DUCTILE CONCRETE USING STRUCTURAL FIBERS

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ABSTRACT

Recent advances in cementitious materials, particularly Engineered Cementitious Composites (ECC) have been touted as alternatives to overcome performance limitations of traditional concrete. ECC is a material designed to be much more ductile than traditional concrete and is often referred to as bendable concrete. The components of ECC are similar to normal concrete, except that there are no coarse aggregates, have reduced aggregate volumes, and includes polymer fibers that contribute to the plastic material behavior of the composite. ECC is offered as a more durable, environmentally friendly and cost effective alternative to traditional concrete. Numerous potential applications have been proposed for ECC, such as in buildings and bridge decks, and for projects involving repair or rehabilitation work.

The focus of this paper is to develop using various types of polymer fibers a ductile ECC based on the published work of Dr. Victor C. Li at the University of Michigan[1]. Varying the type and amount of cementitious materials and varing the w/cm ratio of the ECC mixes was examined in terms of ductility and compressive strength. Limited success in developing a ductile ECC was achieved. More research is needed, which will significantly enhance the performance of this type of construction material.

Keywords: Ductile concrete, Bendable concrete, Engineered cementitious composites.

INTRODUCTION

In the last few decades, growing interest has developed in using fibers in ready-mixed concrete, precast concrete and shotcrete. Fibers made from steel, plastic, glass, wood and other materials have been used in concrete. Fibers are typically added to concrete mixes in low volume dosages often at rates less than 1.0 percent by volume for the purposes of reducing plastic shrinkage cracking[2]. However, fibers do not significantly affect the free shrinkage of concrete, but given high enough dosages, fibers can increase the resistance to cracking and decrease the size of the crack widths[3].

Generally, fiber reinforced concrete (FRC) is grouped into two classes: thin sheet products and bulk structure products. Fiber fraction volumes further determine sub-classifications and uses for each class, with low-volume fiber fractions (<1%) primarily serving to resist plastic shrinkage and high-volume fiber fractions (3-10%) serving to provide additional or secondary reinforcement to main reinforcing steel. High volumes (up to 20% steel fibers) have been demonstrated to significantly improve all strength properties. FRC has become synonymous with various steel fiber reinforcements. This reinforcement comes with the penalty of extra weight of the member. ECC was developed with the goal of capitalizing on the additional strength of fibers, while providing a significantly lighter composite material. ECC relies exclusively on synthetic polymer fibers.

Synthetic fibers are the result of research and development in the petrochemical and textile industries. Synthetic fibers that have been used in portland cement concrete include: acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene. One problem associated with synthetic fibers is the ability of the fibers to bond with the cementitious paste. Polypropylene fibers are commonly used as a fiber in portland cement concrete since the fibers are chemically inert, hydrophobic, and lightweight. Fibers of this type are generally added at a rate of 0.1 percent by volume of concrete. Polypropylene fibers can reduce plastic shrinkage cracking and help reduce spalling of concrete.

For many years, researchers have attempted to produce concrete that is more ductile in behavior[4,5]. See Figure 1. In most cases, ductile concrete has been achieved using fiber reinforcement[1]. ECC is the result of this development effort. ECC has demonstrated impressive ductile behavior. Bending of ECC can be achieved with a high level of inelastic deformation resulting from the development of numerous micro-cracks with limited crack widths. This is in sharp contrast to traditional concrete where a single point of failure (crack with a large crack width) develops from excessive bending.

Pioneering research and development by Dr. Victor C. Li of the University of Michigan, Ann Arbor has developed a type of ECC which is very ductile in behavior[6,7]. This material has been used in a number of projects worldwide and is proposed for many other projects[8]. The largest use of this material to date has been as a 5mm thick topcoat on the Mihara Bridge in Hokkaido, Japan. Domestically, the Michigan Department of Transportation (MDOT) has used ECC for various surface patches and as a flex joint (replacement for steel expansion joint) on a bridge deck crossing over I-94 in Ypsilanti, Michigan.

