SHOTCRETING WITH ECC

HOCHDUKTILER SPRITZBETON

Prof. Victor C. **Li**, PH.D. FASCE, FASME, FWIF, University of Michigan, Ann Arbor, Michigan, USA
Gregor **Fischer**, Ph.D., Technical University of Denmark, Lyngby, Denmark
Michael D. **Lepech**, Ph.D. Stanford University, Stanford, California, USA

Engineered Cementitious Composites (ECC) is a new class of high performance fiber reinforced cementitious composite (HPFRCC) which exhibits pseudo-strain hardening ductility in uniaxial tension between 4 % and 5 %, over 400 to 500 times that of ordinary concrete. This high ductility has been leveraged in a number of applications to improve the static load carrying capacity, structural durability, impact resistance, or seismic performance for a number of building and infrastructure systems. This paper summarizes the general performance of ECC, techniques that can be used to spray ECC materials, and the specific performance of a number of sprayed ECC structures.

Engineered Cementitious Composites (ECC) ist eine neue Klasse von Hochleistungsfaserbeton (HPFRCC), welcher ein sogenanntes Pseudoverfestigungsverhalten und Duktilität unter direkter Zugbelastung mit einer Dehnungsfähigkeit von 4% bis 5%, etwa 400 bis 500 größer als in herkömmlichem Beton, aufweist. Diese hohe Duktilität kommt in einer Vielzahl von Anwendungen zur Verbesserung der Festigkeit, Dauerhaftigkeit, Stoßfestigkeit und Erdbebensicherheit von Ingenieurbauwerken und Infrastruktursystemen zum Einsatz. Dieser Beitrag erläutert die allgemeinen Grundlagen und Voraussetzungen für ECC, beschreibt die Entwicklung als ECC-Spritzbeton und stellt abschließend einige Anwendungsbeispiele vor.

1. Introduction

Approaching nearly 100 years of age (first introduced in 1910), shotcrete is now accepted as a reliable, economical, and efficient concrete construction method around the world [1]. As noted by Banthia nearly a decade ago [2], the use of reinforcing fibers in shotcrete has a number of distinct advantages over traditional shotcrete. These include the reduction or elimination of rebar (thereby reducing rebound from rebar impacts while allowing for greater flexibity in slender member design), potential for application in more slender structural shotcrete shapes (vis-a-vis no need for minimum rebar cover), and a potential for faster buildup due to the cohesive effect fibers have on fresh shotcrete (assuming the fibers are not wasted in rebound).

However, these advantages were also accompanied with a number of disadvantages. Due to the high proportion of large aggregate in rebound materials, shotcrete often exhibits higher shrinkage with a potential for increased shrinkage variability within a single application. Fiber reinforced concrete also relies on the random, three dimensional orientation of fibers within the matrix. While a reasonable assumption for cast materials, due to their pneumatic placement, fibers in shotcrete can become aligned in a quasi-two-dimensional pattern resulting in anisotropy, although this can be an advantage in thin members. Additionally, previous researchers have shown that up to 75% of fibers can be lost in rebound, causing great concern over *in situ* material uniformity and structural reliability of sprayed FRC [3].

More recently, work has been carried out to leverage specific strengths of fiber reinforced concrete and mitigate the disadvantages of conventional shotcrete and fiber reinforced shotcrete mentioned previously through new materials design or improved characterization of fiber shotcrete material variability. Such work has focused on the development of new fibers for use in shotcrete which are shaped to reduce fiber rebound [4], characterization of fiber reinforced shotcrete testing standards [5, 6], and determination of fiber reinforced shotcrete structural performance [7] at various maturities [8].

2. US performance requirements for shotcreting and current performance

To provide perspective for the development of sprayable ECC, the current performance requirements and performance characteristics of shotcrete in the United State are briefly reviewed. A number of international standards, building codes, and practical guidelines currently govern the practice of shotcreting. Within the American Concrete Institute's "Guide to Shotcrete" a number of materials guidelines are set forth to ensure quality shotcrete construction. These include the use of ASTM C150 cement, ASTM C33 aggregates (with additional gradation recommendations for shotcrete), and ASTM-compliant deformed steel rebar, welded wire fabric, steel fibers, glass fibers, or synthetic fibers [1]. Such general concrete provisions are in place to provide the same mechanical performance from shotcrete as is expected from cast-in-place concrete.

Aside from these basic material requirements a number of requirements are made on the training and certification of the nozzleman. As noted in the ACI "Guide to Shotcrete",

> "The quality of shotcrete application depends to a large extent on the gun operator and nozzleman, control of mixing water, nozzle velocity, and nozzle technique. In each case, the expertise and experience of the responsible crew member determines the adequacy and quality of operation. [1]"

Recognizing the importance of the individual crew, a number of certifications, guidelines, and references are provided for the training of shotcrete nozzlemen and gun operators. These guidelines focus on spraying and nozzle techniques to effectively reduce rebound, improve consolidation, and manage overspray buildup in formwork corners or projections.

With regard to structural shotcrete, particular attention is paid to the proper encasement of rebar by nozzlemen. To prevent voids and sand pocket shadows, particular recommendations are made for minimum rebar spacing. Specifically in the case of two-curtain reinforcement, the curtain nearest the nozzle must have a minimum bar spacing of 12 diameters in both directions, and the back curtain must have a minimum bar spacing of 6 diameters in both directions [1].

