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Large-Scale Processing of Engineered Cementitious Composites

by Michael D. Lepech and Victor C. Li

The design, processing, and evaluation of engineered cementitious composites (ECC) is investigated at large scales, up to 3 m^3 (4 yd^3). The design of ECC is undertaken to retain the pseudo-tensile strain-hardening properties characteristic of high-performance fiber-reinforced cementitious composites (HPFRCC) while optimizing for transit truck mixing procedures and short mixing times. Material design is based on tensile multiple cracking and grain size distribution criterion. Success of this design procedure is demonstrated at both small scales of 200 L (7 ft^3) and large scales of 3 m^3 (4 yd^3). Large-scale mixing specimen material properties are tested to establish a preliminary set of design values based on statistical analysis of large-scale mixing test results. Tests show that design parameters for compressive strength, tensile strength, and tensile strain capacity can be set at 60 MPa (8.75 ksi), 4.35 MPa (630 psi), and 2.0%, respectively, for the ECC-M45 material tested with 99% confidence.

Keywords: concrete truck; engineered cementitious composites; mixing.

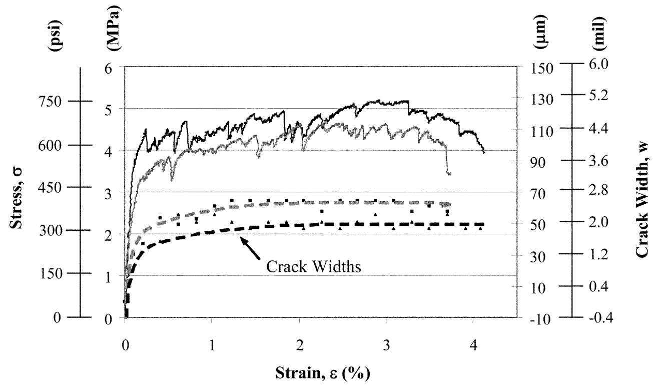

Fig. 1—Uniaxial tensile response of ECC.

INTRODUCTION

The on-site processing and mixing capabilities of concrete have played a crucial role in its ascendancy as one of the most heavily used anthropogenic materials worldwide.[1] In addition to its low cost and formable properties, the local nature of concrete processing, due in part to both convenience and hydration-imposed time limitations, is central to its increasing use, particularly in developing countries. Without the ability to use locally produced components, such as sand and gravel, in regional large-scale batching and truck transit operations, concrete construction projects on any scale would not be possible. Therefore, for new cement-based materials to be successfully introduced to the construction industry, they must be easily produced using existing technologies and equipment.

Engineered cementitious composites (ECC) are high-performance fiber-reinforced cementitious composites (HPFRCC) designed to resist large tensile and shear forces while remaining compatible with ordinary portland cement (OPC) concrete in almost all other respects such as compressive strength and thermal properties.[2] ECC materials are best suited for structural applications that require large ductility such as seismic-resistant structures[3] or high durability such as bridge decks, pavements, and other infrastructure exposed to harsh environmental conditions.[4] The high ductility and unique microcracking behavior allow ECC to outperform traditional concrete in these severe applications.

Figure 1 shows the uniaxial tensile response of two ECC (M45) test specimens reinforced with polyvinyl alcohol (PVA) fiber as characterized by Lepech and Li.[5] After first cracking, the composite undergoes plastic yielding and pseudo-strain hardening to a tensile strain of 3.5% prior to developing a macroscopic crack. This tensile strain capacity is approximately 350 times that of normal concrete (0.01%) and has demonstrated importance in improving ECC structural seismic resistance, impact resilience, and durability.[3,4,6] The microcrack development of ECC as material strain increases is also shown in Fig. 1. Rather than widening with greater strain as in typical fiber-reinforced concrete, microcracks within ECC maintain a constant width as strain increases beyond 1%, governed by fiber bridging behavior. Increasing deformation is accommodated by formation of additional microcracks up to saturation of the material and associated crack localization. Using a set of micromechanical tailoring tools, ECC achieves this strain-hardening and microcracking behavior using only a moderate amount of randomly distributed PVA fibers (typically 2% by volume) compared to other HPFRCC. Such high fiber volume requirements (>3% fiber volume fraction), or the use of continuous fibers, have prevented past HPFRCC field implementation efforts in large cast-in-place applications where conventional concrete mixing trucks and placing equipment is used such as bridges, pavements, or large structural elements that cannot be precast.