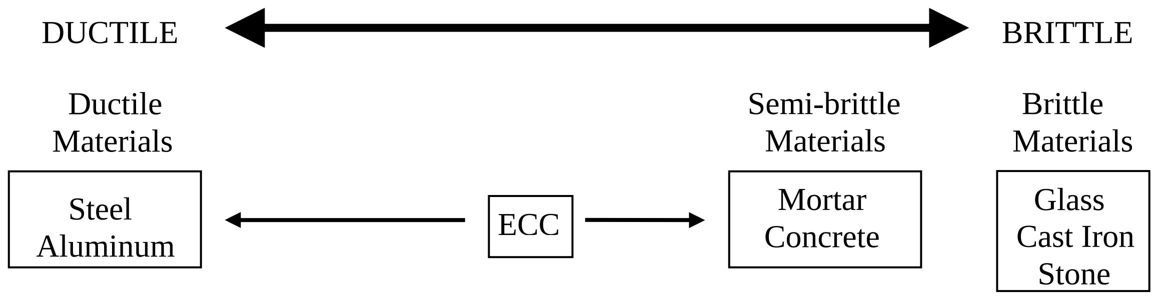


Fig. 1 Range of Ductile to Brittle Behavior of Materials

The research herein on ECC was conducted in two phases. The objective of the first phase was to reproduce a ductile ECC based on the ECC M45 formula using various types of polymer fibers[1]. The second phase objective was to experiment with other cementitious materials and to vary the w/cm ratio to determine the effects on ductility and compressive strength.

PHASE 1

1.1 GOAL

Based on information available in the literature, the goal of the first phase was to reproduce a ductile ECC based on the ECC M45 formula using various types of polymer fibers[1]. A typical concrete mixture with no fiber reinforcement was used as a basis for ductile comparison.

1.2 MATERIALS

Cement

Type I or type III portland cement, meeting the requirements of ASTM C150, was used in all mixes[6].

Fly Ash

Type C fly ash, meeting the requirements of ASTM C618, was used in all mixes[1].

Fine Aggregate

Natural sand with a maximum aggregate size of 4.75 mm and fineness modulus of 2.79 was used. The sand met the gradation requirements of ASTM C33. Physical properties in accordance with ASTM C127 and C128 were determined, including: bulk specific gravity, absorption capacity, and effective absorption. The bulk specific gravity of the sand was 2.65. The absorption capacity and the effective absorption were 1.0 percent and 0.5 percent, respectively.

Fibers

Four types of fibers were investigated: Durafibers, Fibermesh 150 (Figure 2), Fibermesh 300, Fibercast 500, and PVA-RECS15 Fibers. Durafibers are made by Durafiber, Inc., Fibermesh 150 and Fibermesh 300 are produced by Propex Concrete Systems Corp., and PVA-RECS15 Fibers are produced by Kuraray Co. Ltd. Durafibers and Fibermesh 150 are monofilament polypropylene material designed to disperse into the composite mix and separate to form a network of individual fibers. Fibermesh 300 is fibrillated polypropylene material designed to disperse out into the composite mix and spread out forming many small net like formations of fibers throughout the mix. Durafibers have a denier value of 15. (A denier equals 1 gram per 9000 meters.) Fibers are generally considered as micro-fibers if the denier value is less than 1. Fibermesh 150, Fibermesh 300, and PVA-RECS15 are micro-fibers.

Superplasticizer

Glenium 3000 NS admixture, meeting the requirements of ASTM C494 for Type F, high-range water-reducing admixture (HRWRA), was used as the surperplasticizer for all ECC mixes[6].

Fig. 2 Micro-fibers (Fibermesh 150 shown)

1.2 PROPORTIONING, CASTING AND TESTING

Nine total mixes were developed and cast. The batches included one baseline reference concrete mix and eight ECC mixes. See Figure 3. The water-to-cementitious-material (w/cm) ratio for the concrete batch was 0.44. The w/cm ratio for the ECC batches was 0.26, except for batches D-2 and D-4. The proportions for each batch are given in Table 1. All batches were mixed in accordance with ASTM C192[6]. For each batch, three 400 x 87½ x 25 mm (16 x 3½ x 1 in) bars were cast, consolidated in a single layer and left in the preparation room covered in plastic for 18 hours. See Figure 4. The bars were then de-molded and placed in a moist curing room until testing.

