behavior accompanied by multiple cracking. It also has high ultimate tensile strength (5–10 MPa), modulus of rupture (8–25 MPa), fracture toughness (25–30 kJ/m^2) and compressive strength (up to 80 MPa) and strain (0.6%). A typical tensile stress–strain curve is shown in Fig. 1. ECC has its uniqueness not only in superior mechanical properties in tension or in relatively small amount of chopped fiber usage but also in micromechanical methodology in material design.

The use of ECC for concrete repair was proposed by Li et al. [4], and Lim and Li [5]. In these experiments, specimens representative of an actual repair system – bonded overlay of a concrete pavement above a joint, were used. It was shown that the common failure phenomenona of spalling or delamination in repaired concrete systems were eliminated. Instead, microcracks emanated from the tips of defects on the ECC/concrete interface, kinked into and subsequently were arrested in the ECC material (see Fig. 2, [5]). The tendency for the interface crack to kink into the ECC material depends on the competing driving force for crack extension at different orientations, and on the competing crack extension resistance along the interface and into the ECC material. A low initial toughness of ECC combined with a high Mode II loading configuration tends to favor kinking. However, if the toughness of ECC remains low after crack kinking, this crack will propagate unstably to

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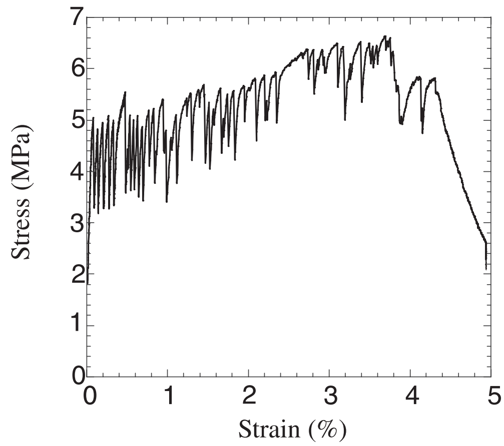


Fig. 1. Tensile strain-hardening behavior of ECC.

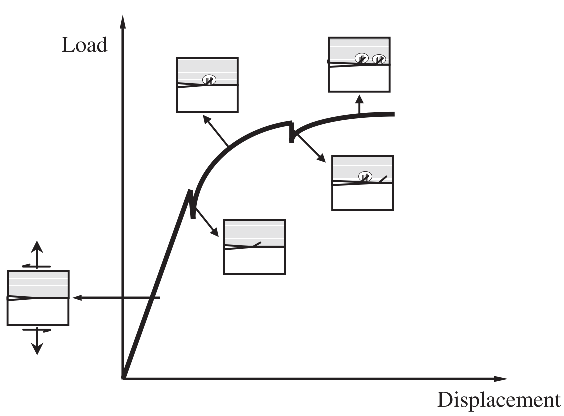


Fig. 2. The conceptual trapping mechanism with load–displacement relation.

the surface, forming a surface spall. This is the typically observed phenomenon associated with brittle concrete and even fiber-reinforced concrete (FRC). In the case of ECC, the kinked crack is trapped or arrested in the ECC material, due to the rapidly rising toughness of the ECC material. Conceptually, the ECC behaves like a material with strong R-curve behavior, with low initial toughness similar to that of cement (0.01 kJ/m^2) and high plateau toughness (25–30 kJ/m^2). After kinked crack arrest, additional load can drive further crack extension into the interface, followed by subsequent kinking and arrest.

Details of the energetics of kink-crack trapping mechanism can be found in [5]. It was pointed out that this kink-crack trapping mechanism could serve as a means for enhancing repaired concrete system durability.

In standard concrete repair, surface preparation of the substrate concrete is considered critical in achieving a durable repair [6]. In the study of Lim and Li [5], the ECC is cast onto a diamond saw cut surface of the concrete. Hence, the concrete surface is smooth and is expected as a result to produce a low toughness interface. Higher interface roughness has been associated with higher interface toughness in bi-material systems [7].