Kanda et al.[7] studied the tensile properties of ECC material in full-scale production in Japan. ECC compositions containing OPC and moderate heat-of-hydration portland cement were tested for large-scale production at ambient temperatures for both summer and winter conditions. ECC materials were mixed at a concrete prefabrication plant using a 1 m^3 (1.3 yd^3) omni-mixer, which agitated the material through external mixing paddles to deform a rubber mixing drum containing the cementitious material. This material

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was tested in the fresh state for yield, temperature, specific gravity, air content, and self-consolidation. Mechanical properties tested in the hardened state included compressive strength, elastic modulus, ultimate tensile strength, and ultimate tensile strain capacity. Eleven ECC batches ranging in size from 0.3 to 0.8 m^3 (8 to 28 ft^3) were mixed. These efforts comprise the largest scale of ECC production yet achieved.

Averaging over all three batch sizes 0.3 to 0.8 m^3 (8 to 28 ft^3), the ECC material exhibited a mean tensile strain capacity of approximately 2.9% for tensile coupon specimens, and a 96% confidence interval lower limit of 1.9% tensile strain capacity, from which Kanda et al.[7] concluded that full scale-production of ECC is possible and the material performance can be mechanically similar to that from laboratory preparation. Additionally, the quality control of ECC processed using large-scale omni-mixers could be controlled and confidence intervals could be formed to statistically manage the performance of the material.

Fischer et al.[8] have proposed a set of design procedures and workability requirements for large-scale processing of ECC materials. Fischer et al.[8] focused on the application of Fuller curve grain size distributions to proportion the various ECC matrix components, thereby producing a free-flowing mixture inside the mixing equipment and a self-consolidating material during placement. Relying heavily on optimization of the combined grain size distribution of all the matrix components to achieve a highly dense and closely packed material matrix, this methodology is analogous to creating a densely packed soil that is subject to liquefaction under earthquake vibration. Just as these soils identified by Fuller and Thompson[9] turn liquid under the slight agitation of an earthquake, the fresh matrix of closely packed, specifically graded particles easily liquefies from the agitation of a concrete mixer.

A major difference in constituents between ECC and ordinary concrete materials is the absence of coarse aggregate in ECC. Such large particles are intentionally eliminated from the composite to meet stringent low matrix fracture toughness requirements and to keep the large aggregates from dominating the microscale interactions between fiber and matrix, which are critical to strain-hardening behavior. During large-scale concrete batching and transit mixing, however, coarse aggregates facilitate material processing by effectively breaking up coagulate cement and sand within the mixer. Without such large stone particles and due to a low water-cementitious material ratio (approximately 0.25), ECC materials that are not intentionally designed to remain flowable within concrete mixing trucks throughout the mixing process can quickly flocculate, rendering the material unusable and potentially damaging mixing equipment.

Without the capability of easy processing using large-scale commercial batching plants and industry-wide concrete mixing trucks, HPFRCC such as ECC will continue to see little use within the concrete construction industry. Within this paper, a theory is presented for the design of ECC materials for large-scale commercial batching and mixing within a concrete mixing truck along with results from a series of large-scale ECC mixing trials. Intended applications for these ECC materials are large cast-in-place structures where conventional concrete mixing trucks and placing equipment is used, such as bridges, pavements, or large structural elements that cannot be precast off site. Additionally, statistical analysis of material testing from large-scale mixing trials is used to develop material design values with appropriate confidence levels.

RESEARCH SIGNIFICANCE

Concrete construction projects rely on local capabilities and resources to produce large quantities of fresh concrete in commercial batching plants and transit mixing trucks. Until new HPFRCC materials, such as ECC, have demonstrated proven processing capabilities using construction equipment common throughout the industry, they will continue to comprise a small portion of concrete construction work. By establishing a theoretical basis for ECC materials with large-scale mixing functionality, and quantifying the material properties associated with commercially produced ECC material, more widespread adoption of this HPFRCC material can be possible with confidence.

LABORATORY INVESTIGATIONS

Material design

The design of ECC materials for large-scale batching and mixing requires meeting two goals. First, the newly designed composite must exhibit the pseudo-tensile strain-hardening behavior characteristic of all HPFRCC materials, including ECC tested at quasi-static strain rates up to 10^{-3}/s. This behavior, which characterizes HPFRCC materials as ductile rather than quasi-brittle, sets them apart from traditional concrete and fiber-reinforced concrete. Without retaining highly ductile tensile material properties, this investigation is identical to large-scale mixing of tension-softening fiber-reinforced mortars or concrete, an endeavor undertaken daily throughout the concrete industry with great success. Second, the newly designed ECC composite must be tailored to mix thoroughly, meeting a defined set of fresh material properties and using commonly available construction mixing equipment (that is, gravity mixer, paddle mixer, or concrete transit mixing truck), in a reasonable amount of time.