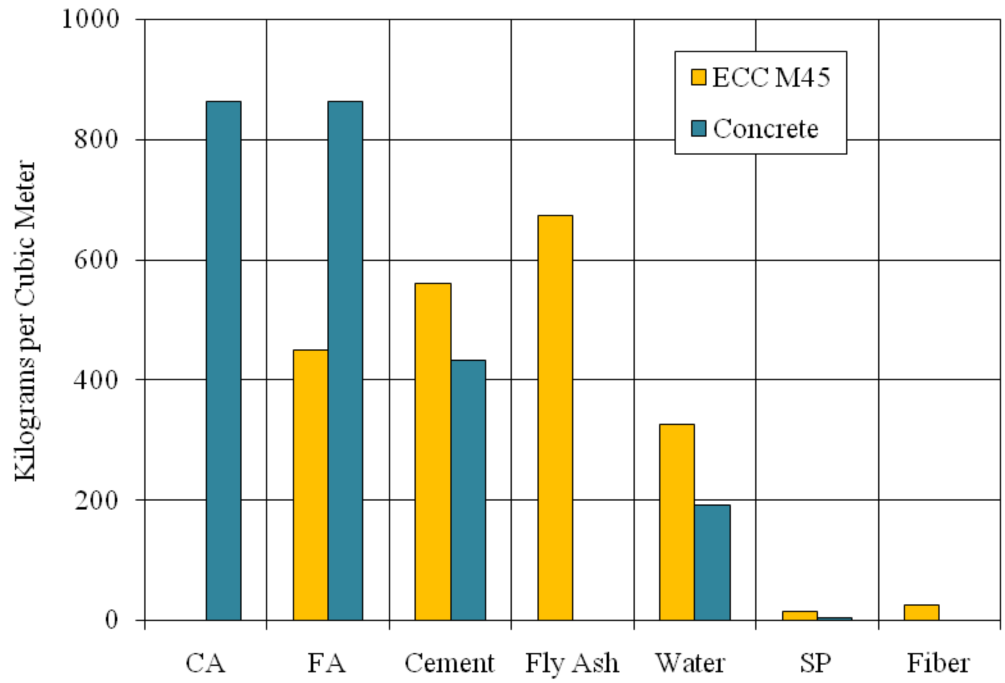


Fig. 3 ECC M45 Mix vs. Typical Concrete Mix

Table 1 Constituent Content of Phase 1 Mixes, kg/m^3 (lb/yd^3)

Batch	Fine Aggregate	Water	Cement		Fly Ash	Micro-fibers	Super-plasticizer
Concrete†	864 (1456)	192 (324)	I	432 (728)	0 (0)	0 (0)	4.3 (7.2)
D-1	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.0 (43.9)	14.0 (23.6)
D-2	611 (1031)	234 (394)	I, II	543 (916)	68 (115)	4.0 (6.8)	8.0 (13.5)
D-3	448 (756)	327 (551)	I	561 (945)	673 (1134)	10.7 (18.0)	6.7 (11.3)
D-4	667 (1125)	263 (443)	I, II	561 (945)	267 (450)	8.0 (13.5)	6.7 (11.3)
FM150	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
FM300	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
PVA-1	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
PVA-2	448 (756)	380 (641)	I, II	1233 (2079)	0 (0)	26.7 (45.0)	14.7 (24.8)

†A size 8 natural coarse aggregate (CA), meeting the requirements of ASTM C33, was used at a rate of 864 kg/m^3 (1456 lbs/yd^3).

Fig. 4 Casting ECC Bar Specimens

The bars were tested in a modified four point bend test as shown in Figure 5. The purpose of the test was to observe bending (ductile behavior) of the bars made from the ECC mixes as compared to brittle behavior observed with the concrete bars. The concrete bars were expected to behave in a brittle manner, where a single or dominant vertical crack develops on the underside of the beam near midspan and propagates upward rapidly until failure. The ECC bars were expected to noticeably bend in flexure developing numerous transverse cracks on the underside of the bar. The resulting crack pattern should be nonlocalized and more distributed in the midspan region. See Figure 6.

