Title no. 101-M05

Mechanical Performance of Sprayed Engineered Cementitious Composite Using Wet-Mix Shotcreting Process for Repair Applications

by Yun Yong Kim, Gregor Fischer, Yun Mook Lim, and Victor C. Li

This paper presents an experimental study on the fundamental performances of a sprayed engineered cementitious composite (ECC) in repair systems. ECC serving as a repair material has been expected to be highly effective in providing durable repaired structures because of the tight crack width control and high delamination resistance. For this study, a polyvinyl alcohol (PVA) fiber-reinforced ECC (PVA-ECC) that exhibits suitable properties for wet-mix shotcreting in the fresh state and strain-hardening behavior in the hardened state was sprayed and tested. The experimental results show that the sprayed ECC exhibits strain-hardening behavior with strain capacities comparable with the cast ECC with the same mixture proportion. It is also revealed that when sprayed ECC is used as a repair material, both load-carrying capacity and ductility represented by deformation capacity at peak load of repaired beams in flexure are obviously increased in comparison with those of commercial prepackaged mortar (PM) repaired beams. The significant enhancement of energy absorption capacity and tight crack width control in ECC repair systems using a wet-mix shotcreting process suggests that sprayed ECC can be effective in extending the service life of rehabilitated infrastructures.

Keywords: cementitious; concrete; crack; deformation; durability; repair; strain; wet-mix shotcrete.

INTRODUCTION

Engineered cementitious composite (ECC) is a high-performance fiber-reinforced cementitious composite designed with micromechanical principles. Micromechanics allows optimization of the composite for high performance represented by extreme tensile strain capacity while minimizing the amount of reinforcing fibers, typically less than 2% by volume V_f. A variety of applications of this material ranging from repair and retrofit of structures, cast-in-place structures to precast structural elements requiring high ductility, are being developed.[1,2] The use of ECC as a repair material has been proposed by Lim and Li,[3] Kamada and Li,[4] and Zhang and Li.[5] Their works revealed that superior tensile ductility of ECC material appeared to provide significant enhancement of the performance of repaired structural systems resulting in tight crack width control and high delamination resistance.

The potential advantage of using ECC as a repair material is further demonstrated in a numerical study by Lim et al.[6] In that work, the flexural performance of a repaired system with high ductility such as ECC showed improvement of post-peak behavior and total energy absorption compared with that of high-strength repair material with low ductility. Also, the crack width on the tensile surface and the stress distribution along the reinforcement in a flexural member were found to be dramatically reduced in the repair system with ECC. These advantages should lead to enhanced durability of repaired structure systems.

High ductility has been achieved with some fiber-reinforced concrete (FRC) that uses a large amount of fibers. As the fiber content exceeds a certain value, typically 4 to 10% depending on fiber type, matrix composition, and interfacial properties, the conventional FRC may exhibit moderate strain-hardening behavior. The high volume fraction of fiber, however, results in a considerable workability problem. Fiber dispersion becomes difficult because of the high viscosity of the mixture due to the presence of a high surface area of the fibers and the mechanical interaction between the fibers, along with the difficulties in handling and placing. In spraying FRC using a wet-mix shotcreting process, the material has to be conveyed through the pump and hose. High fiber content can lead to high internal friction during conveyance and can require excessive pumping pressure. Thus, the implementation in construction site, particularly by wet-mix shotcreting of such high fiber content FRC, has not been successful due to lack of processibility. It is well known that it is almost impossible to pump and shoot most synthetic fibers available on the market at fiber addition rates in excess of 1.0% in terms of fiber volume fraction. It was also demonstrated by the authors that increasing the fiber volume fraction is significantly detrimental to achieving the desired pumpability.[7]

To overcome the shortcomings of both fresh and hardened properties of fiber-reinforced shotcrete, the authors have developed a new class of ECC suitable for wet-mix shotcreting, which can be defined as the ECC conveyed through a hose and pneumatically projected at high velocity from a nozzle onto a surface. The rheological properties of the ECC in the wet-mix shotcreting are obviously critical from mixing through placing and prior to hardening. These properties were shown to be controllable for wet-mix shotcreting by the authors in a previous paper.[7] Sprayed layer thicknesses of 45 mm on the vertical surface and 25 mm on the overhead surface were obtained.

Wet-mix shotcrete application has a number of advantages over cast, hand-applied, and dry-mix shotcrete applications, including the reduction or elimination of formwork, faster and more efficient construction, and elimination of environmental

ACI Materials Journal, V. 101, No. 1, January-February 2004.
MS No. 02-473 received December 11, 2002, and reviewed under Institute publication policies. Pertinent discussion including authors' closure, if any, will be published in the November-December 2004 *ACI Materials Journal* if the discussion is received by August 1, 2004.

Yun Yong Kim *is a research assistant professor in the Department of Civil and Environmental Engineering at the Korea Advanced Institute of Science and Technology, Daejeon, Korea, where he received his PhD. His research interests include the design of fiber-reinforced cementitious composites and their structural applications, including repair and retrofit of infrastructures.*

Gregor Fischer *is an assistant professor in the Department of Civil and Environmental Engineering at the University of Hawaii, Honolulu, Hawaii. He received his PhD from the University of Michigan. His research interests include the material design and structural applications of fiber-reinforced cementitious composites and the durability and repair of infrastructures.*

Yun Mook Lim *is an associate professor in the Department of Civil and Environmental Engineering and Vice Director of the Applied Mechanics Lab at Yonsei University, Seoul, Korea. His research interests include rehabilitation of aged infrastructures based on interfacial fracture concept with the simulation of failure mechanisms and numerical analysis of rate dependency in structural level.*