In this paper, this particular aspect of the influence of surface preparation on the kink-crack trapping phenomenon is investigated. Specifically, the base concrete surfaces were prepared by three different methods. The first surface was obtained as cut surface by using a diamond saw (smooth surface), similar to that used in the previous study [5]. The second one was obtained by applying a lubricant on the smooth surface of the concrete to decrease the bond between the base concrete and the repair material. This surface was applied only in one test case to examine the effect of weak bond of interface on the fracture behavior of the repaired specimen. The third surface was prepared with a portable scarifier to produce a roughened surface (rough surface) from a diamond saw-cut surface.

Regarding the repair materials, the water/cement ratio of ECC was varied to control its toughness and strength. Thus, two different mixtures of ECC were used for the comparison of fracture behavior in both smooth and rough surface case. Concrete and steel fiber-reinforced concrete (SFRC) were also used as control repair materials instead of ECC.

2. Experimental procedure

2.1. Specimens and test methods

The specimens in this experiment were designed to induce a defect in the form of an interfacial crack between the repair material and the base concrete, as well as a joint in the substrate. Fig. 3 shows the dimensions of the designed specimen and the loading configuration,

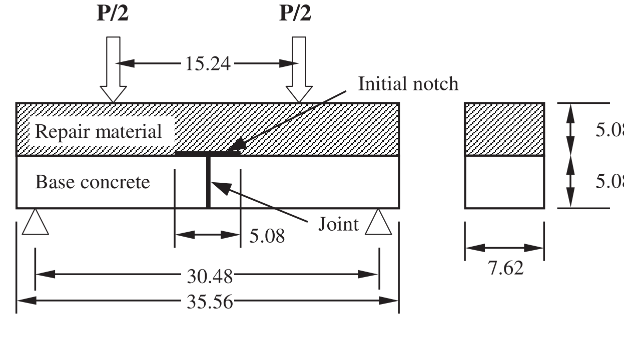


Fig. 3. Outline of test specimen.

Table 1
Test case

Repair material	Surface preparation	No. of specimens
Concrete	Smooth	2
	Smooth (with lubricant)	2
	Rough	2
SFRC	Smooth	2
	Rough	2
ECC ($W/C=0.28$)	Smooth	4
	Rough	4
ECC ($W/C=0.60$)	Smooth	4
	Rough	4

and these were the same as those of the previous experiment [5]. This loading condition can provide a stable interface crack propagation condition, when the crack propagates along the interface [8].

In this experiment, concrete, SFRC and ECC (with two different W/C ratios) were used as the repair materials. Table 1 illustrates the combinations of the repair material and the surface condition of test specimens. The numbers of specimens are also shown in Table 1. Only in the concrete overlay specimens, a special case where lubricant was smeared on the concrete smooth surface was used.

The mix proportions of materials are shown in Table 2. Ordinary mixture proportions were adopted in concrete and SFRC as controls for comparisons with ECC overlay specimens. The steel fiber for SFRC was "I.S fiber", straight with indented surface and rectangular cross-section (0.5×0.5 mm^2), 30 mm in length. An investigation using a steel fiber with hooked ends had already been performed in the previous study [5]. Polyethylene fiber (Trade name Spectra 900) with 19 mm length and 0.038 mm diameter was used for ECC. The elastic modulus, the tensile strength and the fiber density of Spectra 900 were 120 GPa, 2700 MPa and 0.98 g/cm^3, respectively. Two different ECCs were used with different water/cement ratios. The mechanical properties of the base concrete and the repair materials are shown in Table 3. The tensile strain capacity of the ECC materials are not measured, but are estimated to be in excess of 3% based on test results of similar materials [2].

Table 3
Mechanical properties of materials

Material	Compressive strength (MPa)	Elastic modulus (GPa)
Base concrete	32.1	26.6
Repair concrete	33.3	27.0
SFRC	47.2	27.5
ECC ($W/C=0.28$)	64.5	19.6
ECC ($W/C=0.60$)	32.2	15.0

An MTS machine was used for loading. Load and load point displacement were recorded. The loading rate in this experiment was 0.005 mm/s. After the final failure of specimens, interface crack (extension) lengths were measured at both (left and right) sides of a specimen as the distance from a initial notch tip to a propagated crack tip along the interface between the base concrete and the repair material.