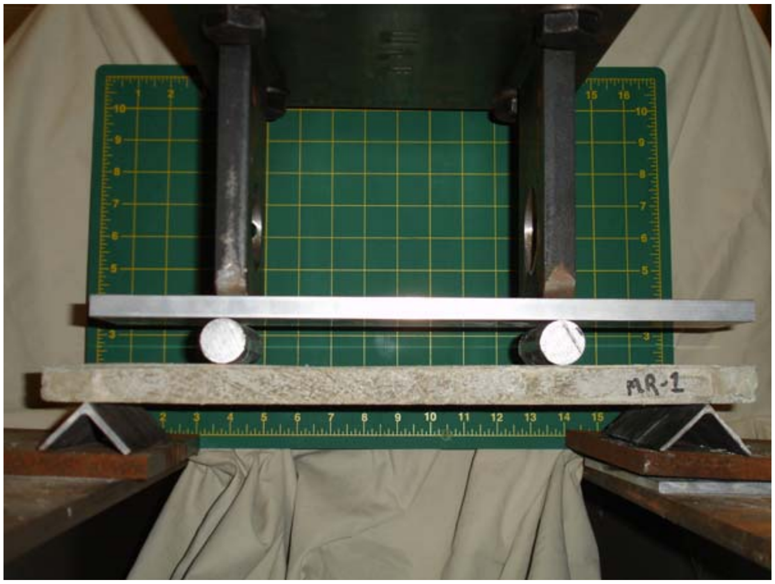
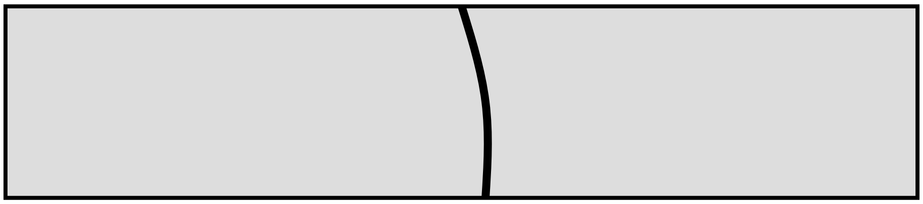
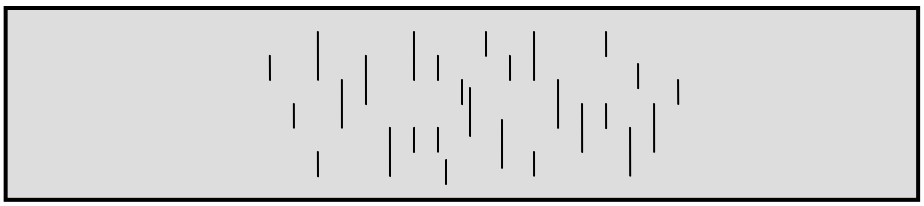


Fig. 5 Four Point Bend Test



(a) Localized Crack Failure of Concrete Bars



(b) Nonlocalized Cracking of ECC Bars

Fig. 6 Cracking of Bar Specimens

1.3 RESULTS OF BEND TESTS

The concrete bar specimens produced demonstrated brittle behavior as expected. A dominant vertical crack formed and developed on the underside of the bar until failure occurred suddenly and abruptly. The “D” batches with type I portland cement listed in Table 1 were the first attempt at trying to achieve ductile behavior. Unfortunately, all bars made from the from the “D” batches with type 1 portland cement exhibited brittle behavior. However, after the dominant vertical crack had formed and developed on the underside of the bars, the Durafibers continued to be able to take load. Many of the fibers did not appear to bond well with the cementitious paste. Batches D-2 and D-4 were then cast with type III portland cement, which is finer than type I, in hopes of achieving a better bond between the fiber and the cementitious paste. Once again, the bars exhibited brittle behavior. As a result, the Durafibers and the mix proportions for the batches were investigated based on findings in the literature. This search indicated that although the fibers were extremely small, the fibers were not small enough to be classified as micro-fibers. Micro-fibers typically have a denier value of less than 1 (1 gram per 9000 meters). The Durafibers had a denier value of 15. Research by Dr. Victor Li at the University of Michigan, Ann Arbor indicated that bendable concrete can be achieved by using micro-fibers[1,5,6]. Three other micro-fibers were used in the subsequent testing and results are discussed as follows.