ACI member **Victor C. Li** *is a professor in the Department of Civil and Environmental Engineering at the University of Michigan. He is a member of ACI Committee 544, Fiber Reinforced Concrete. His research interests include the design of ultra-ductile cementitious composites, their application to innovative infrastructure systems, and material ductility-based durable repair and retrofit.*

problem associated with heavy dust resulting from dry-mix shotcreting. Thus, the application of ECC to a wet-mix shotcreting process is regarded as beneficial for the repair of infrastructures, such as bridges, culverts, underground structures, and other aged structures. For the success of remedial work, the hardened properties of sprayed ECC using a wet-mix shotcreting process are as important as the rheological properties of ECC fresh mix. In addition, the interaction between the substrate concrete and the repair ECC is also critical so that a durable and long-lasting repair can be obtained. Mechanical properties of sprayed ECC was presented by Kanda et al.[8] In their study, it was shown that sprayed ECC exhibits comparable tensile and flexural properties with those of cast ECC.

The purpose of this article is to demonstrate the potential enhancement of durability of repaired infrastructures by the use of an ECC sprayed using a wet-mix shotcreting process as well as to illustrate the mechanical advantages of sprayed ECC over current repair materials. To assess mechanical superiority, uniaxial tensile and flexural tests were carried out and the results were compared with those of cast ECC and other commercially available prepackaged shotcreting mortars (PMs) typically used in repair works. The repair performance was evaluated by employing two kinds of ECC/concrete composite beams sawn from ECC/concrete composite panels produced by shotcreting ECC onto a concrete substrate. The test results were compared with those of PM/concrete composite beams.

RESEARCH SIGNIFICANCE

In this study, the hardened performance of the ECC sprayed using the wet-mix shotcreting process, which was designed on the basis of parallel control methodology, is evaluated and compared with those of current sprayed repair mortars. Specifically, the significance of this investigation lies in the improved performance of repair material and repair system made with the sprayed ECC in terms of tight crack width, tensile ductility, energy absorption capacity, and delamination resistance. The rehabilitation of infrastructures is expected to benefit from the use of ECC as a repair material due to the potential enhancement of durability in the ECC repair system using a wet-mix shotcreting process.

Table 1—Mixture proportion of ECC suitable for wet-mix shotcreting

C	W	S	FA	HPMC	HRW	CA	V_f
0.95	0.46	0.80	0.30	0.0005	0.0075	0.05	0.02

Note: C = cement; W = water; S = sand; FA = fly ash; HPMC = hydroxypropylmethylcellulose; HRW = high-range water-reducing admixture; CA = calcium aluminate cement; and V_f = fiber volume fraction. All numbers are mass ratios except V_f.

Table 2—Properties of PVA fiber used in ECC material

Diameter, μm	Length, mm	Nominal strength, MPa	Elongation, %	Oiling agent content, %	Young's modulus, GPa
39	8	1620	6	0.8	42.8

DESIGN OF ECC SUITABLE FOR WET-MIX SHOTCRETING

Based on the parallel control of micromechanical design and rheological process design,[7] the mixture proportion of ECC suitable for wet-mix shotcreting was optimized as given in Table 1. The water-cement ratio (*w/c*) of 0.46, *s/c* ratio of 0.8, and an oiling agent content of 0.8% for fiber coating were employed to obtain a matrix and fiber/matrix interface suitable for achieving strain-hardening behavior and robust composite performance. Given the fiber diameter (d_f = 39 μm) and fiber volume fraction (V_f = 2.0%, 26 kg per 1 m^3 ECC), the fiber length chosen was 8 mm based on pumpability in the fresh state and fiber/matrix interfacial properties in the hardened state. Fly ash (FA) particles (FA/C = 0.3) with a comparable size with cement particles were introduced to enhance the viscosity with the increase of total solid concentration.

To create a two-stage rheological property, that is, moderate pumpability during the pumping and conveyance stage, and coherence and adherence after placing onto the surface of the substrates, dosages of hydroxypropylmethylcellulose (HPMC, 0.05%), high-range water-reducing admixture (HRW) (0.75%) and calcium aluminate cement (CA) (5%) were adjusted by rheological process design. The fresh performance of ECC suitable for wet-mix shotcreting was also accomplished by employing the appropriate mixing procedure. First, dry ingredients, that is, cement, FA, and silica sand were mixed. Then water was added to form the basic mortar matrix. The HRW solution was added prior to the addition of polyvinyl alcohol (PVA) fibers to ensure fiber dispersion. In the last step, HPMC and CA particles were added to increase the viscosity of cement suspension and to achieve accelerated setting, respectively.

MATERIALS

ECC

PVA fiber, tailored based on micromechanical principles,[9] is adopted in the present study. The fiber properties are listed in Table 2. ASTM Type 1 ordinary portland cement (OPC) (average particle diameter = 11.7 ± 6.8 μm), silica sand (average particle diameter = 110 ± 14.8 μm), FA (average particle diameter = 26.9 ± 7.0 μm), and CA (average particle diameter = 5.5 ± 1.5 μm) were used as the major ingredients in the matrix. All of the cementitious raw materials were used as received. HRW and HPMC were used as chemical admixtures.

Prepackaged mortars (PMs)

There are several hundred commercially available shotcreting mortars for repair work that can be categorized into a few generic types.[10] Of these, the most widely used type is

Fig. 1—Wet-mix shotcreting process of ECC.