2.2. Specimen preparation

Most of the specimen preparation procedures followed those of the previous work [5]. The base concrete was prepared by cutting a concrete block (see Fig. 4(a)) into four pieces (see Fig. 4(b)) using a diamond saw. Two out of the four pieces were used for one smooth surface repair specimen. In order to make a rough surface, a cut surface was roughened uniformly with a scarifier for 30 s. To prepare a repair specimen in the form of an overlay system, a repair material was cast against either the smooth surface or the rough surface of the base concrete blocks (see Fig. 5). Special attention was paid both to maintain cleanliness and to provide adequate moisture on the base concrete surface just before the casting. In two of the concrete overlay specimens, lubricant was sprayed on the smooth surface just before concrete casting. The initial notch and joint were

Table. 2
Mix proportions of material[a]

Material	Cement	Water	FA	CA	SP	HPMC	V_f
Concrete	1.0	0.5	2.27	1.8	–	–	–
SFRC	1.0	0.5	2.27	1.8	–	–	0.010
ECC ($W/C=0.28$)	1.0	0.28	0.50	–	0.03	0.0005	0.015
ECC ($W/C=0.60$)	1.0	0.6	0.50	–	0.01	0.007	0.015

[a] FA: fine aggregate; CA: coarse aggregate; SP: superplasticizer; HPMC: methyl cellulose; V_f: fiber volume fraction.

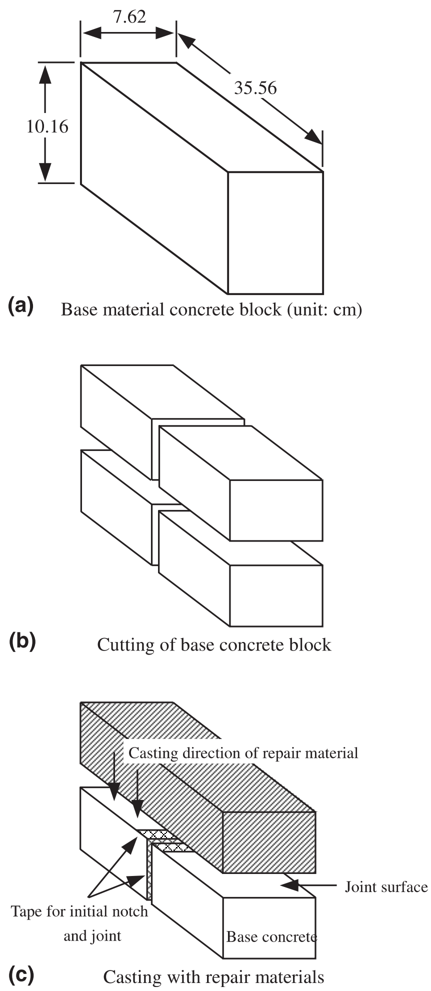


Fig. 4. Procedure of specimen preparation.

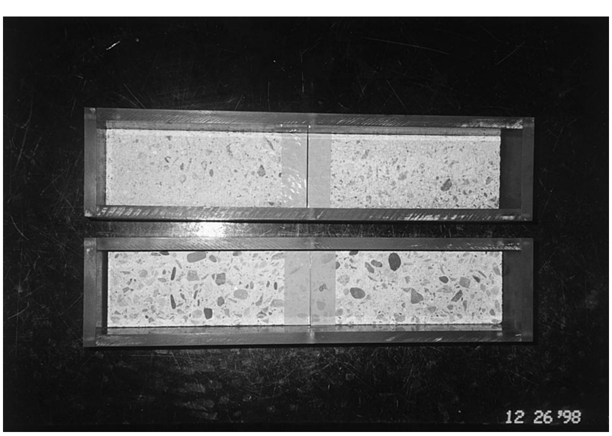


Fig. 5. Rough surface (top) and smooth surface (bottom).

made by applying a smooth tape on the base concrete before casting the repair materials (see Fig. 4(c)).

