Project-Based Learning: Developing Ductile Concrete

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Abstract – In recent years, materials like Engineered Cementitious Composites (ECC) have been in development. ECC is a material designed to be ductile and is referred to as bendable concrete. The components of ECC are similar to normal concrete except no coarse aggregates are used and air entrainment is not necessary. Like concrete, ECC is designed to be cost effective and has numerous potential applications, such as in buildings and bridge decks, and for projects involving repair or rehabilitation work. The focus of this paper is to present the results and work performed by students in a construction materials course to develop a type of ductile concrete based on information available in the literature. Students were required to work in teams to perform a literature search; build molds; develop mix designs; cast and test beam specimens; and write a report. This project offered students the opportunity to develop a product that has potential use in the community, and the students really appreciated this aspect.

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. In general, fibers are typically added to concrete mixes in low volume dosages often at rates less than 1 percent by volume for the purposes of reducing plastic shrinkage cracking[1]. However, fibers do not significantly effect 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[2].

Synthetic fibers are man-made fibers resulting from 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. Polyropylene 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 ductile in behavior. See Figure 1. In most cases, ductile concrete has been achieved using fiber reinforcement[3]. In the last decade, Engineered Cementitious Composites (ECC, also know as Bendable Concrete) have developed that are more cost effective and durable than earlier attempts. ECC is a ductile material. 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.

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One of the leading researchers in this area is Dr. Victor C. Li of the University of Michigan, Ann Arbor[5,6]. He has developed a type of ECC, which is very ductile in behavior. Using this published work as well as other published work as a place to start, students were asked to develop ductile concrete by working in teams.

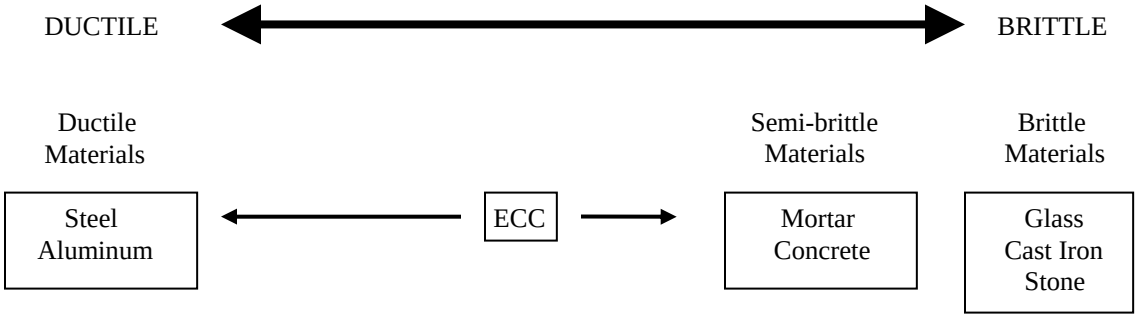


Figure 1. Range of ductile to brittle behavior of materials

MATERIALS

Cement

Type I or type III portland cement, meeting the requirements of ASTM C150, was used to make the engineered cementitious composite (ECC) mixes [6].

Fly Ash

Type C fly ash meeting the requirements of ASTM C618 were used for all ECC 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, including: 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 out into the composite mix and separate to form a network of individual fibers. Fibermesh 300 is fribrillated 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 general considered as micro-fibers if the denier value is less than 1. Fibermesh 150, Fibermesh 300, and PVA-RECS15 are all micro-fibers.

Figure 2. Micro-fibers, Fibermesh 150 shown

Superplasticizer

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

PROPORTIONING, CASTING, AND TESTING

A total of nine batches of mixes were cast. The batches included one concrete mix and nine engineered cementitious composite (ECC) mixes. The water-to-cement ratio for the concrete batch was 0.44. The water-to-cementitious material ratio for the ECC batches was 0.26, except for batches ECC-D-2 and ECC-D-4 where students chose to use a different ratio. 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) beams were cast (see Figures 3 and 4), rodded and vibrated in one layer and left in the preparation room covered in plastic for 18 hours. The beams were then demolded and placed in a moist curing room until testing.