Due to the high amount of rebound, which is primarily comprised of large aggregate, *in situ* shotcrete material is often much richer (i.e. higher cement content) than cast-in-place concrete with an identical initial mix design [1]. Therefore, there is a greater tendency toward shrinkage cracking. To alleviate this, proper curing of structural shotcrete is critical. A continuous wet cure of 7 days with at a minimum temperature above 5°C is recommended.

Noted by its worldwide acceptance, the performance of shotcrete in both non-structural and structural applications has been highly successful. However, a number of shortcomings associated with shotcrete persist, thus hampering even greater acceptance. The strong correlation of overall shotcrete quality with nozzleman and gun operator performance leads to higher variability in the quality of placed shotcrete. As noted, this individual performance can directly affect the volume of rebound, proper encasement of steel reinforcement, and control of shrinkage cracking. Therefore, a new materials solution using sprayable Engineered Cementitious Composites (ECC) that is independent of the quality or training of the shotcrete installation team has been under development and commercialization. Relying on unique mix proportions that exclude large aggregates, polymer fibers that reduce high volume fraction rebound, high material ductility which does not rely on steel reinforcement for tensile strain capacity, and inherent crack control properties which intrinsically limit the durability impact and aesthetic appearance of restrained shrinkage cracking, sprayable ECC has been designed to counteract a number of the remaining shortfalls of both traditional shotcrete and fiber reinforced shotcrete.

3. Sprayable Engineered Cementitious Composites

Engineered Cementitious Composites (ECC) is a specific class of high performance fiber reinforced concrete (HPFRCC) that exhibits high ductility ranging from 1-5 % under uniaxial tension. ECC attains this high ductility through the formation of multiple microcracks with self-controlled crack widths ranging from 20-100 micron. This high ductility and tight crack width is a result of a micromechanical design procedure [9] that suppresses localized fracture phenomena typical in brittle cementitious materials under tensile load. The ultimate tensile strength of ECC ranges from 3-8 MPa, with first cracking occurring at about 80% of ultimate strength. Between first cracking and ultimate tensile strength, ECC undergoes pseudo strain-hardening behavior during which multiple cracking occurs. The effective stiffness of the material at this stage is substantially reduced (> 50 times) from the elastic modulus (15-20 GPa) resulting in a bilinear stress-strain response. The compressive strength of ECC is between 20 MPa and 90 MPa. The property ranges given above reflect the material performance of a number of standard ECC mix designs. Specific versions of ECC have also been developed with special attributes such as lightweight and high early strength. An overview of ECC mechanical and durability properties can be found in Li [10].

To provide increased flexibility, ECC materials with different rheologies have been developed for self-consolidating casting, spraying and extrusion applications. A composition of ECC optimized for wet process shotcreting is shown in Table 1. PVA (poly-vinyl alcohol) fiber with properties shown in Table 2 was used in this composite. As mentioned previously, in most ECC materials coarse aggregates are not used. Instead very fine sand with an average particle size of 110 micron (maximum size of 210 micron) is adopted. The amount of sand is limited to a relatively low level. The binder includes both ordinary Portland cement and Class F flyash, resulting in a w/b ratio of 0.35. The high cement content leads to high autogenous and drying shrinkage that can be overcome by use of expansive cements and/or shrinkage reduction agents. Additionally, the microcracking behavior and ductility of ECC can prevent large shrinkage cracks from forming in restrained structural applications [11].

Table 1: Mix proportions of Sprayable ECC

Mix	C	W	S	FA	HPMC	MFS	CA	V_f
S-3	0.95	0.46	0.80	0.30	0.0005	0.0075	0.05	0.02

(C: cement; W: water; S: sand; FA: fly ash; HPMC: hydroxypropylmethylcellulose; MFS: melamine formaldehyde sulfonate; CA: calcium aluminate cement; V_f: fiber volume fraction) All numbers are weight ratios except for 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

Sprayable ECC requires a fresh rheology very different from cast ECC. A two-stage rheology is preferred: low initial viscosity suitable for pumping at relatively low pressure followed by a rapid increase in viscosity after a designed resting time to achieve material coherence and good adherance to the substrate after the material leaves the nozzle. This two-stage rheology has been designed with careful control of admixtures of high range water reducers (HRWR), thickening agents (HPMC), and calcium aluminate cement [12] as well as through the mixing sequence. The ECC paste can maintain a viscosity below 3 kPa•s for the first ten minutes after mixing, but increases to over 20 kPa•s after twenty minutes. These admixtures and their contents were chosen to minimize conflicting requirements for tensile ductility of ECC that constrains the fresh mix composition.

4. Sprayable performance of ECC

To examine the shotcrete performance of sprayable ECC, fresh ECC mixed in a 40 L-capacity drum mixer was pumped through a 25 mm-diameter rubber hose to a spray gun, from where it was sprayed pneumatically with an air pressure of 700 kPa onto a formwork substrate. A N2V spiral pump designed for pumping mortar with maximum 3 mm aggregate was used.

To characterize the pumpability in terms of pumping pressure, pump-out tests were performed through the open hose without a nozzle. The pumping pressure monitored was found to be less than 1 MPa. For comparison, the pumping pressure for a commercial prepackaged repair mortar with synthetic fibers was found to cause a pressure rise exceeding the maximum 4MPa allowable by the pump equipment manufacturer. This high pumpability of the sprayable ECC mix was due to moderate deformability achieved through stabilization of the particles by admixture control as explained above. Thus the pumpability of sprayable ECC was found to be excellent, despite the relatively high fiber content of 2% by volume.