The FM150 bars also exhibited brittle behavior. The bars behaved similarly to the bars with the Durafibers; however, better bond was achieved within the matrix. After cracking the micro-fibers remained bonded and began to stretch until the tensile capacity was exceeded. The FM300 bars were cast but not tested. The micro-fibers did not distribute evenly into the mix and stayed clumped together. Even with the addition of the superplasticizer, the mix was soupy yet relatively harsh since the micro-fibers remained clumped together. After limited success of the FM150 bars, the research then focused on the micro-fibers that were successfully used to make bendable concrete as done by Dr. Victor Li. This researcher was successful in developing bendable concrete that used PVA micro-fibers produced by Kuraray Co., Ltd. These fibers have a high tensile capacity and high modulus of the elasticity compared to other micro-fibers. Bar specimens from cementitious mixes with these types of fibers were cast. The bars corresponded to batches PVA-1 and PVA-2 in Table 1.

The PVA bars for both mixes behaved somewhat similarly to the FM150 bars. However, a more ductile behavior was observed as shown in Figure 7. More dispersed cracking occurred in the PVA bars than in other bars (see Figure 8), which typically had a single dominating crack. Unfortunately, significant ductile behavior as shown in the literature by the work of Dr. Victor Li was not achieved.

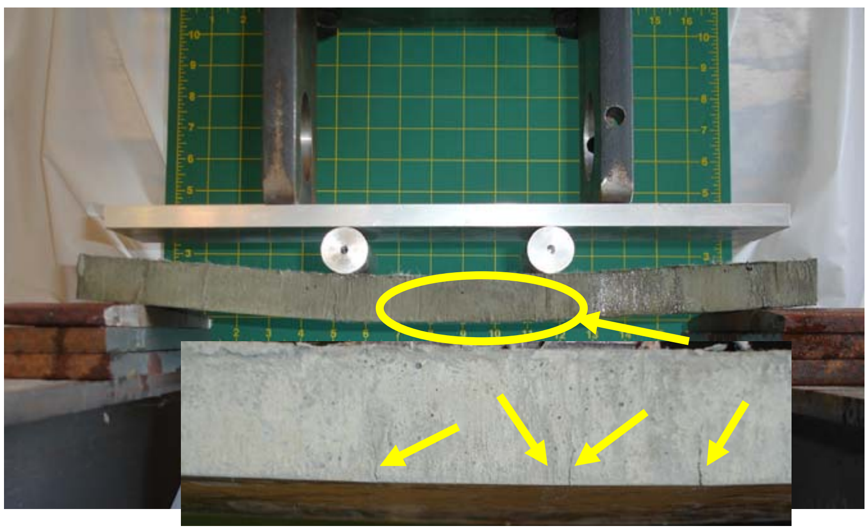


Fig. 7 Flexural Cracking of PVA Bar

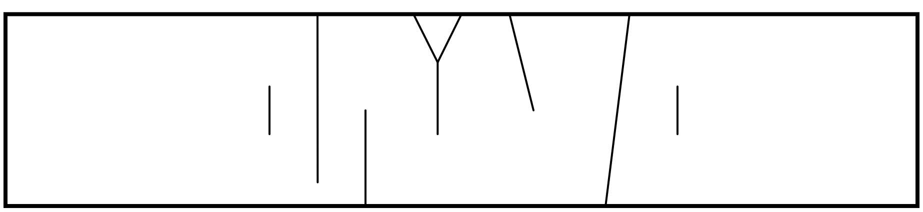


Fig. 8 Dispersed Flexural Cracking

1.4 PHASE 1 CONCLUSIONS

Of the mixes used to cast the beams, none exhibited truly ductile behavior as shown in the literature. Improved bond characteristics between the cementitious paste and fibers were achieved by using PVA micro-fibers. Further research into improving fiber bonding within the matrix was conducted in the second phase using exclusively PVA micro-fibers and varying the type and amount of cementitious materials and varying the w/cm ratio.