Table 1. Constituent Content of Mixes

Batch	Fine aggregate	Water	Cement		Fly ash	Micro-fibers	Super-plasticizer
	kg/m^3 (lb/yd^3)						
Concrete†	864 (1456)	192 (324)	I	432 (728)	0 (0)	0 (0)	4.3 (7.2)
ECC-D-1	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.0 (43.9)	14.0 (23.6)
ECC-D-2	611 (1031)	234 (394)	I, II	543 (916)	68 (115)	4.0 (6.8)	8.0 (13.5)
ECC-D-3	448 (756)	327 (551)	I	561 (945)	673 (1134)	10.7 (18.0)	6.7 (11.3)
ECC-D-4	667 (1125)	263 (443)	I, II	561 (945)	267 (450)	8.0 (13.5)	6.7 (11.3)
ECC-FM150	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
ECC-FM300	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
ECC-PVA-1	448 (756)	327 (551)	I	561 (945)	673 (1134)	26.7 (45.0)	14.7 (24.8)
ECC-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, meeting the requirements of ASTM C33, was used at a rate of 864 kg/m^3 (1456 lbs/yd^3).

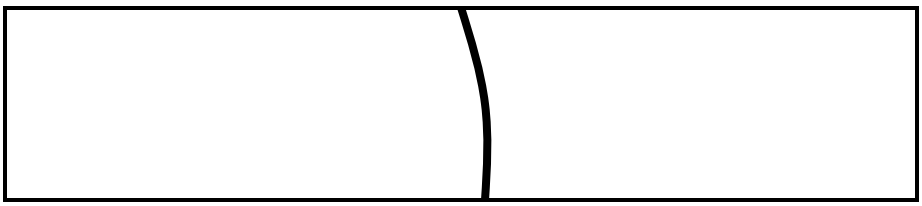
Figure 3. Students mixing an ECC batch

Figure 4. Student casting beam specimens

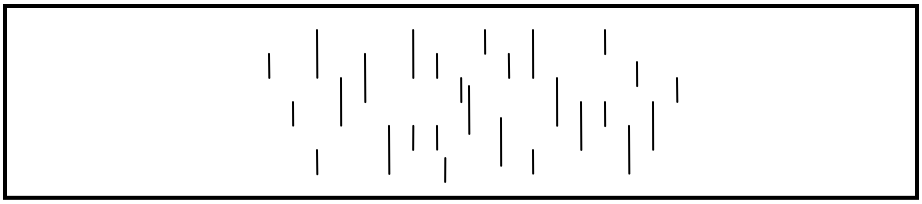
The beams were tested in a modified four point bend test as shown in Figure 5. The purpose of the test was to observe bending (ductile behavior) of the beams made with the engineered cementitious composites as compared to brittle behavior observed with the concrete beams. The concrete beams were expected 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 until final failure. It was hoped that the beams made of the ECC mixes would bend in flexure and that cracking would develop in a non-localized manner, where cracking would be more distributed in the midspan region as shown in Figure 6.

Figure 5. Four point bend test

(a) Four point bending of a beam



(b) Localized crack failure indicating brittle behavior



(c) Non-localized cracking failure indicating a more brittle behavior

Figure 6. Cracking on beam underside

RESULTS OF BEND TESTS

The concrete beams behaved as expected in a brittle manner. A dominant vertical cracked formed and developed on the underside of the beam until failure occurred suddenly and abruptly. The ECC-D batches listed in Table 1 were the first attempt at trying to achieve beams with ductile behavior. Unfortunately, all of the beams behaved as brittle materials. However, after the dominant vertical crack had formed and developed on the underside of the beam, the Durafibers continued to be able to take load. Many of the fibers did not appear to bond well with the cementitious paste. Batches ECC-D-2 and ECC-D-4 were cast with type III portland cement, which is finer than type I, in hopes of achieving a better bond. However, a similar result occurred. As a result, the Durafibers and the mix proportions for the batches were investigated based on findings in the literature. The students discovered that although the fibers were extremely small, they were not small enough to be classified as micro-fibers. Micro-fibers typically have a denier value of less than 1. Note, a denier has a value of 1 gram per 9000 meters. The Durafibers had a denier value of 15. Research by Victor Li indicated that he had developed bendable concrete using micro-fibers[3-5]. The students believed that the bond between the fibers and cementitious paste could be enhanced if actual micro-fibers were used in place of the others. Three types of micro-fibers were then investigated and the resulting batches are discussed as follows.