Sprayability of ECC was assessed with spray-on tests (Figure 1). A 15-minute rest time between mixing and spraying was used. The adhesion of the ECC shotcrete onto concrete and wood surfaces was found to be adequate. Good cohesiveness of the material ingredients was demonstrated. The buildup thickness of 45 mm and 25 mm were attained for spraying vertical surfaces and overhead surfaces respectively in the laboratory, without sloughing. In field applications (see Gifu and Montana demonstrations discussed in Section 7 below), a range of 25 - 75 mm thick ECC layers has been attained.

(a)

(b)

Figure 1: Spray test on vertical surface for (a) spraying sequence onto a vertical surface; (b) 45 mm thick sprayed ECC layer [12].

Unlike traditional or steel fiber reinforced shotcrete, negligible rebound was found in shotcreting with ECC. This low rebound is likely a result of the small sand particle size in the ECC mix. In addition, the synthetic fiber adopted has a relatively low mass given a density about one sixth that of steel. The low bending stiffness of the fiber probably contributes to the low rebound of the fibers as well. The low rebound has been confirmed in field demonstration (see Section 7 below) of sprayable ECC. This unique characteristic of sprayable ECC is important in maintaining consistent mechanical properties of the composite with that of cast ECC since the loss of fiber content can lead to a loss of tensile ductility.

The density of the sprayed ECC was found to be 2093±5 kg/m^3, very similar to the 2067±3 kg/m^3 measured for cast ECC based on the same mix. This suggests that the pneumatic pressure applied was adequate in consolidating the sprayed ECC material.

5. Hardened properties of Sprayable ECC

5.1 Uniaxial tension

The tensile stress-strain curve of a sprayed ECC tensile coupon at 28-days is shown in Figure 2. The tensile coupon specimens were obtained by sawing panels of ECC sprayed into wood molds positioned vertically. The sprayed ECC panels were demolded one day after shotcreting and then cured in air.

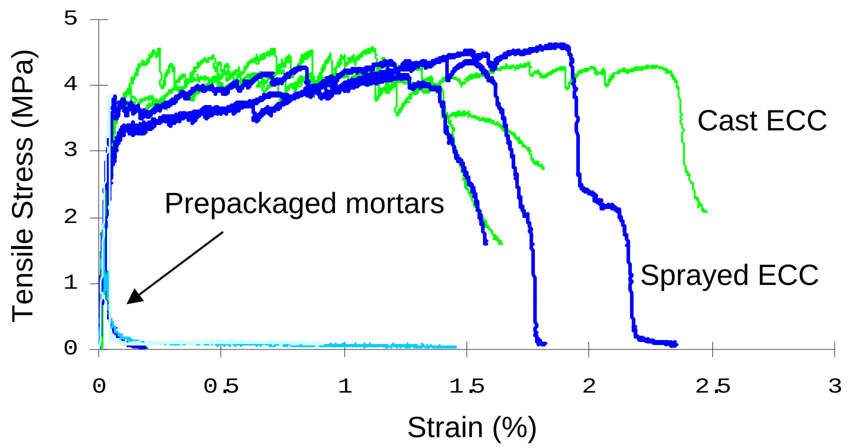


Figure 2: Tensile stress-strain curve of sprayed and cast ECC in comparison to commercial shotcrete prepackaged mortar [13].

It can be seen in Figure 2 that the sprayed ECC exhibits a strain-hardening response with a tensile strain capacity of 1.63 ± 0.26 %. This is lower than most ECC mixes, but remains two orders of magnitude higher than typical concrete or shotcrete. The reduced tensile strain capacity of sprayed ECC is likely a result of the inclusion of calcium aluminate cement that may alter the matrix toughness and the fiber/matrix interface properties. The stress-strain curves of two sprayed commercial prepackaged mortars are also shown for comparison.

During strain-hardening, the average microcrack width in the sprayed ECC was found to be 30 microns. The prepackaged mortars failed with a single continuous enlarging crack at descending load.

5.2 Flexural response

The flexural response of sprayed ECC under four point bending at 28 days is shown in Figure 3. The specimens were sawn from sprayed-up panels. Kim et al [13] found that the flexural response was not sensitive to putting the top of the sprayed layer in the tension or compression side of the beam.