Meeting the first criteria requires that the ECC material satisfy the two material conditions—one energy-based and one strength-based—for development of steady-state multiple cracking and pseudo-tensile strain-hardening behavior.[10,11] The formation of steady-state flat-cracks within ECC is essential to the formation of multiple cracks, the source of pseudo-strain in ECC, and governed by the interplay between the bridging stress versus crack width opening relation ($\sigma(\delta)$ relationship) and the fracture toughness of the mortar matrix, K_m. To attain this multiple cracking phenomenon, the inequality shown in Eq. (1) must be satisfied

$$J_b' = \sigma_0\delta_0 - \int_0^{\delta_0}\sigma(\delta)d\delta \geq J_{tip} \approx \frac{K_m^2}{E_m} \tag{1}$$

where J_b' is defined as complimentary energy; σ_0 and δ_0 are the maximum crack bridging stress and corresponding crack

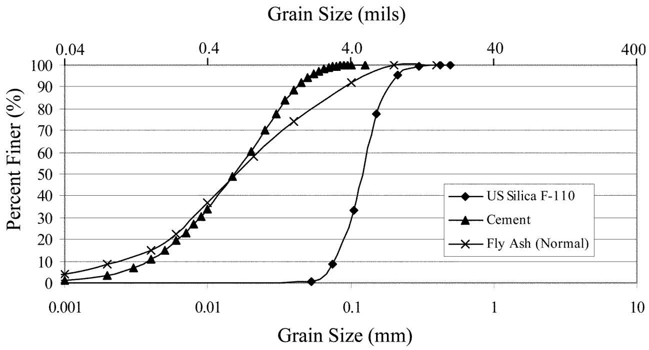

Fig. 2—Grain size distribution for ECC component materials.

Table 1—ECC mixture proportions by weight for ECC M45 to M48

Mixture designation	Cement	Fly ash	Sand	Water	HRWR*	Fiber, volume %
M45	1.0	1.2	0.8	0.56	0.012	0.02
M46	1.0	1.2	1.2	0.58	0.012	0.02
M47	1.0	1.2	1.4	0.59	0.012	0.02
M48	1.0	1.2	1.6	0.60	0.012	0.02

*High-range water reducer.

opening at maximum bridging stress; $\sigma(\delta)$ is the function describing crack bridging versus crack opening; J_{tip} is the fracture energy of the mortar matrix crack tip; K_m is the fracture toughness of the mortar matrix, and E_m is the elastic modulus of the mortar matrix. In addition to the fracture energy criterion of Eq. (1), a strength criterion expressed in Eq. (2) must also be satisfied to achieve the multiple cracking phenomenon.

$$\sigma_0 > \sigma_{fc} \tag{2}$$

where σ_0 is the maximum crack bridging stress, and σ_{fc} is the first cracking strength of the mortar matrix. For saturated multiple cracking, Wang and Li[12] found that Eq. (2) must be satisfied at each potential crack plane, where σ_{fc} is understood as the cracking stress on that crack plane. Within this study, the ability of ECC materials to exhibit tensile strain-hardening behavior is demonstrated through coupon tests run at quasi-static speeds to show composite multiple cracking performance and tensile strain hardening, rather than independent determination of fracture and $\sigma(\delta)$ curve parameters to numerically prove tensile strain-hardening capabilities. These relationships, however, form the basis behind the micromechanics-based design of ECC materials and the selection of specific ECC constituents and mixture proportions. Tensile tests were run at quasi-static speed to better observe crack formation. Yang and Li[13] have found that ECC test results run at quasi-static rates remain valid up to dynamic strain rates of 10^{-3}/s.

To meet the second criteria for design of ECC materials for large-scale processing, mixing thoroughly in a standard transit concrete mixing truck, the grain size distribution of mortar matrix components is designed to require minimal agitation, or mixing energy, to produce a construction-quality composite material. As mentioned previously, Fischer et al.[8] used the Fuller curve to design for optimal particle packing, resulting in a continuously free-flowing fresh material requiring little agitation energy. Material designed with this methodology can be processed using nearly any equipment, not only high-energy, force-based mixers commonly used in academic research laboratories or precast concrete plants.