The ECC-FM150 beams also behaved as a brittle material as shown in Figure 7. The beams behaved similarly to the beams with the Durafibers; however, better bond was achieved. After cracking the micro-fibers remained bonded and began to stretch until their tensile capacity was exceeded. The ECC-FM300 beams were cast but not tested. The micro-fibers did not distribute evenly into the mix. They stayed clumped together. Even with the addition of the superplasticizer, the mix was soupy yet relatively harsh since the micro-fibers were clumped together. Based on the limited success of the ECC-FM150 beams, the students again decided to go back to the

literature. Many of the students thought that potentially stronger fibers with increased tensile capacity would improve the bending behavior although they were not sure as to why. Some students were troubled as to why they were not achieving the final goal of getting beams that bend with ductile behavior.

In the literature, the students looked for more information about the micro-fibers that were successfully used to make bendable concrete by other researchers. According to research by Dr. Victor Li, he was successful developing bendable concrete that used micro-fibers produced by Kuraray Co. Ltd. that have a high tensile capacity and high modulus of the elasticity as compared to ordinary micro-fibers. The students began to research to try and find other micro-fibers with similar mechanical properties. Due to time constraints, the students chose to use micro-fibers produced by Kuraray Co. Ltd. As a result, beams were cast using micro-fibers similar to the ones used by Dr. Victor Li. These beams corresponded to batches ECC-PVA-1 and ECC-PVA-2.

The ECC-PVA beams for both mixes behaved somewhat similar to the ECC-FM150 beams as a brittle material. But, a more ductile behavior was observed. More cracking occurred in the ECC-PVA beams than in other beams, which typically had a single dominating crack. See Figure 8. Unfortunately, ductile concrete as shown in the literature was not achieved. However, a more ductile behaving concrete was achieved as shown in Figure 9.