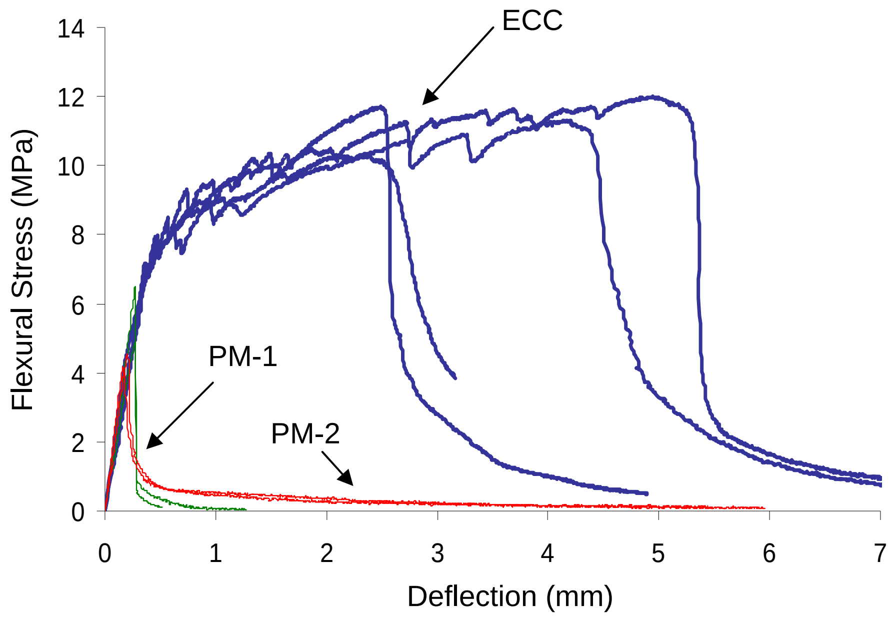


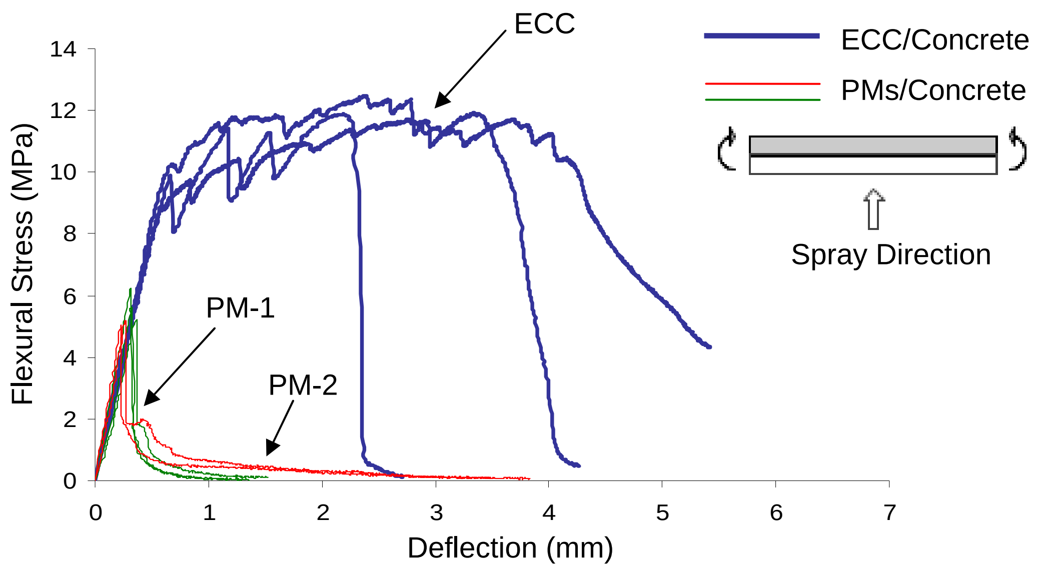
Figure 3: Flexural stress-deflection curves at 28 days for Sprayed ECC and two prepackaged mortars [13].

In Figure 3, it can be seen that deflection hardening of the sprayed ECC is attained, with a Modulus of Rupture (MOR) measured at 12±1.2 MPa. Two prepackaged mortar subjected to the same test yielded an MOR of about 6 MPa.

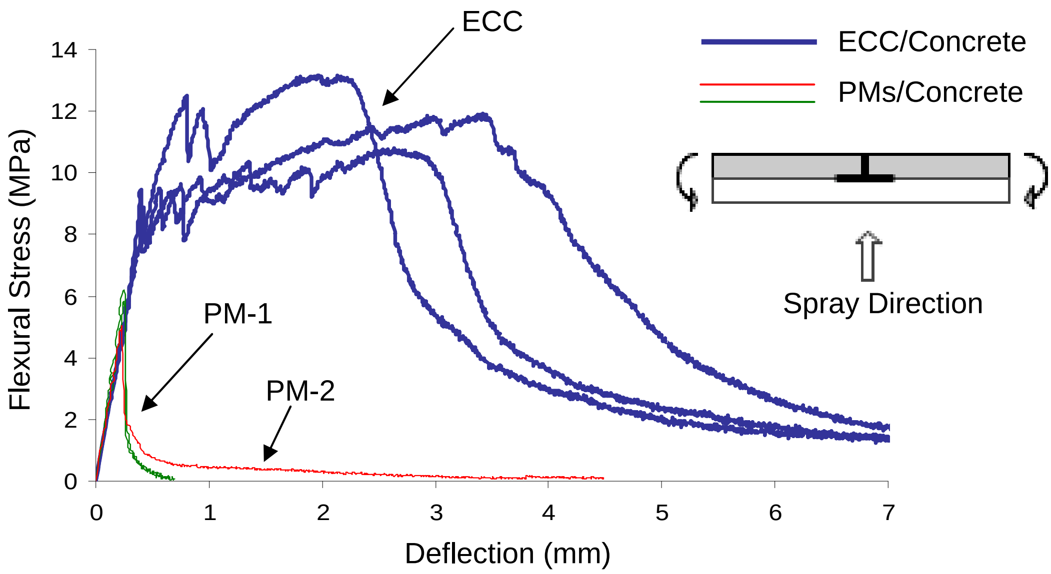
To examine the interface bond between ECC and a concrete substrate in shotcrete repair situations, two types of repair specimens were tested. The repair panels were made by spraying ECC onto a concrete substrate and subsequently sawn into repair beam specimens. The first specimen subjects the ECC repair layer in the beam to tension and the concrete in compression. The second kind of specimen simulates the condition where the concrete has a crack that may reflect upwards into the repair layer. A horizontal interface crack is also introduced to represent bonding defect. The test results are shown in Figure 4.