Developed over a century ago, the Fuller curve estimation for particle packing has since been improved upon to produce an optimal grain size distribution for improved particle packing and, therefore, free-flowing, highly liquid conditions under agitation. The Alfred grain size distribution curve has been proven successful for such material design of ceramics and is shown as Eq. (3)[14]

$$\text{CPFT} = 100\left(\frac{D^q - D_s^q}{D_L^q - D_s^q}\right) \tag{3}$$

where CPFT is the cumulative percent of particles finer than a particle with a diameter of D; D_s is the diameter of the smallest particle in the distribution; D_L is the diameter of the largest particle in the distribution; and q is the distribution modulus. Whereas a variety of optimization forms for particle size distributions exist, Eq. (3) is selected for specific application to concrete and mortar particle distribution optimization, which is characterized by a wide range of particle sizes (that is, large aggregate to cement or fly ash). One shortcoming of the Fuller curve is the assumption that the finest particle size has minimal influence on the overall distribution behavior—in effect, that fine particles can be infinitely small. To account for the finite lower limits on particle size in mortar and concrete materials, Eq. (3) limits small particle size to D_s. As determined by Funk and Dinger[14] through analytical combination of polydisperse particle systems, optimal packing distribution is achieved with a distribution modulus equal to 0.37, which is different from the Fuller curve characterization but optimal for this characterization.

ECC dry material components used within this research are Type I portland cement, F-110 foundry sand, and Class F normal fly ash. The individual grain size distributions for each of these materials are given in Fig. 2. A baseline ECC mixture proportion, designated ECC-M45, which regularly exhibits tensile strain capacities between 3 and 4% in laboratory test results at 28 days, was adopted as a potential large-scale processing candidate for further grain size optimization (tensile response and crack development shown in Fig. 1). Randomly designated ECC-M45 in a series of previously carried out laboratory tests, mixture proportions were originally designed for superior mechanical material properties, based primarily on the pseudo-tensile strain-hardening conditions presented previously, and were intended to be processed using a high-energy laboratory mixer. No material design for ECC-M45 has considered potential mixing in lower-energy large-scale mixers (that is, gravity-based drum mixers or screw-based transit truck mixers).

Using the ECC-M45 mixture proportions given in Table 1, an aggregated grain size distribution was determined (Fig. 3). At small particle sizes, the ECC-M45 matrix closely follows the optimal grain size distribution calculated using the Alfred curve (Eq. (3)) with distribution modulus equal to 0.37, but deviates at larger particle sizes. To bring the distribution closer to optimal, a larger portion of sand particles was added to experimental mixtures ECC-M46 through ECC-M48. All proportions are given with materials in the dry state; therefore, water was proportionally added to each experimental mixture to return the additional sand to the saturated surface-dry (SSD) state. Aggregated particle size distributions for Mixtures ECC-M46 through ECC-M48 are shown in Fig. 3 along with the optimal grain size curve. To promote easier mixing in large-scale mixers, PVA fiber lengths were shortened from the typical 12 mm (0.5 in.) length to 8 mm (0.33 in.). Based on separate analytical studies, this fiber length change was shown to have a minimal effect on the crack bridging stress versus crack width opening curve $\sigma(\delta)$ and, therefore, little expected effect on the overall pseudo-tensile strain-hardening behavior of the ECC composite.

Experimental material design results

To evaluate the effect of changes in particle size distribution, a flowability test was performed on the fresh ECC immediately after processing of the material as outlined in Kong et al.[15] To perform this test, a standard concrete slump cone was filled with fresh ECC material and emptied onto a level Plexiglas or glass plate. The flowable ECC material flattened into a large pancake-shaped mass. Two orthogonal diameters of this pancake were measured and a characteristic flowability factor, denoted by Γ, was calculated (Eq. (4))

$$\Gamma = \frac{(D_1 - D_0)}{D_0} \tag{4}$$

where Γ is a fresh ECC deformability factor; D_1 is the average of two orthogonal diameter measurements after slump cone removal; and D_0 is the diameter of the bottom of the slump cone.