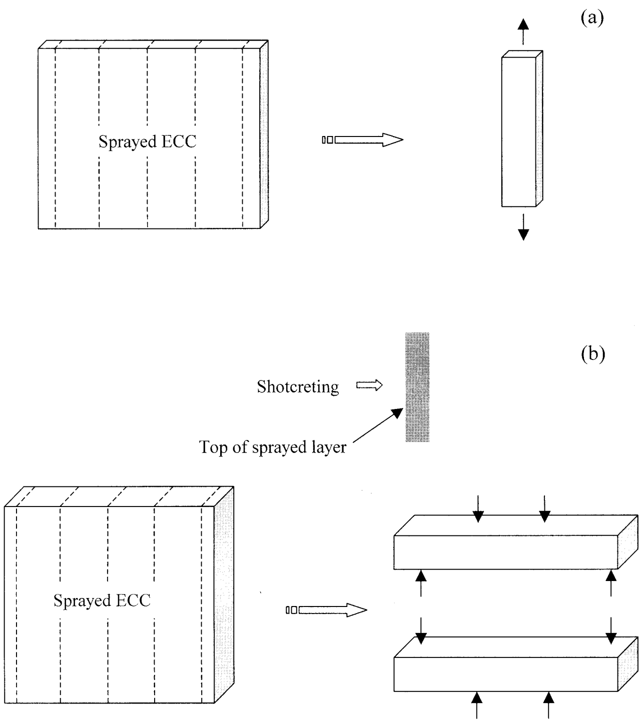

Fig. 2—(a) Tensile coupon (305 x 76 x 13 mm); and (b) beam specimens (356 x 76 x 51 mm), sawn from sprayed ECC panels.

OPC/sand shotcreting mortar. As a reference material for ECC, two kinds of OPC/sand PMs were used in this investigation. One (PM-1) is a kind of polymer-modified mortar for wet and dry shotcreting. The other (PM-2) is a kind of synthetic fiber-reinforced shotcreting mortar with silica fume. The details of these products, however, are not available due to the proprietary nature of their formulations.

SPECIMEN PREPARATION

Shotcreting process system

For the preparation of the fresh ECC mixture, a 40 L capacity drum mixer was used. The PMs were also mixed in the drum mixer according to the manufacturers' instructions with 2.7 to 3.4 L of water per 25 kg bag of dry material and a mixing time of approximately 4 min. An N2V spiral pump

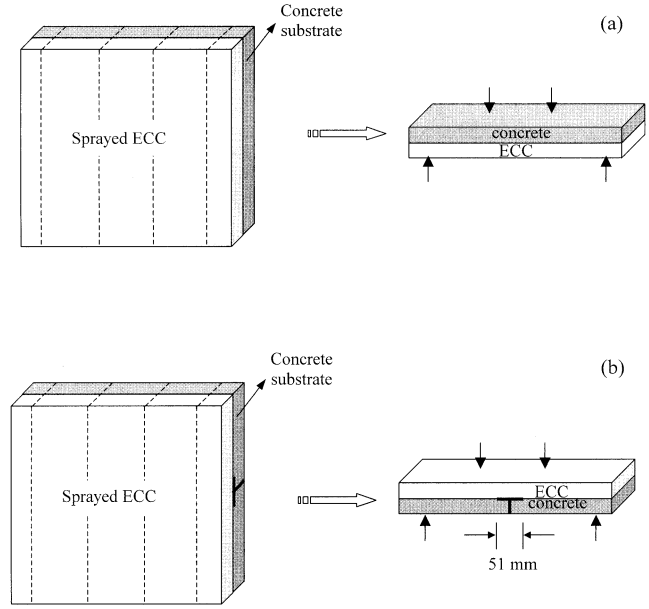

Fig. 3—(a) Composite beam (356 x 76 x 51 mm) sawn from repaired composite panel; and (b) composite beam (356 x 76 x 51 mm) sawn from repaired composite panel with initial cracks introduced in substrate and interface.

was used for the wet-mix shotcreting process in this study. This system was known to be particularly suitable for premixed liquids and mortar with the maximum grain size of 3 mm. Fresh ECC and PMs were pumped through this spiral pump and then down a 25 mm-diameter rubber hose to a spray gun, from where it was sprayed pneumatically with an air pressure of approximately 700 kPa onto a substrate, as illustrated in Fig. 1.

Test specimens

All ECC panels were sprayed in wood molds positioned vertically during shotcreting. In Fig. 2(a) and (b), two panels were sprayed for the determination of tensile and flexural performances. Another two panels containing a concrete substrate (Fig. 3(a) and (b)) were sprayed to produce repaired composites. Care was taken to ensure that the surfaces of sprayed panels were properly finished without any excessive consolidation. All sprayed ECC panels were decoded 1 day after shotcreting and then cured in air. PMs were also sprayed into the same molds that were used for ECC panels. The shotcreting process of PM-2 was interrupted due to the excess pumping pressure. Subsequently, PM-2 panels had to be cast. PM panels were cured in water. All the panels were sawn into test specimens approximately 5 days after shotcreting (or casting).

Additional ECC specimens were prepared by casting into 305 x 76 x 13 mm tensile coupon molds and 356 x 76 x 51 mm beam molds for comparison with the specimens sawn from sprayed ECC panels. Cast ECC specimens were also cured in the same manner as sprayed ECC. These specimens were used to investigate the influence of wet-mix shotcreting (versus casting) on the properties of the ECC with the same mixture proportion.

Surface preparation of concrete substrates

In the present investigation, ASTM Type I OPC, natural river sand with an approximate particle size of 0.3 to 4 mm

Table 3—Mixture proportions and compressive strength of substrate concrete

Cement	Sand	Stone	Water	Compressive strength
1.00	1.62	1.62	0.45	42.83 ± 1.90 MPa

and crushed natural stone with maximum particle size 10 mm were used in the substrate concrete panels. The mixture proportions and compressive strength of substrate concrete adopted in this study are given in Table 3.

Before shotcreting process for concrete repair, the deteriorated part of old concrete should be removed by hydro or mechanical method. Then the surfaces of the exposed reinforcing steel and concrete are cleaned by using acceptable methods such as sandblasting. To create a similar surface condition as that for repaired concrete in the field, the surfaces of all concrete substrates were sandblasted after curing in water for 28 days.