The specimens were cured for 4 weeks in water. Eventually, the base concrete was cured for a total of 8 weeks, and repair materials were cured for 4 weeks in water. The specimens were dried for 24 h before testing.

3. Results and discussion

3.1. Comparison of the ECC overlay system with the control systems

Fig. 6 shows the representative load–deflection curves in each test case. The overall peak load and deflection at peak load are recorded in Table 4. In the ECC overlay system, the deflections at peak load, which reflect the system ductility, are considerably larger than those of both the concrete overlay (about one order of magnitude higher) and the SFRC overlay system (over five times). These results show good agreement with the previous results [5]. Moreover, it is clear from Fig. 6 that the energy absorption capacity in the ECC overlay system is much enhanced when it is compared with the other systems. This significant improvement in ductility and in energy absorption capacity of the ECC overlay system is expected to enhance the durability of repaired structures by resisting brittle failure. The ECC overlay system failed without spalling or delamination of the interface, whereas, both the concrete and SFRC overlay systems failed by spalling in these experiments (Fig. 7).

3.2. Influence of surface preparation

Both in the concrete overlay system and the SFRC overlay system, the peak load and the deflection at peak load do not show significant differences between smooth surface specimen and rough surface specimen (Table 4). The typical failure mode for both overlay systems (for smooth surface) is shown in Fig. 7. In the concrete overlay specimen with lubricant on the interface, delamination between repair concrete and substrate

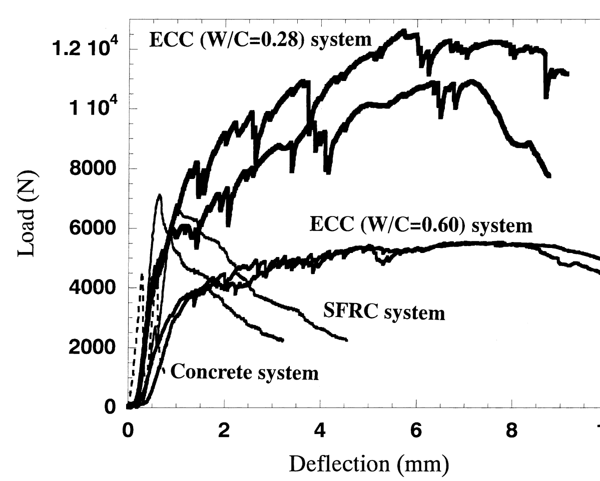


Fig. 6. Load–deflection curves of four overlay systems.

Table 4
Peak load and deflection at peak load

Repair materials	Surface	Peak load (kN)	Peak load average (kN)	Deflection at peak load (mm)	Deflection average (mm)
Concrete	Smooth	4.65	4.65	0.60	0.60
		–		–	
	Rough	4.28	4.40	0.32	0.30
		4.51		0.28	
SFRC	Smooth	6.57	6.91	1.08	0.86
		7.25		0.63	
	Rough	5.99	6.56	0.51	0.58
		7.13		0.64	
ECC ($W/C = 0.28$)	Smooth	8.66	9.57	2.05	4.30
		10.93		7.14	
		8.69		4.59	
		10.00		3.43	
	Rough	6.72	8.81	1.71	3.69
		5.27		1.72	
		10.61		5.59	
		12.64		5.72	
ECC ($W/C = 0.6$)	Smooth	3.63	4.53	1.83	4.83
		4.93		5.50	
		5.52		7.52	
		4.04		4.45	
	Rough	3.78	4.43	2.72	3.89
		3.83		1.56	
		5.55		7.71	
		4.54		3.55	