The sprayed ECC/concrete repair specimens showed an average MOR of 12.03 MPa, not substantially different from that of the ECC beams alone. No delamination between the ECC and concrete was observed, indicating adequate bonding between the ECC and substrate concrete. In the specimen with a cast-in notch, no reflective cracking was observed in the ECC repair layer. Instead, the high stress concentration just above the notch was absorbed by the tensile ductility of ECC resulting in the formation of many microcracks in the ECC layer.

In the tensile and flexural tests described above, sprayable ECC exhibits higher load capacity and substantially higher deformation capacity and energy absorption capacity as measured by the area under the load-deformation curves, when compared with the prepackaged repair mortars.



(a)



(b)

Figure 4: 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 a vertical crack introduced in the old concrete substrate and an initial interfacial crack [13].

6. Other properties of ECC relevant to shotcrete applications

The above test results for sprayable ECC suggest that ECC with high tensile ductility can perform well in situations where ground/rock movements could lead to high tensile loading and large deformation. Previous researchers have noted the addition of short fibers enhances the toughness of shotcrete [2]. The high tensile ductility of ECC implies a ductile deformation analogous to plastic yielding of ductile steel, so that large imposed deformations would be accommodated by ECC in an inelastic manner without localized fracture. The strain-hardening behavior of ECC maintains load-carrying integrity of the sprayed ECC element when overloaded, even in the absence of steel reinforcement.

In shotcrete applications where impact loading (such as rock bursts) may occur, the high energy-absorption capacity of ECC under impact loading may be advantageous. When ECC is properly designed, the energy absorption capacity can be at least an order of magnitude higher compared with normal shotcrete material [14]. Figure 5 shows the load-deformation curves of an ECC beam versus that of a normal concrete (f'_c = 40 MPa) beam. These tests were performed by lifting a 50 kg impact tup with flat impact surface to a height of 50 cm and allowing it to drop freely under its free weight onto the center of the specimen.

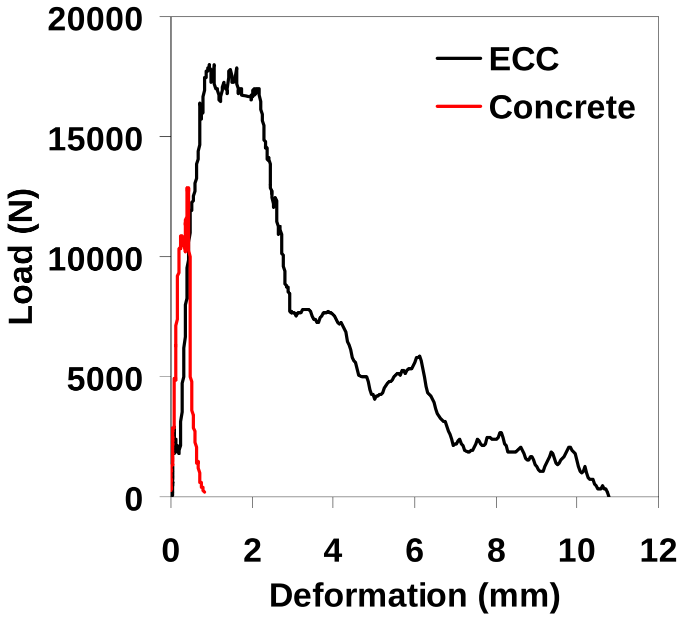


Figure 5: Load-deformation curve of drop weight tests for ECC and normal concrete beams (compressive strength = 40 MPa) [14].

Sprayed ECC may also have advantages in the elastic range for smaller imposed deformations by virtue of its lower elastic stiffness. As a result of eliminating coarse aggregates and the relatively small amount of fine sand, the Young's Modulus of ECC is approximately 15-30% below that of typical shotcrete. A sprayed ECC element can minimize tensile stress build-up for a given dimensional change (e.g. due to wetting and drying or temperature variation) under restrained conditions.

In underground structures, water tightness or impermeability may also be important. The tight crack width formation in ECC implies a low material permeability even in the cracked state. Permeability studies of ECC [15] subjected to a hydraulic gradient indicate that ECC with crack widths below 100 microns behave similarly to normal concrete without cracks, with regard to water permeation under hydrostatic pressure. Further, these tests demonstrated that in the presence of permeating water, ECC microcracks tend to reveal strong self-healing capabilities and further reduce the tendency for water transport through the sprayed ECC element. Figure 6 shows the effect of tight self-controlled crack width of ECC in maintaining low permeability even after subjected to large imposed deformation.