EXPERIMENTAL PROGRAM

Density test of sprayed ECC

To assess the quality of the shotcreting process, the hardened densities of the ECC cubes sawn from sprayed ECC panels were measured and compared with those of cast ECC. The hardened densities of the ECC cubes ρ_{ECC} were calculated by measuring their weight in air $W_{ECC,\ in\ AIR}$ and in water $W_{ECC,\ in\ WATER}$. The cubes were tested at 28 days in a water-saturated state with the excess water wiped from surfaces

$$\rho_{ECC} = \frac{W_{ECC,\ in\ AIR}}{W_{ECC,\ in\ AIR} - W_{ECC,\ inWATER}} \times \rho_w \qquad (1)$$

where ρ_w is the density of water assumed to be 1000 kg/m^3. During sampling, panel edges were discarded to ensure that the effects of finishing and mold surfaces were removed. The cast ECC cubes were also prepared in the same manner for comparison.

Mechanical tests of sprayed ECC

To verify the strain-hardening behavior of the sprayed ECC using the wet-mix shotcreting process and to compare it with the test results of PMs and cast ECC coupons, a series of direct tensile tests were performed using an MTS 810 load frame. The specimens were loaded with a constant cross head speed, and the loading force and deflections were measured. Two linear variable differential transducers (LVDTs) attached to both sides of the center of the tensile coupon with a gage length of 180 mm were used for monitoring the deflection. In addition to the tensile stress-strain curves, the first crack strength, ultimate tensile strength, and ultimate tensile strain were measured.

The flexural tests were carried out at 28 days under four-point bending in the same MTS testing machine. The specimens were loaded to complete failure with a constant cross head speed (0.01 mm/s). The load, head displacement of the machine and deflection of the beams at the midpoint were recorded in each test. The beams of 76 x 51 mm cross section and 356 mm length sawn from sprayed panels were employed. The top of the sprayed layers may be orientated as the tensile or compressive face in repaired members. To reflect such a different loading direction, two beams were tested with the top of the beam as tensile face, and the other two beams were tested turned upside down, as shown in Fig. 2(b).

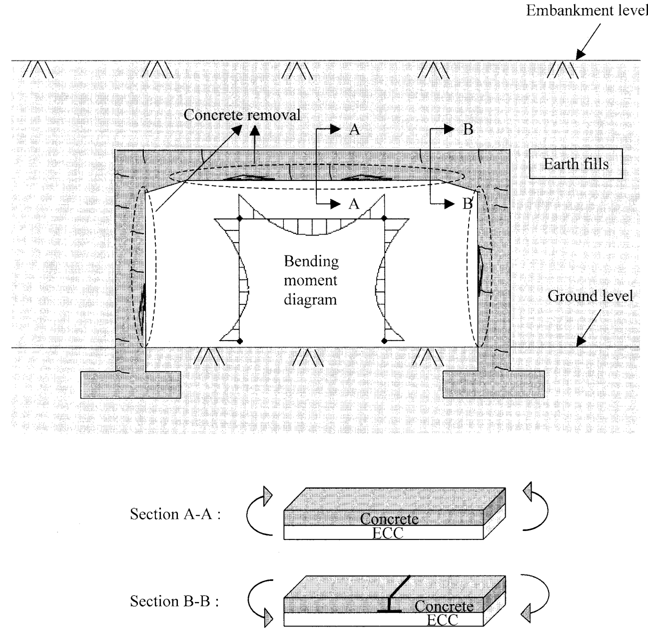

Fig. 4—Conceptual illustration of potential crack and damage pattern developed in plane of cross section of culvert and possible loading on composite members after repair work.

For comparison, cast ECC beams as well as PM beams were tested.

Flexural test of sprayed ECC/concrete composite

As mentioned in the previous section on the surface preparation of concrete substrates, the deteriorated part of old concrete, caused by external load, freezing and thawing, chemical attack, carbonation, and incompatible deformation should be removed before repair work. Concrete removal might be limited to the accessible inner part of structures, however, when an underground structure such as a culvert is repaired. Considering the member forces in the plane of cross section, Fig. 4 illustrates the possible cracks in the tensile faces of these members. Further deterioration may result from exposure to environmental loading. Supposing the repair of inner parts, the midspans of the wall and slab will be properly repaired (Section A-A in Fig. 4), while some main cracks may still remain in outer faces in contact with earth fills. In addition, due to the difference in deformation behavior between the new-sprayed layer and the substrate concrete, delamination along the interface between two material layers, starting from the existing cracks, may take place (Section B-B in Fig. 4).

To simulate these different repair conditions, two kinds of ECC/concrete composite beams of 356 x 76 x 51 mm were employed. The first type of composite beam represents a composite beam without any initial cracks in substrate concrete and interface (Fig. 3(a)). The second type includes a vertical crack introduced in the old concrete substrate and an initial interfacial crack of 51 mm length in the center of the beam (Fig. 3(b)). The resistance against delamination failure and spall resistance of the sprayed ECC can also be evaluated with these beams. The previous studies[4,5] on ECC repair with existing cracks indicated that the smooth surface of the substrate exhibited improved flexural performances, compared with the rough sandblasted surface. This is because the smooth interface allows extension of the delaminated length

Table 4—ECC density at 28 days

	Measured density (water-saturated), kg/m^3	Average density, kg/m^3
Sprayed ECC	2094, 2096, 2086, 2096	2093 ± 5
Cast ECC	2070, 2068, 2066, 2063	2067 ± 3