Whereas the overall impact of changing the amount of sand is minimal over the experimental mixture proportions investigated, a slight improvement is seen in ECC-M46 over ECC-M45, as expected from grain size distribution analysis (Table 2). A reduction of flowability occurs, however, with greater sand contents beyond ECC-M46 against expected results. This may be due to the drier nature of ECC-M47 and ECC-M48 compared with ECC-M45 and ECC-M46, as observed during the mixing process. Even with proper water adjustments to bring additional dry material to an SSD state, the flowability of high sand content materials continued to fall. This may also be a result of the mismatch between grain size distribution modeling assumptions and actual grain size distributions. The Alfred model was developed for optimal combination of a number of continuous grain size distributions, whereas some distributions used, particularly that for F-110 sand, are practically discreet. As a result of this grain size distribution analysis, only ECC-M45 and ECC-M46 were advanced beyond laboratory flowability testing as potential candidates for large-scale mixing trials.

Tensile coupon specimens were tested for laboratory-grade ECC-M45 and ECC-M46 to validate and compare multiple cracking and pseudo-tensile strain-hardening behavior of each composite mixture proportion. Uniaxial tension test procedures for ECC coupon specimens have been outlined by Li et al.[16] The tensile mechanical performance of laboratory-produced ECC-M45 or ECC-M46 in the hardened state did not differ significantly. Fifteen specimens were tested for both ECC-M45 and ECC-M46, showing an average tensile strain capacity of 3.1% and 3.0%, respectively. The standard deviation of tensile strain capacity among tested coupon specimens was lower for ECC-M45 as compared with ECC-M46—0.30% to 0.38%, respectively. Due to the lack of

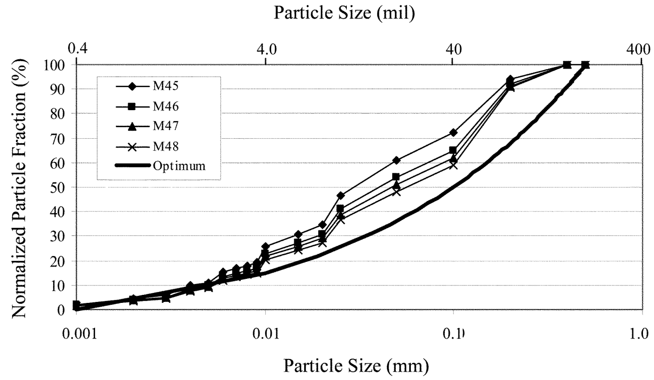

Fig. 3—Aggregated grain size distributions for M45, M46, M47, M48, and optimal aggregated grain size distribution curves.

Table 2—Fresh deformability of ECC M45 to M48

	Γ		
Mixture designation	Mean (μ)	Standard deviation σ	Count N
M45	3.4	0.4	6
M46	3.6	0.5	6
M47	3.2	0.4	6
M48	2.5	0.4	6

significant improvement in either fresh material flowability or mechanical tensile behavior with the increase of sand content, the original mixture proportions of ECC-M45 were advanced for further large-scale mixing trials and demonstration.

EXPERIMENTAL BATCH SEQUENCING

To scale up ECC material batching from small laboratory mixers into large transit mixing trucks, the sequence of mixture batching had to be adjusted from laboratory batching procedures to promote homogeneity of the material when finally discharging from the truck. In a laboratory setting, during which high shear mixers were used, all dry components of the matrix (cement, fly ash, and sand) were initially added to the mixer and blended. Following complete mixing of these dry materials, water was slowly added to gradually turn the mixture more liquid. After all water was added, a high-range water-reducing admixture was added. Finally, fibers were slowly added and dispersed throughout the mixture. The overall laboratory mixing sequence lasted between 10 and 15 minutes.

For large-scale batching and mixing, this processing sequence was not possible. Even in small batches at laboratory scales, the addition of all dry components followed by small amounts of water created a large mass of very dry material that was difficult for a lower-energy gravity-paddle mixer or a transit mixing truck to fragment without the benefit of coarse aggregate. Therefore, the batching sequence was adjusted to keep the mixture as fluid as possible throughout the mixing process and attaining its most viscous state at the very end of mixing (after the addition of the fibers). To examine the effect of the mixing sequence on ECC processing, two gravity-based paddle/drum mixers were used. A small drum mixer was used for initial investigations ranging up to 28 L (1 ft^3), and a larger drum mixer was used for investigations up to 200 L (7 ft^3). Seven mixing sequences were investigated in the 28 L (1 ft^3) mixer, of

Table 3—ECC mixing sequences and mixing results

Trial no.	Sequence	Mixer size		Mixing time, minutes
		28 L (1 ft^3)	200 L (7 ft^3)	
1	C + S + FA; W (95%); HRWR; W (5%); Fiber	Clumping	N/A	N/A
2	C; W (50%); S + FA; W (50%); HRWR; Fiber	Clumping	N/A	N/A
3	C (50%); W + HRWR; S + FA; C (50%); Fiber	Clumping	N/A	N/A
4	W; C + S + FA; HRWR; Fiber	Passed	Excessive mixing time	25
5	W + HRWR (50%); C + S + FA; W + HRWR (50%); Fiber	Passed	Minor clumping	14
6	S; W + HRWR; C + FA; Fiber	Passed	Passed	12
7	FA; W + HRWR; C + S; Fiber	Clumping	N/A	N/A

Notes: C = cement; S = sand; FA = fly ash; W = water; HRWR = high-range water reducer; Fiber = polyvinyl alcohol fiber; and N/A = not available.