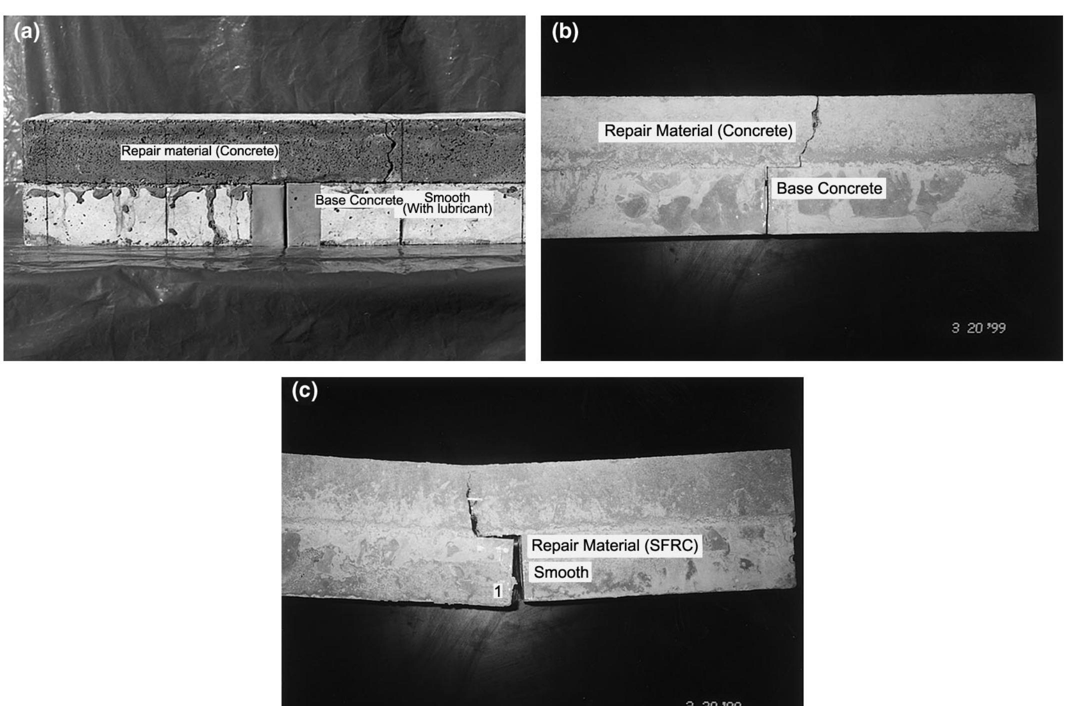


Fig. 7. Failure modes of the concrete system and the SFRC system: (a) and (b) the concrete system; (c) the SFRC system.

occurred first, followed by a kinked crack which propagates unstably to the surface of the repair concrete. On the other hand, in the concrete overlay system without lubricant, the initial interface crack kinked out from the interface into the repair concrete with a sudden load drop, without any interface delamination. The fractured halves of the specimens separated completely in both smooth surface specimens and rough surface specimens. In the SFRC overlay system, the initial interface crack also kinked out into the SFRC and the load decreased gradually in both surface conditions of specimen. In all these repair systems, a single kink-crack always leads to final failure, and the influence of surface preparation is not reflected in the experimental data. Instead, only the fracture behavior of the repair material (concrete versus SFRC) are revealed in the test data. These specimen failures are characterized by a single kinked crack with immediate softening following elastic response.

Figs. 8–11 illustrate the load–deflection behavior of the ECC overlay systems. Strain-hardening behavior is observed in every test case. The smooth surface specimens generally show larger amount of strain hardening than that of the rough surface specimen regardless of the water/cement ratio of the ECC. The deflections at peak load are 15% and 25% higher in smooth surface specimens for $W/C = 0.28$ and 0.6, respectively (Table 4).

Typical crack patterns of the ECC overlay system in each test case are illustrated in Fig. 12 ($W/C = 0.28$) and Fig. 13 ($W/C = 0.60$). In the ECC overlay systems with smooth surface, several kinking and trapping behaviors are observed (see Figs. 12(a) and 13(a)). These are through-thickness propagations, and interface and kink crack extensions can be seen on both front and back sides of the specimens. However, interface crack propagation cannot be seen in the ECC overlay system with rough surface (see Figs. 12(b) and 13(b)). Moreover, two