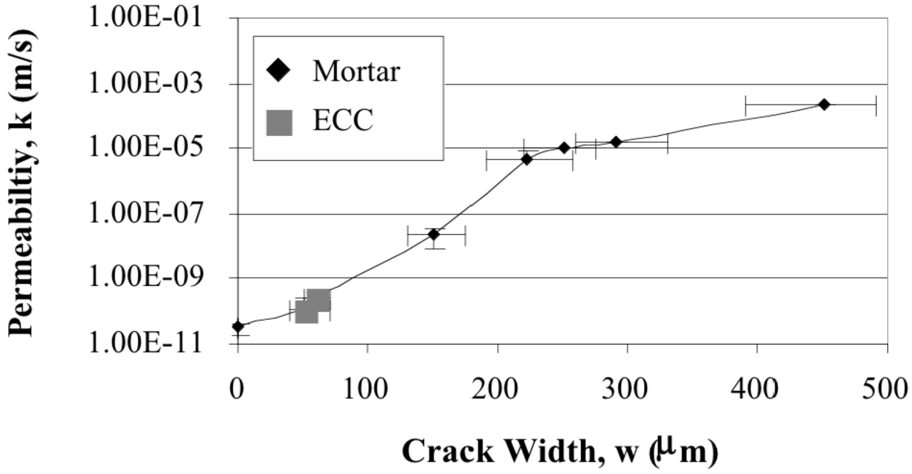


Figure 6: Measured permeability of preloaded ECC and mortar [15].

In shotcrete applications where fatigue loading is expected, such as in bridge structural repairs or tunnel linings subjected to repeated suction loads (i.e. air pressure differentials from passing high speed trains), the fatigue performance of sprayed ECC can extend the service life of these structures. The flexural fatigue performance of ECC has been studied by Suthiwarapirak et al [16] and found to exhibit a fatigue life several orders of magnitude higher than normal repair mortar. Figure 7 shows the bilinear fatigue curve of ECC while the control tests of repair mortars exhibit a linear fatigue curve. When the load amplitude falls below 50% of flexural strength, no fatigue failure was observed at 2 million cycles.

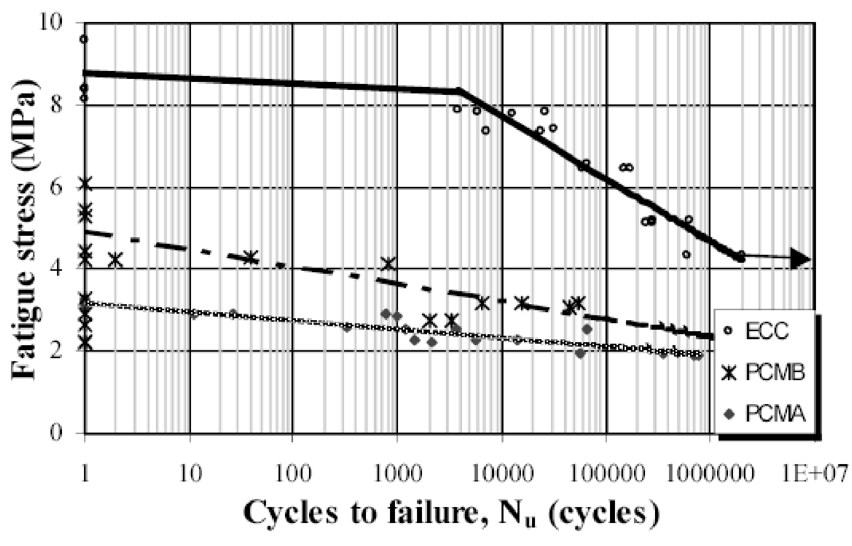


Figure 7: Fatigue stress-cycle relationship for ECC and two prepackaged repair mortars [16].

While laboratory studies of ECC show promising trends in its use for shotcreting applications, their purported performance must be verified by full-scale field studies. At the moment, there are only limited field applications of sprayable ECC. Some of these are described in the next section.

7. Sprayed ECC field applications and practice recommendations

Sprayed Engineered Cementitious Composites have been used in various types of shotcrete applications such as surface repair of damaged concrete structures, tunnel linings, and stabilization of waterways. Some of these applications are briefly illustrated below.

7.1 Retrofitting and surface repair

Retrofit is considered one of the most beneficial applications of ECC. Numerous retrofit projects applying ECC have been carried out in which ECC was used as a surface protection layer to recover the function of damaged concrete structures. Figure 8 shows the application of ECC on a retaining wall that has been severely damaged resulting from cracking due to alkali silica reaction. Wet sprayed ECC was applied as the protection layer with 15 mm thickness on the concrete surface. Due to the small coating thickness and the restraint exercised by the existing structure, cracking on the protection layer was to be minimized by using ECC with intrinsic crack control functionality. A similar concept was adopted in retrofitting an aged waterway structure as shown in Figure 12.

(a) *(b)*

(c) *(d)*

Figure 8: a) Application of ECC layer, b) Close-up of nozzle, c) Finished and spayed surfaces, d) Application of surface coating.

ECC has also been used in repairing road tunnels (Figure 9), where the existing chloride-infested concrete layer has been removed and replaced by ECC.

Figure 9: Replacement of chloride-infested concrete with ECC (left) and prefinished surface after replacement (right).

7.2 Tunnel lining

A sprayed multilayered FRC tunnel lining system with ECC as the top layer was used in the newly constructed Hida Tunnel in Japan with a length of 10.7 km as shown in Figure 10 instead of a conventionally cast concrete lining at the more than 20 emergency parking zones along the tunnel. The intention of the ECC layer covering the conventional steel fiber reinforced concrete (SFRC) is to protect against carbonation of the SFRC layer (Figure 11) and resulting corrosion of the steel fibers as well as to prevent concrete spalling in case of fire.

The ECC layer was added to a sprayed SFRC layer through embedded carbon fiber grids, resulting in an increased quality of the surface finish and improved water tightness of the lining. This method remarkably reduced the construction time and cost due to the absence of formwork and therefore is expected as a quick repair method for damage caused by fire or earthquakes.