Table 4—Large-scale ECC batching sequence times

Activity no.	Activity	Elapsed time, minutes
1	Charge all sand	2
2	Charge approximately 90 to 95% of mixing water, all HRWR, all hydration stabilizer	2
3	Charge all fly ash	2
4	Charge all cement	2
5	Charge remaining mixing water to wash drum fins	4
6	Mix at high rpm for 5 minutes or until material is homogenous	5
7	Charge fibers	2
8	Mix at high rpm for 5 minutes or until material is homogenous	5
	Total	24

Note: HRWR = high-range water reducer.

which three were successful to warrant testing in the larger 200 L (7 ft^3) mixer.

Three objectives were sought when performing this mixing. First, the material must remain highly fluid throughout the entire mixing process, and through the addition of fibers in the last mixing step. Second, the mortar matrix should be nearly homogenous after only a short mixing time and immediately prior to adding fibers. Third, the mixing sequence should allow for as short a mixing time as possible to keep pace with ongoing operations at commercial concrete batching plants. The mixing sequences tested and the results of these tests are shown in Table 3.

The most successful mixing sequence for both 28 and 200 L (1 and 7 ft^3) trials was Trial 6, which began with the addition of all the dry sand, along with the addition of all water and high-range water-reducer. Once these three components were well mixed (1 to 2 minutes), all other dry (nonfiber) components were added (cement and fly ash). The complete mortar matrix was then mixed for approximately 3 to 4 minutes or until the material was homogenous and sufficiently fluid to allow for efficient fiber dispersion. After this mortar mixing time, the fibers were added and the complete ECC composite was mixed for an additional 5 to 6 minutes or until the fibers were well dispersed. This mixing sequence resulted in an overall mixing time between 9 and 12 minutes.

Scaling up to 0.75, 1.5, and 3m^3 (1, 2, and 4 yd^3), mixing was accomplished using a commercial batching plant and transit mixing trucks. Adapting the Trial 6 batching sequence selected from preliminary 200 L (7 ft^3) mixing trials, and based on discussions with batching plant operators, a large-scale ECC batching sequence was devised for transit truck batching and mixing (Table 4). The elapsed time shown is the recommended time for execution of each of these activities at the time of batching. At the recommendation of batch plant operators, approximately 10% of mixing water was reserved for drum washing purposes. After all dry materials were added, this reserved mixing water was charged to wash dry material residue from the screw fins high within the mixing drum and move all materials to the bottom of the drum (Step 5 in Table 4). During the course of this washing, the remainder of the reserve mixing water was added into the truck to maintain the correct water-cement ratio (w/c). This step proved critical in getting all materials well mixed within the mixing drum.

As expected, due to the absence of large aggregate to agitate materials within the mixing drum, additional mixing time is needed between charging of the matrix materials and the fibers. This 5 to 10 minutes of mixing time provides further agitation and time for the high-range water-reducer to liquefy the material. To reduce batching time at the concrete plant and make use of travel time to the site, this mortar mixing time can take place in transit. After arriving at the job site, the fibers can then be added. Once the fibers are charged into the drum, the composite is mixed (at high RPM) on site for an additional 5 minutes for proper dispersion.

LARGE-SCALE MIXING RESULTS

The weather conditions for both 0.75 and 3 m^3 (1 and 4 yd^3) trial days were sunny, with high temperatures of 17 and 25 °C (62 and 77 °F) for each trial, respectively. Conditions for the 1.5 m^3 (2 yd^3) trial were a light rain with temperature of 8 °C (47 °F). Because a number of raw materials within ECC-M45 are not typically stored in concrete plant batching towers within Michigan (that is, F-110 silica sand and Type F fly ash), it was not practical to charge these materials into the concrete mixing truck from the batching tower during the large-scale trials. Therefore, the sand, fly ash, fibers, and admixtures were manually charged into the batching funnel according to the batching sequence (Table 4), whereas cement and mixing water (which are common concrete components in Michigan) were charged using the plant batching tower. While this does not exactly duplicate the times within batching sequence expressed in Table 4, this scenario was as close as possible to reality. The batching was done according to the ECC-M45 batch weights set forth in Table 1.