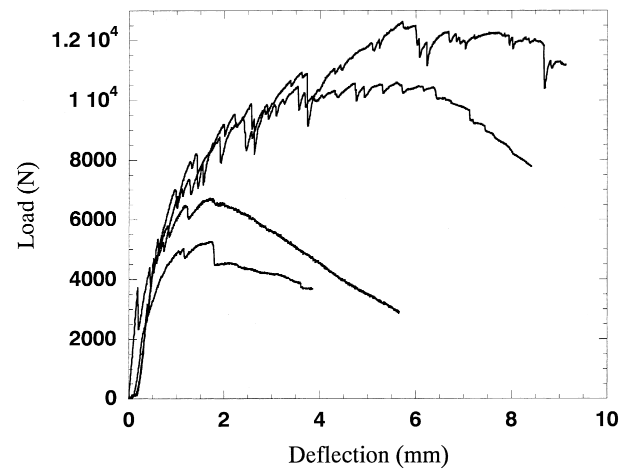


Fig. 9. Load–deflection behaviors of the ECC ($W/C = 0.28$ rough) overlay system.

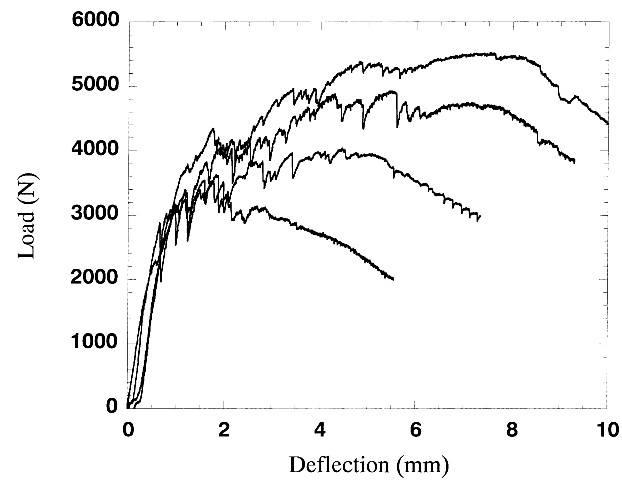


Fig. 10. Load–deflection behaviors of the ECC ($W/C = 0.60$ smooth) overlay system.

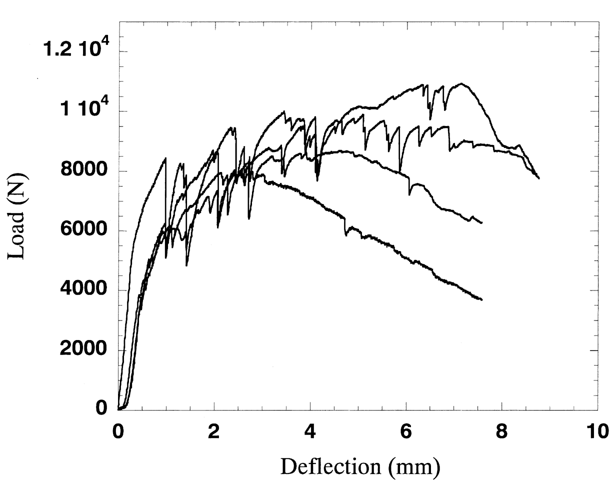


Fig. 8. Load–deflection behaviors of the ECC ($W/C = 0.28$ smooth) overlay system.