Figure 10: ECC application at emergency parking zones (left) and surface finish of ECC coating after completion (right).

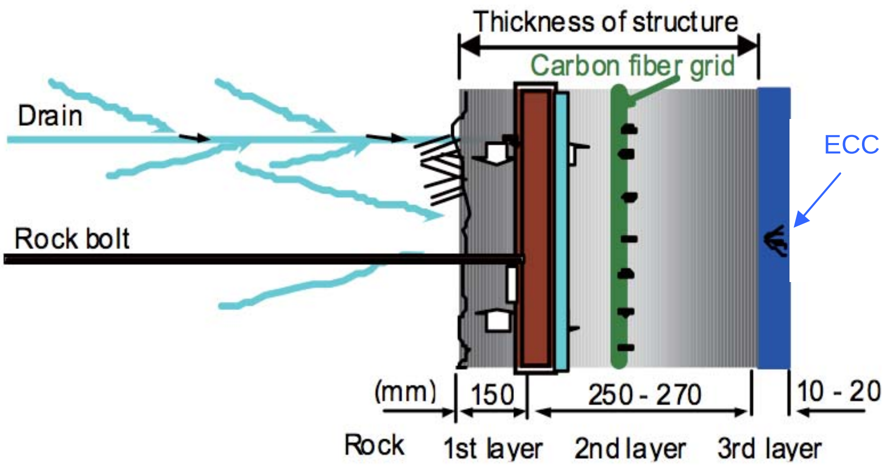


Figure 11: Cross-section of tunnel lining with ECC cover layer for carbonation and spalling protection [17].

7.3 Irrigation Channel Lining

In arid regions throughout the world, the movement of water for agriculture irrigation requires major infrastructure investments in large networks of irrigation canals, pumping stations, aqueducts, or siphons. Underwater for much of the year, and subjected to potential scour in addition to freeze-thaw exposure, these irrigation canals or channels both in Japan and the western United States have used sprayable ECC to either repair damaged concrete walls or to line existing earthen canals.

As shown in Figure 12, sprayable ECC has been used to repair the damaged concrete lining of long-used irrigation channels. The existing linings were damaged by a combined loading of scour and freeze-thaw exposure. This combination of loads, acting nearly year round, had badly damaged the channel lining causing leaks and slowing the flow rate. A thin layer of ECC (15 mm to 25 mm) was sprayed onto the surface of the channel to seal the surface while protecting the underlying concrete structure.

In the western US, a large network of earthen irrigation canals, in combination with dams and pumping stations, provides water to hundreds of thousands of hectares of agricultural land. As seen in Figure 13, an average earthen canal is approximately 2 m wide at its bed, 3 m wide at its top, and between 2 m and 3 m deep. Measuring hundreds of kilometers long, a cost-effective, easy to apply, and structurally sound lining was sought. For this application, sprayable ECC was used to create a durable structural lining that is also highly impermeable, thereby improving water conservation and the efficiency of the irrigation system.

Applied at a thickness between 15 mm and 25 mm on all faces of the channel, several hundred meters can be lined each day at a cost far below traditional reinforced concrete linings (with a minimum thickness of 75 mm for proper rebar clear cover) or large polyethylene lining tarpaulins. Additionally, the sprayed ECC system can be easily repaired if damaged by farming equipment or livestock. Unlike polyethylene linings that require specialized surface preparation and heat guns, the ECC lining can be repaired by spraying a new layer of ECC over the damaged area. As discussed previously, due to the unique ductility of ECC the high potential for debonding and fracture failure is suppressed in ECC repair applications [11].

Specifically for this application, the ECC material was premixed and delivered to the rural jobsite in 1000 kg bags. This greatly simplified the onsite batching and mixing process in large, 7-cubic-meter mixing trucks. Additionally, this reduced the variability associated with using sprayable ECC materials in a large-scale demonstration with crews that were inexperienced at mixing and placing ECC material.

Figure 12: Irrigation channel repaired using sprayed ECC in Japan

Figure 13: Irrigation channel lining installation using sprayed ECC in the western United States

8. Conclusions

The use of shotcrete, and specifically fiber reinforced shotcrete, has seen increasing acceptance within the construction industry since its introduction nearly a century ago. However, the quality of traditional shotcrete and FRC shotcrete applications continues to be challenged by densely steel reinforced sections leading to higher material variability, along with the effects of high rebound on shrinkage properties and fiber volume fraction. Therefore, a great deal of effort is placed on the proper training and certification of shotcrete nozzlemen and their crews.

Engineered Cementitious Composite (ECC) materials have undergone development over the past 5 years allowing for application via wet process shotcreting. This development has produced a solution to many shotcrete application challenges and which has been used in a number of field demonstrations. Relying on unique mix proportions that exclude large aggregates, polymer fibers that reduce high fiber volume fraction rebound, high ductility which does not rely on steel reinforcement for tensile strain capacity, and inherent crack control properties which intrinsically limit the durability impact and aesthetic appearance of restrained shrinkage cracking, sprayable ECC has been designed to counteract a number of remaining shortfalls of both traditional shotcrete and fiber reinforced shotcrete. Additionally, ECC exhibits a number of desirable characteristics for shotcrete applications including high impact resistance and water impermeability.

A number of field applications have been completed that use sprayable ECC materials. These include the repair of a dam in Japan, a tunnel lining in Japan, an irrigation channel lining in Japan and the United States, and the development of a premixed ECC material that is specially formulated for spraying. Accompanying these field demonstrations, the Japan Society of Civil Engineers has published a set of recommendations for the use and application of sprayable ECC [18]. Such recommendations bring this technology to the forefront of wider commercialization.