Quantitative evaluation of the fresh ECC was carried out through flowability testing of the material as described previously. Minimum fresh material property requirements were adopted from the Michigan Department of Transportation's "General Contract Special Provision for ECC Bridge Deck Link Slab."[17] A minimum deformability value Γ of 2.75 was established within this contract provision for acceptance of ECC material on Michigan highway projects

Table 5—Compressive strength, tensile strength, and ductility test results for large-scale ECC batching

Age, days	Compressive strength, MPa (ksi)	Standard deviation, MPa (ksi)	No. of samples
4	30.31 (4.40)	3.22 (0.47)	9
7	51.96 (7.54)	3.03 (0.44)	9
14	61.52 (8.92)	2.66 (0.39)	9
28	64.20 (9.31)	2.72 (0.40)	9
Age, days	First cracking strength, MPa (ksi)	Standard deviation, MPa (ksi)	No. of samples
4	3.94 (0.57)	0.26 (0.04)	18
7	4.41 (0.64)	0.21 (0.03)	18
14	4.78 (0.69)	0.37 (0.05)	18
28	4.79 (0.70)	0.32 (0.05)	18
Age, days	Ultimate tensile strength, MPa (ksi)	Standard deviation, MPa (ksi)	No. of samples
4	4.80 (0.70)	0.22 (0.03)	18
7	5.34 (0.78)	0.48 (0.07)	18
14	5.52 (0.80)	0.57 (0.08)	18
28	5.94 (0.86)	0.50 (0.07)	18
Age, days	Tensile strain capacity, %	Standard deviation, %	No. of samples
4	2.4	0.41	18
7	2.3	0.16	18
14	2.2	0.20	18
28	2.2	0.17	18

and based on small-scale trial roadway patching projects using ECC batched in small-scale mixers. According to the construction contract provision, this deformability value was required to be held for 60 minutes after batching to allow for transit of the ECC material to the job site. Through proper grain size distribution, an initial value of 2.75 was surpassed for ECC-M45 (Table 2). Using a hydration stabilizer at a dosage of 325 mL/100 kg cement (5 fl oz/100 lb cement), the minimum flowability value of 2.75 was retained for approximately 30 minutes for the 0.75 m^3 (1 yd^3) trial (Fig. 4). Therefore, the hydration stabilizer dosage was increased to 400 mL/100 kg cement (6 fl oz/100 lb cement) for the 1.5 and 3 m^3 (2 and 4 yd^3) trials, resulting in acceptable flowability for the required 60-minute transit mixing time (Fig. 4).

During each large-scale trial, a series of twelve 100 x 200 mm (4 x 8 in.) compressive cylinders were cast. Four cylinders were cast immediately after initial batching, four after 30 minutes, and four after 60 minutes. This series of cylinders allowed for an evaluation of compressive strength gain over time, but also allowed for differences in the material that may result from longer mixing times. The strength gain of the trial mixture material was similar to that of the laboratory material (Fig. 5 and Table 5). Ultimately, the large-scale mixing material showed a compressive strength of between 62 and 69 MPa (9 and 10 ksi), similar to laboratory-grade material. Also seen in Fig. 5, specimens from each trial that were cast at different times during the required 1 hour of mixing are indistinguishable from one another and show similar development of compressive strength. Regardless of how long the material mixes within the truck, as long as it is discharged before the 1-hour time limit has expired, good confidence can be held in the hardened mechanical properties of the ECC-M45 material.

Uniaxial tension testing coupons were cast during each large-scale mixing trial. Eight plates were cast at times of initial batching, 30 minutes, and 60 minutes. Six plates from

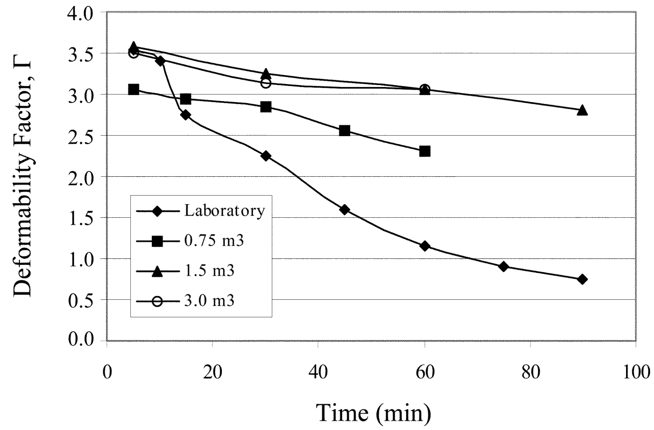

Fig. 4—Deformability of fresh ECC over time for various large-scale trial mixtures.