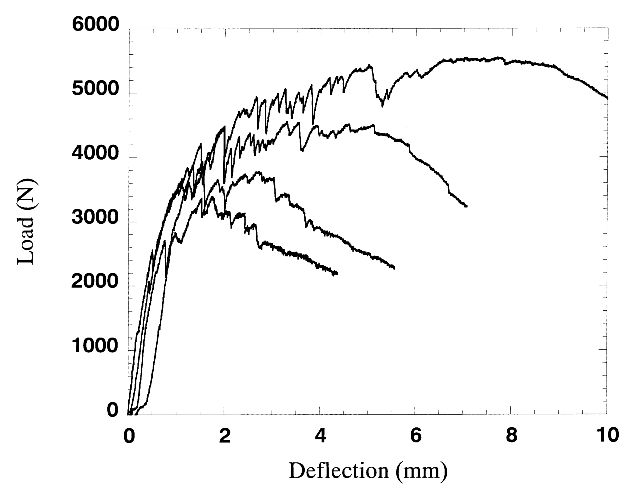
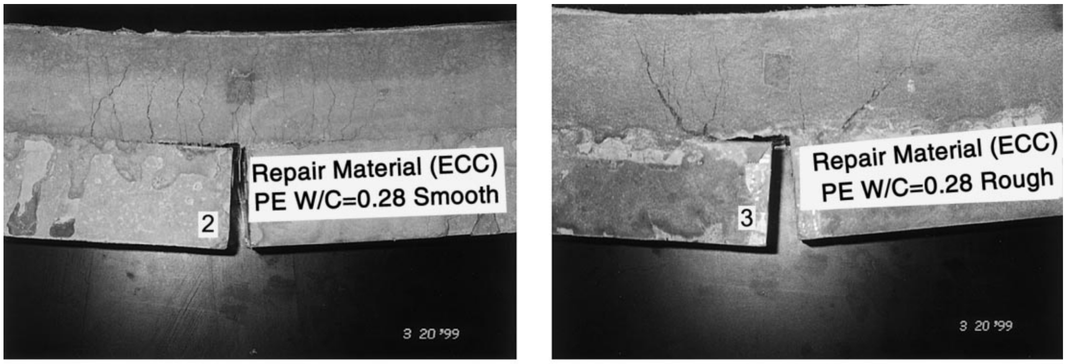
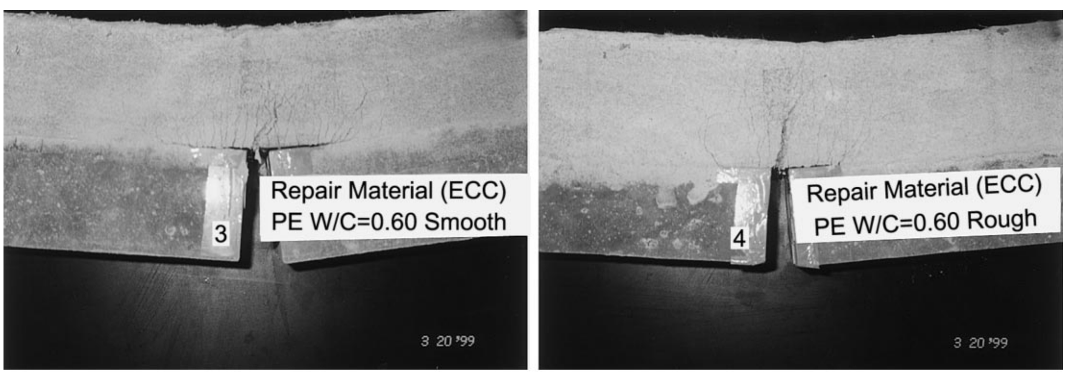


Fig. 11. Load–deflection behaviors of the ECC ($W/C = 0.60$ rough) overlay system.



(a) Smooth (b) Rough

Fig. 12. Crack patterns of the ECC ($W/C = 0.28$) overlay system: (a) Smooth; (b) Rough.



(a) Smooth (b) Rough

Fig. 13. Crack patterns of the ECC ($W/C = 0.60$) overlay system: (a) smooth; (b) rough.

macro cracks at both of the initial notches in the overlay system are found in Fig. 12(b) and one macro crack at the center of the overlay system is observed in Fig. 13(b). In fact, it is clear from Table 5 that the interface crack length in the smooth surface overlay system is about 3 times larger than that of the rough surface system. Presumably, the higher interface fracture toughness of the rough surface system makes it difficult to develop the interface crack. This forces the kinked microcrack to develop into a fracture, albeit only after much damage development in the ECC, as is expected in such strain-hardening material. In the ECC overlay system with smooth surface however, the kink-crack is arrested when the energetics favors interface defect to propagate along the interface. This preference is aided by a lower interface toughness associated with the "smooth surface" specimens. Hence the smooth surface specimen was able to redistribute the load and utilize more materials than the rough surface specimens to resist the final failure.