PHASE 2

2.1 GOAL

The second phase of the research was to enhance the behavior of the PVA mixes by varying the type and amount of cementitious material as well as the w/cm ratio. The ultimate goal was to cast and test beams to demonstrate the utility of ECC as a method for reducing structural steel requirement. While the goal of this phase was generally consistent, the process was evolutionary.

2.2 MATERIALS

Cement

Type I portland cement, meeting the requirements of ASTM C150, was used in all mixes.

Fly Ash

Type C fly ash, meeting the requirements of ASTM C618, was used in all mixes[1].

Silica Fume

Silica fume meeting the requirements of ASTM C1240 was used in selected mixes.

Fine Aggregate

Manufactured limestone sand meeting the gradation requirements of ASTM C33 was used in all mixes. Compliance with ASTM C127 and C128 was ensured by supplier. All material was saturated-surface-dry.

Coarse Aggregate

Manufactured limestone coarse aggregate meeting the gradation requirements of ASTM C33 was used in selected mixes. Compliance with ASTM C127 and C128 was ensured by supplier. All material was saturated-surface-dry.

Fibers

PVA-RECS15 micro-fibers (Nykon) produced by Kuraray Co. Ltd. were used in all cementitious mixes with fibers.

Superplasticizer

W. R. Grace & Co. ADVA 140M high range water reducing admixture, meeting the requirements of ASTM C494 for Type A and F, was used as a superplasticizer for all mixes[7].

2.3 PROPORTIONING, CASTING AND TESTING

Six total mixes were developed and cast in the second project phase. The initial three mixes were designed to improve on the PVA mix by using silica fume. It was posited that the nature of silica fume, an extremely fine pozzolan cementitious material, would improve the bonding with the micro-fibers[10]. The final three mixes were intended to determine the effects of w/cm ratios on the ECC matrix.

2.3.1 SILICA FUME ECC MIXES

The first three mixes included the ECC M45 mix without silica fume as a control, the ECC M45S mix with 3% silica fume (as % of total cementitious material), and the third mix, ECC M45XS as a high strength mix with 8% silica fume. There were no coarse aggregates only fine aggregates. As in the first phase, 400 x 87½ x 25 mm (16 x 3½ x ¾ in) bars were cast from each mix for ductile testing. Cylinders 150 x 300 mm (6 x 12 in) in size were cast for compression testing. The mix ratios are included in Table 2. This table also contains the w/cm ratio for each mix.

Table 2 Constituent Content of Silica Fume Mixes, kg/m^3 (lb/yd^3)

Component	ECC M45 control	ECC M45S with SF	ECC M45XS high strength
Type I Cement	561 (945)	561 (945)	532 (896)
Fine Aggregate	449 (757)	449 (757)	427 (719)
Fly Ash	673 (1134)	673 (1134)	641 (1080)
Silica Fume	0 (0)	40 (67)	100 (169)
Water	327 (551)	327 (551)	313 (527)
Superplasticizer	14 (24)	14 (24)	14 (24)
Micro-fibers	26 (44)	26 (44)	26 (44)
w/cm Ratio	0.26	0.26	0.25

2.3.2 SILICA FUME ECC TEST RESULTS

The addition of silica fume to the ECC matrix clearly added to the compressive strength of the ECC as shown in Figure 9. Unfortunately, the ductile behavior was significantly diminished as compared to the four point PVA bar tests of the first phase.