9. Acknowledgements

The authors would like to thank Mr. David Schwarz, General Manager of the Buffalo Rapids Irrigation District in Terry, Montana, USA for the use of photographs (Figure 13) in the preparation of this article.

10. References

[1] American Concrete Institute:
Guide to Shotcrete. Manual of Concrete Practice, ACI, 2005.

[2] Banthia, N.:
Fiber Reinforced Shotcrete: Issues, Challenges, and Opportunities. In: Reinhardt H.W. and Naaman A.E. (Eds): Proceedings of the Third International Workshop on High Performance Fiber Reinforced Cementitious Composites (HPFRCC3). Mainz, Germany. May 16-19, 1999, pp. 161-170.

[3] Armelin, H.S.; Banthia, N.:
On the Rebound (Minimizing Shotcrete Rebound with Fibres). Concrete International 1998, 20(9) pp. 74-79.

[4] Banthia, N.; Armelin, H.S.:
A Novel Double Anchored Steel Fiber for Shotcrete. Canadian Journal of Civil Engineering 2002, 29(1), pp. 59-63.

[5] Bernard, E.S.:
Correlations in the Behaviour of Fibre Reinforced Shotcrete Beam and Panel Specimens. Materials and Structures 2002, 35(3), pp. 156-164.

[6] Jeng, F.; Lin, M.; Yuan, S.:
Performance of Toughness Indices for Steel Fiber Reinforced Shotcrete. Tunnelling and Underground Space Technology 2002, 17(1), pp. 69-82.
[7] Cengiz, O.; Turanli, L.:
Comparative Evaluation of Steel Mesh, Steel Fibre and High-Performance Polypropylene Fibre Reinforced Shotcrete in Panel Test. Cement and Concrete Research 2004, 34(8), pp. 1357-1364.
[8] Ding, Y.; Kusterle, W.:
Compressive Stress-Strain Relationship of Steel Fibre-Reinforced Concrete at Early Age. Cement and Concrete Research 2000, 30(10), pp. 1573-1579.
[9] Li, V.C.:
From Micromechanics to Structural Engineering – the Design of Cementitious Composites for Civil Engineering Applications. JSCE J. of Struc. Mechanics and Earthquake Engineering, 1993, 10 (2), pp. 37-48.
[10] Li, V.C.:
Engineered Cementitious Composites (ECC) – Material, Structural, and Durability Performance. In: Nawy, E. (Ed.): Concrete Construction Engineering Handbook, Chapter 24, CRC Press, 2008.
[11] Li, M. and Li, V.C.:
Behavior of ECC/Concrete Layered Repair System under Drying Shrinkage Conditions. Journal of Restoration of Buildings and Monuments, 2006, Vol. 12, No. 2, pp143-160.
[12] Kim, Y.Y.; Kong H.J. and Li, V.C.:
Design of Engineered Cementitious Composite (ECC) Suitable for Wet-mix Shotcreting. ACI Materials Journal, 2003, 100 (6), pp. 511-518.
[13] Kim, Y.Y.; Fischer, G.; Lim Y.M. and Li, V.C.:
Mechanical Performance of Sprayed Engineered Cementitious Composite (ECC) Using Wet-mix Shotcreting Process for Repair. ACI Materials Journal, 2004, 101 (1), pp. 42-49.
[14] Yang, E. and Li, V.C.:
Rate Dependence in Engineered Cementitious Composites. In: Proc., Int'l RILEM Workshop HPFRCC in Structural Applications, published by RILEM SARL, 2006, pp. 83-92.
[15] Lepech, M. and Li, V.C.:
Water Permeability of Cracked Cementitious Composites. In: Proc. ICF11, CD-Paper 4539, 2005, Turin, Italy.
[16] Suthiwarapirak P.; Matsumoto, T. and Kanda, T.:
Flexural Fatigue Failure Characteristics of an Engineered Cementitious Composite and Polymer Cement Mortars. J. Materials, Conc. Struc. Pavements, JSCE, 2002, No. 718/V-57, pp. 121-134.
[17] Uchida, Y.; Fischer, G.; Hishiki, Y.; Niwa, J.; Rokugo, K.:
Review of Japanese Recommendations on Design and Construction of Different Classes of Fiber Reinforced Concrete and Application Examples. Proceedings of the 8th International Symposium on Utilization of High-Strength and High-Performance Concrete, Tokyo, 2008, Japan.
[18] Japan Society of Civil Engineers (JSCE):
Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC). Concrete Engineering Series 82, Keitetsu Rokugo (Ed.), July, 2008, ISBN 978-4-8106-0640-9.

Authors

Victor C. Li, PhD, FASCE, FASME, FWIF
E. Benjamin Wylie Collegiate Chair, Professor of Civil and Environmental Engineering, Professor of Material Science and Engineering, Director of the Advanced Civil Engineering Materials Research Laboratory (ACE-MRL), University of Michigan, Ann Arbor, USA.
vcli@umich.edu

Gregor Fischer, PhD
Associate Professor of Civil Engineering, Technical University of Demark, Lyngby, Denmark.
gf@byg.dtu.dk

Michael D. Lepech, PhD
Assistant Professor of Civil and Environmental Engineering, Stanford University, Stanford, California.
mlepech@stanford.edu