Also, the crack width in the smooth surface specimen is much smaller than the rough surface specimen at the peak load (see Fig. 12). Crack width is a very important parameter in concrete structures because it is related to the water and gas flow rates. So, if crack width is smaller, the reduction of water or gas penetration can considerably decrease corrosion rate of reinforcing bars in repaired concrete structures. Hence, the reduction of crack width in the ECC overlay systems with smooth surface is preferable to providing a more durable repair than the rough surface overlay system.

3.3. Influence of water/cement ratio of ECC

As seen from Fig. 6 and Table 4, the peak load in the ECC overlay system with $W/C = 0.28$ is about 2 times higher than that with $W/C = 0.60$, although, the deflection at peak load in the system with $W/C = 0.60$ is slightly higher. In this experiment, the peak load in the ECC ($W/C = 0.60$) overlay system coincides with that of the concrete overlay system, but the deflection at peak load is about 8 times larger in the ECC system than the concrete system.

The most significant differences in external appearance after testing between the ECC overlay system with $W/C = 0.28$ and the ECC overlay system with $W/C = 0.60$ are the crack number and the crack intervals.

Table 5
Interface crack length

Repair material	Surface	IFC length 1[a] (mm)	IFC length 2[a] (mm)	IFC length total (mm)	IFC length average (mm)
ECC ($W/C = 0.28$)	Smooth	0.00	0.00	0.00	1.87
		2.00	1.14	3.14	
		0.37	2.07	2.44	
		1.38	0.51	1.89	
	Rough	0.00	0.00	0.00	0.60
		0.00	0.00	0.00	
		0.18	0.00	1.06	
		0.08	0.00	1.35	
ECC ($W/C = 0.60$)	Smooth	0.00	0.00	0.00	0.94
		0.92	0.19	1.11	
		0.57	1.71	2.28	
		0.00	0.38	0.38	
	Rough	0.00	0.00	0.00	0.25
		0.00	0.14	0.14	
		0.00	0.85	0.85	
		0.00	0.00	0.00	

[a] IFC length 1 and IFC length 2 were measured at both sides of the center notch separately.

More multiple cracks are observed in the case of $W/C = 0.60$, with much closer spacing. The interface crack length for the overlay system with ECC ($W/C = 0.28$) is generally larger (about twice) than that for the system with ECC ($W/C = 0.60$) (Table 5), for the same surface preparation. These observations are consistent with expected multiple cracking behavior in ECCs having lower first crack and ultimate tensile strength as the W/C ratio increases.

4. Conclusions

From this series of experiments, the following conclusions can be drawn:

1. The excellent performance of the ECC overlay system that is based on kink-crack trapping mechanism was reconfirmed in this experiment.
2. No differences were revealed between smooth surface and rough surface for both the concrete overlay system and the SFRC overlay system. However, in the ECC overlay system, the smooth surface system showed more desirable performance in the crack pattern and the crack widths than the rough surface system. This means that the smooth surface system is preferred over the rough surface system to obtain durable repair structure. This is contrary to typical approach in surface preparation when concrete is used as the repair material in concrete patch repair.
3. While a higher W/C ratio in the ECC leads to multiple cracking with closer spacing, the repaired system strength is correspondingly reduced, and the overall deflection capacity remains basically unchanged. The current ECC composition with W/C about 0.28 appears to provide the best result when used as a repair material.

The results of this study, suggest that the interface characteristics between ECC repair material and the substrate concrete is important in controlling the behavior of the overall repaired system behavior. The unique behavior of kink-crack trapping which deters the common failure modes of delamination or spalling in common repaired systems is best revealed when the substrate concrete is prepared to have a smooth surface prior to repair. This is in contrast to the standard approach when the substrate concrete is deliberately roughened to create better bonding to the new concrete. It is thought that a rough surface of the substrate concrete leads to a higher interface toughness which excessively delay interface crack propagation forcing the first kink-crack to eventually localize into a fracture in the ECC repair material (Fig. 12(b)). However, quantification of these concepts requires the measurement of the toughness of the ECC/concrete interfaces with the two types of surface preparation, beyond the scope of this study.

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