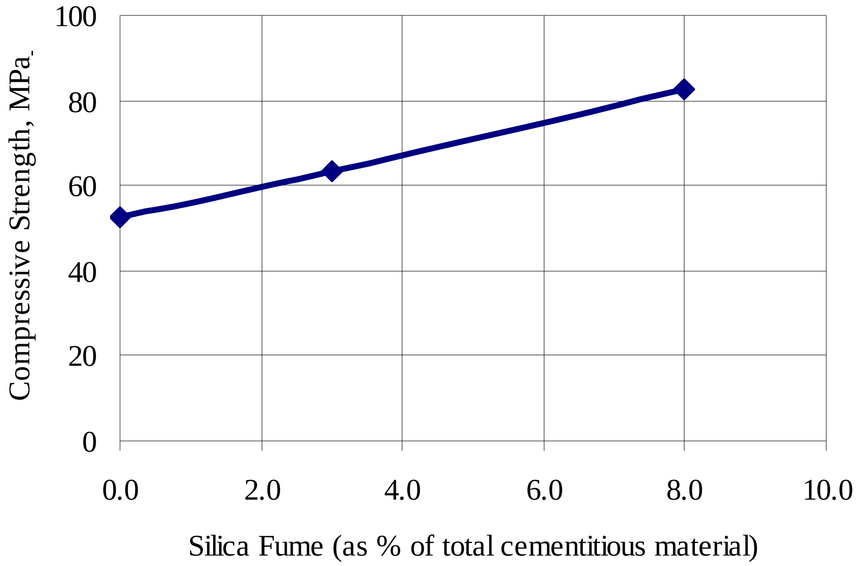


Fig. 9 Silica Fume Effect on ECC Strength

The failure to achieve ductile behavior in the silica fume ECC mixes prompted an inquiry to engineers at the Silica Fume Association (SFA)[9]. Engineering staff at SFA pointed out that the high strength effects of the silica fume may have negated any ductile behavior that may have otherwise been observed. This had been a concern from the beginning. The hardness achieved in the compression resistance comes at the expense of ductility.

Additionally, SFA was pointed out that the low aggregate content of ECC would classify the material as a mortar and not a concrete. SFA suggested that the shrinkage from such a mix design would be unacceptable in a large reinforced slab or beam, and that since silica fume content contributed to greater plastic shrinkage, aggregate ratios would have to be increased to obtain a useable material in field construction.

2.3.4 W/CM RATIO VARIED ECC MIXES

Five mix designs were used to determine the effects of altering the w/cm ratio. The w/cm ratio was varied between 0.27 (ECC M45 baseline), 0.35 and 0.45. These ratios were chosen to reflect practical extremes with a median point between. Mixes at the extreme points were designed with and without PVA micro-fibers to quantify the effect of the micro-fibers on the design. None of the mixes contained silica fume. A summary of the mix proportions is in Table 3. This table also contains the w/cm ratio for each mix.

As in the initial silica fume mixes, 400 x 87½ x 25 mm (16 x 3½ x ¾ in) bars were cast from each mix for ductile testing. Cylinders 150 x 300 mm (6 x 12 in) in size were cast for compression testing.

Table 3 Constituent Content of Varied W/CM Ratio ECC Mixes, kg/m^3 (lb/yd^3)

Component	27ECCWF	27ECCNF	35ECCWF	45ECCWF	45ECCNF
Type I Cement	561 (945)	561 (945)	561 (945)	561 (945)	561 (945)
Fine Aggregate	448 (756)	448 (756)	448 (756)	448 (756)	448 (756)
Fly Ash	673 (1134)	673 (1134)	673 (1134)	673 (1134)	673 (1134)
Water	327 (551)	327 (551)	432 (728)	555 (935)	555 (935)
Superplasticizer	15 (25)	15 (25)	15 (25)	15 (25)	15 (25)
Micro-fibers	27 (46)	0 (0)	27 (46)	27 (46)	0 (0)
w/cm Ratio	0.27	0.27	0.35	0.45	0.45

2.3.4 W/CM RATIO VARIED ECC MIX TEST RESULTS

As before, cylinder testing was performed in a Forney compression testing machine. The compression testing results for the various w/cm ratios are shown in Figure 10.