Table 5—Results of uniaxial tensile tests

		First crack strength, MPa	Ultimate strength, MPa	Ultimate strain, %
7 days	Sprayed ECC	3.07 ± 0.06	4.21 ± 0.04	2.15 ± 0.38
	Cast ECC	3.03 ± 0.42	4.08 ± 0.12	2.43 ± 0.58
14 days	Sprayed ECC	3.29 ± 0.25	4.47 ± 0.23	1.60 ± 0.19
	Cast ECC	3.20 ± 0.19	4.49 ± 0.11	1.76 ± 0.20
28 days	Sprayed ECC	3.21 ± 0.10	4.41 ± 0.23	1.63 ± 0.26
	Cast ECC	3.33 ± 0.15	4.39 ± 0.18	1.71 ± 0.54
	PM-1	2.85 ± 0.65	2.85 ± 0.65	0.030 ± 0.008
	PM-2	2.73 ± 0.50	2.73 ± 0.50	0.029 ± 0.005

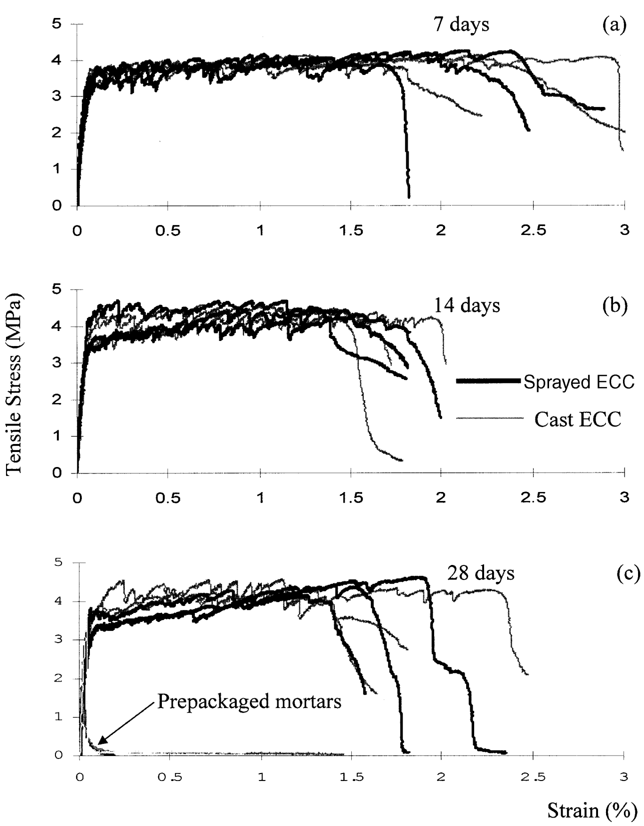

Fig. 5—Uniaxial tensile stress versus strain curves for: (a) ECC at 7 days; (b) ECC at 14 days; and (c) ECC at 28 days.

along the interface, associated with a kink-crack trapping mechanism,[3] thus allowing the multiple cracking zone to extend in ECC repair layer. The surfaces of all concrete substrates in the present test series, however, were sandblasted to make the surface condition similar to in-place repaired concrete. All the tests were carried out at 28 days under four-point bending load applied to the beams sawn from the composite panels produced by shotcreting or casting repair material onto concrete substrate.

RESULTS AND DISCUSSION

Density of sprayed ECC

Table 4 presents the hardened densities of sprayed and cast ECC cubes calculated by measuring weight in a water-saturated state. Sprayed cubes show the densities (2093 ± 5 kg/m^3) slightly higher than those (2067 ± 3 kg/m^3) of ECC cast with external consolidation. It is most likely due to the pneumatic compaction associated with the wet-mix shotcreting process. These test results reflect that ECC was successfully processed by wet-mix shotcreting. Subsequently, it can exhibit mechanical performances consistent with cast ECC. Such a trend was also found in other work on sprayed mortars by Austin, Robins, and Goodier.[11]

Tensile performance of sprayed ECC

Uniaxial tensile tests were performed on sprayed and cast coupons of ECC and PMs to confirm the ductile strain-hardening performance of the sprayed ECC. The test results in terms of first crack strength, ultimate strength, and ultimate strain at the peak stress are displayed in Table 5, and the stress-strain curves are presented in Fig. 5. A significant difference in ultimate strain was observed for the ECC composites and the PMs, as compared in Fig. 5(c). All ECC specimens show strain-hardening behavior with strain capacities from 1.5 to nearly 3.0%, which are estimated to be from 50 to 100 times the ductility of PM-1 (0.030%) and PM-2 (0.029%). The average first crack strengths vary from 3.0 to 3.5 MPa, which are higher than the tensile strengths of PM-1 and PM-2. After first cracking, the load continues to rise accompanied by multiple cracking, which contributes to the inelastic strain as stress increases. The large number of microcracks has very fine crack spacing and small average crack width (30 μm). In contrast, a single crack that continuously opens while stress decreases was observed in prepackaged mortars PM-1 and PM-2. After the peak stress is reached, the localized crack leads to the brittle failure of the composites, although PM-2 shows a longer tail compared with PM-1 due to the pull-out mechanism of fibers at the localized crack.

The ductility and tensile strength of the sprayed ECC is comparable with that of ECC specimens cast with external consolidation. Such consistent material property is likely due to the sufficient compaction during the shotcreting process, as discussed in the previous section on density. It was reconfirmed that the ECC was properly processed by wet-mix shotcreting.