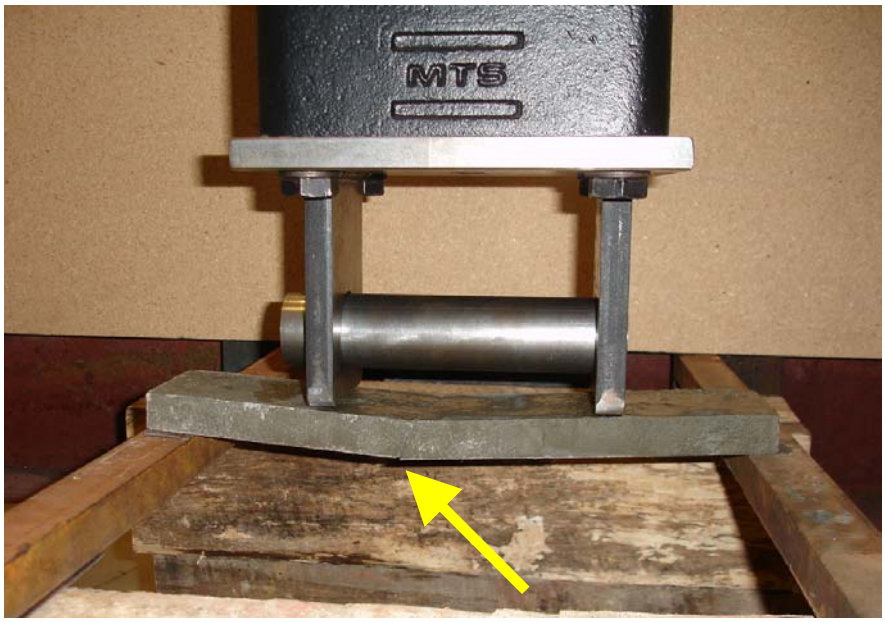


Figure 7. Failure of a ECC-FM150 beam

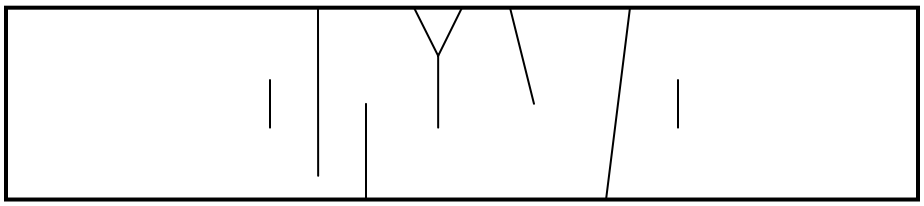


Figure 8. Underside of ECC-PVA beam after failure

WHAT STUDENTS LEARNED

Students learned to work in teams performing a literature search; build molds; develop mix designs; cast and test beams specimens; and write a report. This project was not a "cook book" project, where the faculty members could just lead the students down the correct path to success. Their success was dependent on their work. The students were required to develop their own mix designs based on the current literature on ECC. The faculty member was just a guide, a resource person. For many of the answers to their questions, they had to go to existing literature or

contact the manufacturers for specifications on the micro-fibers. A few students felt frustrated in the sense that success should be easy to accomplish with a clear path. It was important for them to realize that success or lack of success can be a winding road full of twists and turns. Other students became more interested and engaged in the project, when the desired result was not achieved. For these students, the project brought out the very best in them as the students became more eager to accomplish the goal. Other students were indifferent. They did not become frustrated; they participated in the process. However, they did not take an active leadership role.

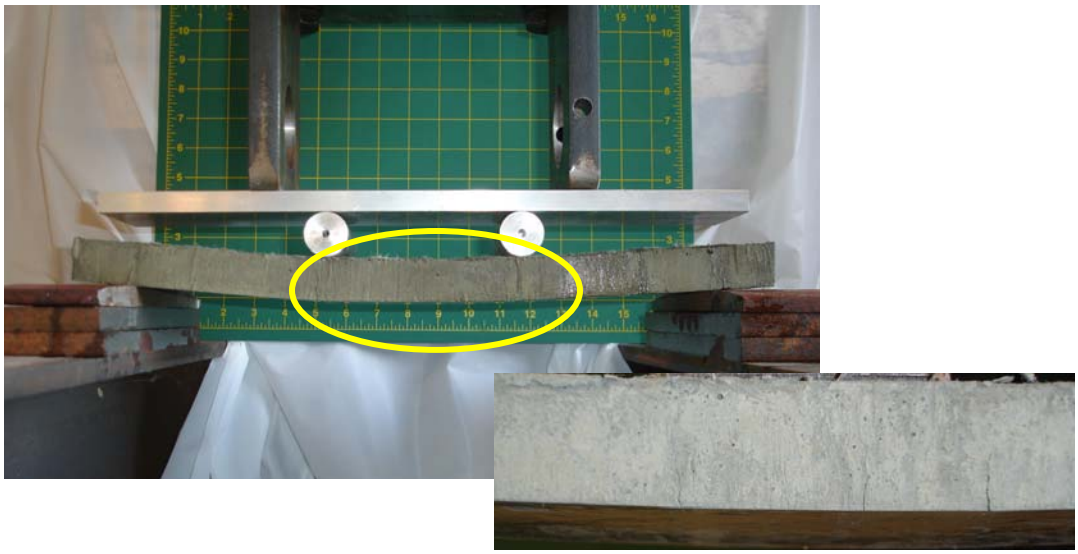


Figure 9. Failure of a ECC-PVA beam

Through the course of the project, the students came to realize that this was a journey, not a destination. And like any journey, a lot of leg work was required in the beginning and during in terms of searching the literature as well as talking with fiber manufacturers. On the materials science side of the project, students got to see and use superplasticizers in concrete. The students were very surprised to see harsh, dry mixes suddenly become very fluid like. Ultimately, the resulting composite mixes were meant to be self consolidating. In addition, the students were surprised to see how quickly the fibers were able in most cases to distribute through out the mix.

CONCLUSIONS

Of the mixes used to cast the beams, none exhibited truly ductile behavior as shown in the literature. Better bond between the cementitious paste and fibers was achieved by using micro-fibers. Further research and testing is required, which will be performed by the next class of the students. The current students learned about and worked hands-on with superplasticizers, type C fly ash, type I and type III portland cements, as well as with fibers. While the final goal may not have been reached at least yet, the students had an opportunity to work on a real research project, which involved developing and testing engineered cementitious composites.

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