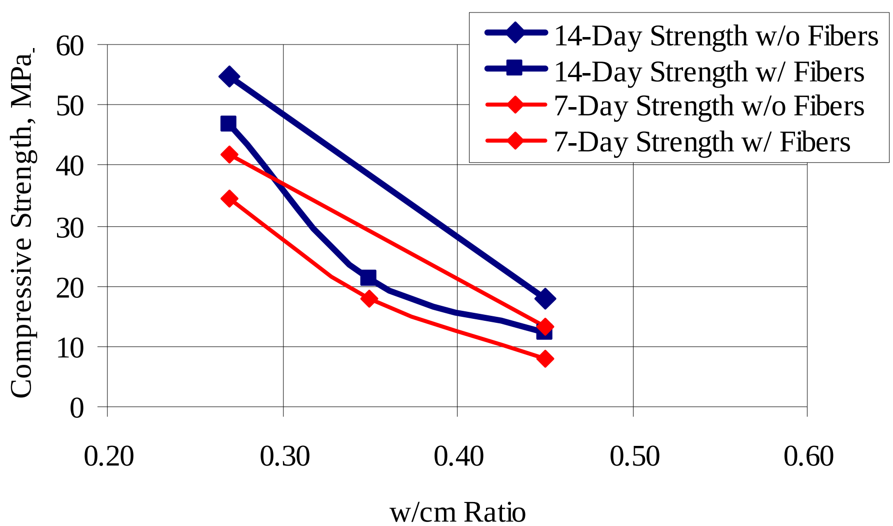


Fig. 10 7- and 14-day Compressive Strength versus w/cm Ratio

The ECC without fiber demonstrated consistently higher compressive strengths of about 15%. The failure mode of the mixes with fiber was also noteworthy in that the fibers allowed the failed specimen to remain intact, whereas the specimens without fiber shears off large segments at failure. This was consistent in all w/cm ratio mixes and slightly more pronounced in the higher w/cm ratio mixes, where the central portion of the ECC cylinders with fibers bulged outward significantly. See Figure 11.

Fig. 11 Compression Test Failures with (Left) and without Fibers (Right) (0.27 w/cm Ratio)

Overall, the various mixes shared common problems noted throughout the research. The aggregate tended to settle and the fiber tended to rise to the surface. This problem was exacerbated by the superplasticizer and increased with higher w/cm ratios. However, the superplasticizer is essential in getting the mixture to "self" consolidate. The rising fibers produced a top surface that was difficult to screed and to finish.

The high w/cm ratio mixes were extremely difficult to work with. The problems of water separation were significant for the mix with a w/cm ratio of 0.35 and much worse for the mix with a w/cm ratio of 0.45. Water could literally be decanted from the top of the cylinders within seconds after consolidation. This led to visually noticeable shrinkage of the cylinders during curing and a rough, pocked, failure-prone top surface. This effect critically flawed the bar surfaces to the point where ductility testing of the bar specimens could not be performed as planned. For this reason, ductility testing was not performed even though it was believed that the higher w/cm ratio mixes might exhibit more ductility as a result of reduced compressive strength.

2.4 PHASE 2 CONCLUSIONS

The second phase of the research failed to produce any significant ductility in ECC as well as failing to produce a material suitable for flexural beams. The basic ECC M45 mix altered with silica fume did produced impressive compressive strengths but failed to produce any real ductility. This served to reinforce the opposing properties of ductility versus hardness. The variations in w/cm ratios also showed that ECC are very sensitive to small changes in this ratio. The baseline 0.26–0.27 w/cm ratio seems to be optimum even though the resulting composite produces a difficult material to consolidate without superplasticizer.

The results of the experiments with ECC seem to conclude that the material may be best suited for thin topcoats as flexible, tight bonding overlays to other R/C materials. Further testing and development is needed for this type of material to be suitable for use in large structural members. ECC as tested herein was very difficult to work with under optimum laboratory conditions and was sensitive to variations in the w/cm ratio. It is important to remember that ECC is a cementitious composite and not concrete. The additional tensile strength of ECC is notable during compression failure, no advantages in compression strength due to micro-fiber content were observed. Actually, slight losses occurred.

EPILOGUE

After considerable setbacks, the Michigan Department of Transportation (MDOT) in Ypsilanti, Michigan was contacted. MDOT has used ECC as a flex joint to replace a steel expansion joint in a bridge. Our objective was to glean information on ECC mixes used, its workability, and its performance to date. While no official report has yet been made available, engineers familiar with the ECC confirmed its extremely high-slump, “self consolidating” nature, and difficulties in finishing the surface of the material. Also noted was significant and unexpected level of cracking of the material over the flex joint. Further investigation of this MDOT project should provide essential information on the performance of ECC as a topcoat material.

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