The strain capacities at 7 days were found to be significantly greater than those at 14 days, while those at 14 days were almost the same as the values at 28 days. This can be explained by tensile first crack strength σ_{fc} and matrix toughness K_m. According to micromechanical principles,[12] the satisfaction of two conditions is necessary to achieve strain-hardening behavior. First the crack tip toughness J_{tip} (K_m/E_c, E_c: composite elastic modulus) should be less than the complementary energy J_b' calculated from the bridging stress σ versus crack opening δ curve

$$J_{tip} \le \sigma_o\delta_o - \int_0^{\delta_o} \sigma(\delta)\,d\delta \equiv J_b' \qquad (2)$$

where σ_o is the maximum bridging stress corresponding to the opening δ_o. Second, the tensile first crack strength σ_{fc} must not exceed the maximum bridging stress σ_o

Table 6—Results of flexural tests at 28 days

		Flexural strength (MOR), MPa	Ultimate deflection, mm	Ratio of MOR to tensile first crack strength
Sprayed ECC	Total	11.12 ± 0.78	3.65 ± 1.34	3.5
	Top—tension*	11.15 ± 1.20	3.85 ± 1.89	
	Top—compression†	11.08 ± 0.61	3.45 ± 1.29	
Cast ECC		10.63 ± 0.57	3.60 ± 0.98	3.1
PM-1		5.70 ± 1.15	0.25 ± 0.04	2.0
PM-2		4.35 ± 0.26	0.25 ± 0.03	1.6

*Beams orientated with top of sprayed layer as tensile face.
†Beams orientated with top of sprayed layer as compressive face.

$$\sigma_{fc} < \sigma_o \quad (3)$$

where σ_{fc} is determined by the maximum preexisting flaw size max a_o and the matrix fracture toughness K_m. Lower tensile first crack strength and lower matrix toughness might, therefore, be favorable for strain-hardening behavior. The first crack strengths at 14 days were higher than those at 7 days due to the continuing hydration process. In contrast, the first crack strengths at 14 days and 28 days possess almost the same values. It is most likely due to much slower development of matrix toughness and strength with respect to age after 14 days.

Flexural performance of sprayed ECC

The test results in terms of flexural strength (MOR), ultimate deflection at the peak stress, and strength ratio are displayed in Table 6, and the flexural stress-deflection curves of the sprayed ECC are compared with those for two PMs in Fig. 6. The flexural stress represents the maximum tensile stress at the bottom fiber of the beams. For the PMs, the flexural stress increases rapidly to the peak point and then suddenly drops with an average ultimate deflection up to 0.25 mm. For the ECC, in contrast, the flexural stress increases at a slower rate along with the development of multiple cracks, wherein the average ultimate deflection of sprayed ECC beams at the peak stress was achieved to be as much as 3.65 mm within the error range. The flexural strength for the ECC was determined to be 11.12 MPa, which was much higher than the MORs of PM-1 (5.70 MPa) and PM-2 (4.35 MPa). Although flexural toughness has not been measured for the ECC, it is expected to be much higher than that of PMs based on the area under flexural stress-deflection diagrams. As illustrated in Fig. 6(b), the beam deflection at peak stress and MOR of the sprayed ECC is comparable with those of cast ECC beams.

The cracking pattern of the ECC beams is also distinctly different from PMs. The first crack started inside the midspan at the tensile face, and multiple cracks developed from the first cracking point and spread. As the MOR is approached, one of the cracks inside the midspan started to open up.

For ideally brittle material, the ratio of MOR to tensile strength (at first cracking) is unity. For quasibrittle material such as concrete or PMs, this ratio lies between 1 and 3. The upper limit describes the case of an elastic, perfectly plastic material. For the case of ECC, this ratio can be expected to be higher than 3 due to the pseudo-strain-hardening nature after first crack.[13] As shown in Table 6, this expectation is confirmed by the test results that show the ratio is equal to 3.5 for the sprayed ECC, compared with about 1.8 for the PMs.

Table 7—Results of flexural tests on repaired composite beams at 28 days

		Flexural strength, MPa	Ultimate deflection, mm
Top—tension*	ECC	12.03 ± 0.40	3.28 ± 0.97
	PM-1	5.69 ± 0.52	0.32 ± 0.01
	PM-2	5.07 ± 0.10	0.24 ± 0.02
Top—compression†	ECC	11.97 ± 1.19	2.94 ± 0.70
	PM-1	6.02 ± 0.27	0.25 ± 0.01
	PM-2	5.12 ± 0.10	0.23 ± 0.01

*Beams orientated with top of repair materials as tensile face.
†Beams orientated with top of repair materials as compressive face with initial cracks introduced in substrate and interface.

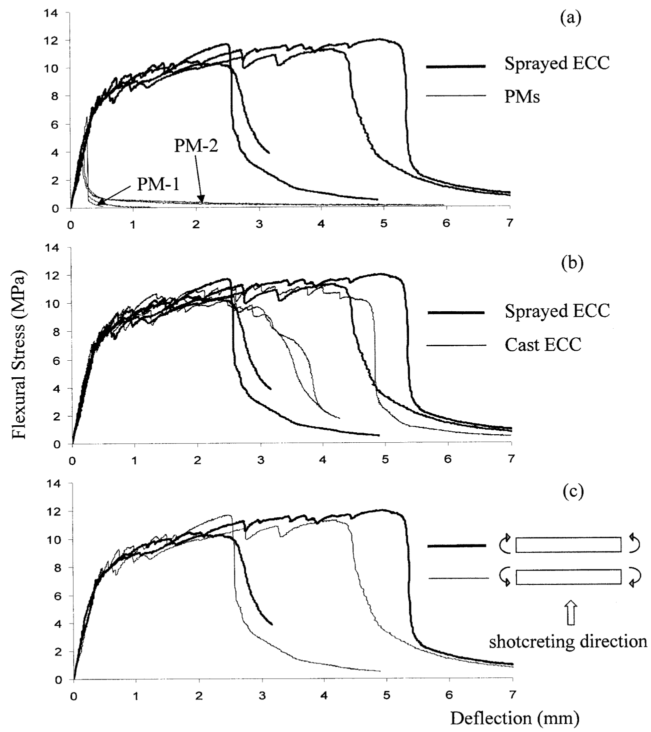

Fig. 6—Flexural stress versus deflection curves at 28 days for (a) sprayed ECC and PMs; (b) sprayed ECC and corresponding cast ECC; and (c) sprayed ECC with different loading directions.

As described in the previous section on the experimental program of flexural test, the top of the sprayed layers can be orientated as tensile or compressive face in a repaired member. Thus, it is important to note that no significant difference was exhibited in the flexural behavior between beams employing the top of sprayed panel as tensile face and compressive face (Fig. 6(c)). It indicates that sprayed ECC exhibits consistent flexural behavior despite the opposite loading direction.

Flexural performance of sprayed ECC/concrete composite

The flexural behavior of the composite beams is presented in Fig. 7 in terms of flexural stress and midpoint deflection curves. The corresponding flexural strength and the ultimate deflection at the peak stress are listed in Table 7. Two kinds of composite beams, which are repaired beams with or without initial cracks in substrate and interface, were tested.

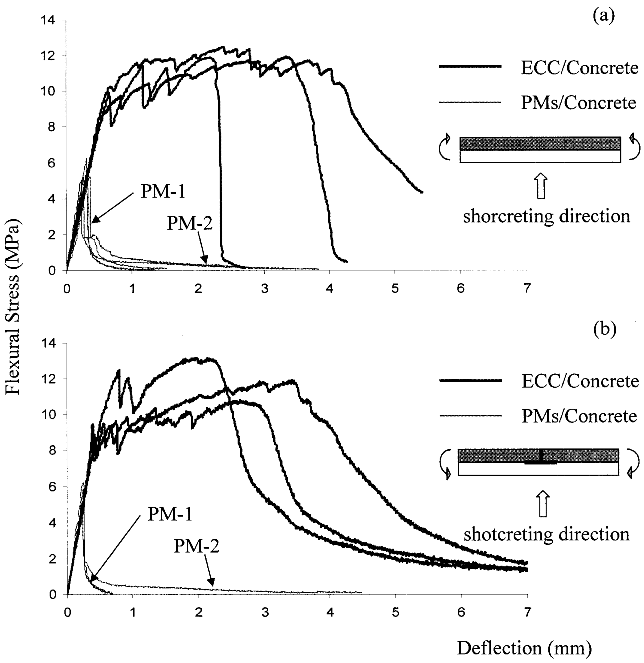

Fig. 7—Flexural stress versus deflection curves of repaired composite beams at 28 days for: (a) beams orientated with top of repair materials as tensile face; and (b) beams orientated with top of repair materials as compressive face with vertical crack introduced in old concrete substrate and initial interfacial crack.

For the composite beam without any initial cracks, the flexural stress represents the maximum tensile stress at the bottom fiber of the repaired composites (Fig. 7(a)). The flexural stress of the composite beam with initial cracks is the maximum tensile stress at the base of the sprayed layer above the initial cracks (Fig. 7(b)), where the depth of the sprayed layer was used for the depth of composite beams because there was no load transferred through the vertical initial cracks in old concrete.

The ECC/concrete composite beam without initial cracks (Fig. 7(a)) also exhibited multiple cracking in the ECC tensile face. As failure is approached, one crack started to develop at the base of the concrete layer, and then the localized crack was connected to one of the multiple cracks in ECC. This linked crack led to final failure with an average ultimate deflection of 3.28 mm, which is more than 10 times larger than that of PM-1/concrete (0.32 mm) and PM-2/concrete (0.24 mm) composites. In contrast, a single localized crack leads to the failure of PM/concrete composite beam with a sudden drop of flexural stress after the first peak stress. The deformation capacity might be more crucial than the strength capacity, especially for infrastructures such as bridges and culverts subjected to traffic loads. Moreover, the deteriorations in many infrastructures can be caused by uneven deflection or imposed straining. The remarkable improvement of deflection capacity in the ECC repair system can provide desirable serviceability without any major failure.

Sprayed ECC/concrete composites show an average flexural strength of 12.03 MPa, which is estimated to be more than twice the strength of PM-1/concrete (5.69 MPa) and PM-2/concrete (5.07 MPa) composites. The energy absorption capacity (the area under the flexural stress versus deflection diagram in Fig. 7(a)) in the ECC repair system is also significantly improved compared with the PM repair systems. All the failures of composite beams were caused not by delamination but by the localized cracking in concrete. This means that the interface bond between the substrate concrete and the sprayed ECC was adequate to ensure composite behavior of composite beams. This desired interfacial performance and the superior energy absorption capacity in the ECC repair system using a wet-mix shotcreting process can contribute to the integrity of repaired infrastructures.

Figure 7(b) illustrates flexural stress-deflection curves of repaired composite beams including a certain delaminated zone along the sprayed layer/concrete interface, starting from the existing crack in substrate concrete. Comparing the overall curves, significant differences between the PM repair system and the ECC repair system with different deformation characteristics can be noted. Similar to the previous test results on composite beams without an initial crack, it is clear that the load-carrying capacity of the composite beams is significantly enhanced by the use of the sprayed ECC in repair system (above 100% of the value of the PM-repaired beam). Moreover, the deformation capacity of the ECC-repaired beam, represented by ultimate midpoint deflection at peak flexural stress, is obviously increased in comparison with those of PM-repaired beams. That is because the delaminated zone in the ECC/concrete interface allows multiple cracking to form at the base of the sprayed ECC layer, while a single cracking leads to the failure of PM-repaired beams. It indicates that the ECC repair system exhibits superior energy absorption capacity, even if the composite beams have an initial delaminated zone due to preexisting defects between the two material layers. Such a significant enhancement of energy absorption capacity in the ECC repair system using a wet-mix shotcreting process can provide a longer life of rehabilitated infrastructures.

CONCLUSIONS

To demonstrate the potential enhancement of durability of repaired infrastructures by the use of ECC sprayed using a wet-mix shotcreting process, flexural tests on ECC/concrete composite beams sawn from ECC/concrete composite panels produced by shotcreting ECC onto concrete substrate were performed. In addition, density, tensile, and flexural properties of sprayed ECC were determined. The following conclusions can be drawn from the current experimental results:

1. The hardened densities of sprayed ECC were measured to be comparable to those of ECC cast with a sufficient external consolidation. It is most likely due to the pneumatic compaction during the shotcreting process. It was demonstrated from these test results that ECC was successfully processed by wet-mix shotcreting;

2. Uniaxial tensile test results revealed strain-hardening behavior of sprayed ECC. Ultimate strain capacities of approximately 1.6% were attained from ECC specimens at 28 days, which are up to 100 times the ductility of commercial PMs. During loading, the crack widths of ECC coupons were tightly controlled with an average of 30 μm. The flexural test results of sprayed ECC showed high MOR and large deflection capacity with a superior energy absorption property compared with PMs. Moreover, consistent flexural behavior was observed for opposite loading direction. It indicates that sprayed ECC can exhibit a ductile behavior in any parts of repaired members;

3. The flexural tests performed on two kinds of composite beams revealed that load-carrying capacity was significantly

enhanced by the use of ECC in the repair by wet-mix shotcreting (above 100% of the value of PM-repaired beam). The deformation capacity of ECC repaired beam, represented by ultimate midpoint deflection at peak flexural stress, was also obviously increased in comparison with those of PM-repaired beams. All composite beams without initial cracks exhibit failures caused by localized fracture in concrete, which means that the interface between the substrate concrete and the sprayed ECC was adequate to ensure composite behavior of composite beams. The ECC/concrete composite beams also possess superior energy absorption capacity, even when the beams have artificially introduced interfacial defects above a concrete crack; and

4. The sufficient interfacial performances and the superior energy absorption capacity in the ECC repair system using wet-mix shotcreting process should contribute to the integrity and durability of repaired infrastructures.

ACKNOWLEDGMENTS

This work was supported by Wonha Construction Co. (Seoul, Korea) to the University of Michigan. Support by the Post-Doctoral Fellowship Program of the Korea Science & Engineering Foundation (KOSEF) is acknowledged.

REFERENCES

1. Li, V. C., "Advances in ECC Research," *Concrete: Material Science to Applications*, SP-206, P. Balaguru, A. Naaman, and W. Weiss, eds., American Concrete Institute, Farmington Hills, Mich., 2002, pp. 373-400.

2. Li, V. C., "Reflections on the Research and Development of Engineered Cementitious Composites (ECC)," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC)—Application and Evaluation (DRFCC-2002)*, Takayama, Japan, Oct. 2002, pp. 1-21.

3. Lim, Y. M., and Li, V. C., "Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites," *Journal of Cement and Concrete Composites*, V. 19, No. 4, 1997, pp. 373-385.

4. Kamada, T., and Li, V. C., "The Effects of Surface Preparation on the Fracture Behavior of ECC/Concrete Repair System," *Journal of Cement and Concrete Composites*, V. 22, No. 6, 2000, pp. 23-431.

5. Zhang, J., and Li, V. C., "Monotonic and Fatigue Performance of Engineered Fiber Reinforced Cementitious Composite in Overlay System with Deflection Cracks," *Journal of Cement and Concrete Research*, V. 32, No. 3, 2002, pp. 415-423.

6. Lim, Y. M.; Kim, M. K.; Kim, J. H. J.; and Shin, S. K., "Is Ductility Important for Repair Applications," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC)—Application and Evaluation (DRFCC-2002)*, Takayama, Japan, Oct. 2002, pp. 199-208.

7. Kim, Y. Y.; Kong, H.-J.; and Li, V. C., "Design of Engineered Cementitious Composite Suitable for Wet-Mixture Shotcreting," *ACI Materials Journal*, V. 100, No. 6, Nov.-Dec. 2003, pp. 511-518.

8. Kanda, T.; Saito, T.; Sakata N.; and Hiraishi, M., "Fundamental Properties of Direct Sprayed ECC," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC)—Application and Evaluation (DRFCC-2002)*, Takayama, Japan, Oct. 2002, pp. 133-142.

9. Li, V. C.; Wu, C.; Wang, S.; Ogawa, A.; and Saito, T., "Interface Tailoring for Strain-Hardening PVA-ECC," *ACI Materials Journal*, V. 99, No. 5, Sept.-Oct. 2002, pp. 463-472.

10. Austin, S. A.; Robins, P. J.; and Goodier, C. I., "The Rheological Performance of Wet-Process Sprayed Mortars," *Magazine of Concrete Research*, V. 51, No. 5, Oct. 1999, pp. 341-352.

11. Austin, S. A.; Robins, P. J.; and Goodier, C. I., "The Performance of Hardened Wet-Process Sprayed Mortars," *Magazine of Concrete Research*, V. 52, No. 3, June 2000, pp. 195-208.

12. Li, V. C., "From Micromechanics to Structural Engineering—The Design of Cementitious Composites for Civil Engineering Applications," *Journal Structural Mechanical Earthquake Engineering*, JSCE, V. 10, No. 2, 1993, pp. 37-48.

13. Maalej, M., and Li, V. C., "Flexural/Tensile Strength Ratio in Engineered Cementitious Composites," *Journal of Materials in Civil Engineering*, ASCE, V. 6, No. 4, Nov. 1994, pp. 513-528.