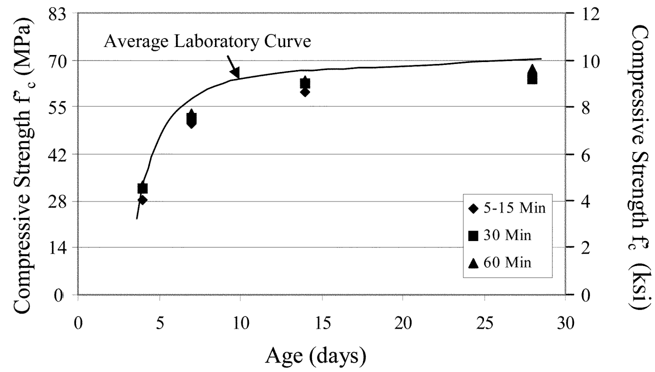

Fig. 5—Development of compressive strength over time for samples taken over 1-hour transit time.

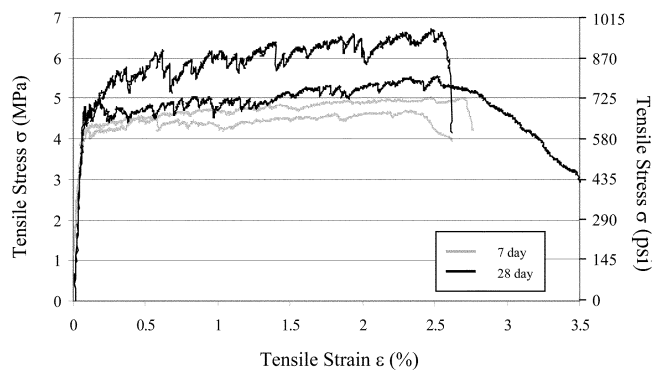

Fig. 6—Uniaxial tensile response of ECC processed using large-scale transit mixing trucks at 7 and 28 days.

each sampling time (24 from each trial mixture) were tested at an age of 4, 7, 14, and 28 days. This testing scheme is very similar to the compressive strength scheme such that the tensile strength and ductility development of the large-scale trial material over time can be observed, but also any variation of the material throughout the 60-minute mixing time. Representative uniaxial tension test results for 7 and 28 days are shown in Fig. 6 with accompanying statistical data in Table 5.

For large-scale trial mixtures, a mean 28-day tensile strain capacity of approximately 2.2% was observed with an average ultimate tensile strength of 5.9 MPa (860 psi). Whereas a strain capacity of between 2 and 2.5% is below

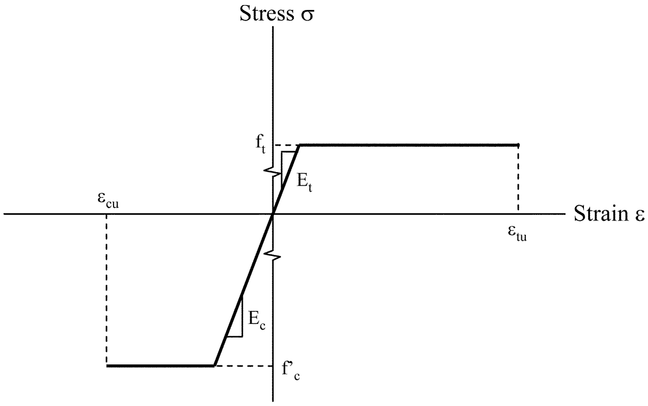

Fig. 7—Elastic-perfectly-plastic constitutive model for ECC materials.

the typical expected values associated with laboratory-grade ECC material, this outcome can be understood in the context of the findings by Kanda et al.[7] showing a drastic reduction between laboratory-grade ECC and ECC material mixed at a large-scale facility in Japan. Over the course of the three trials (0.75, 1.5, and 3 m^3 [1, 2, and 4 yd^3]), overall tensile response of the material improved (28-day tensile strain capacity increased from 2.1% for the first large-scale trial to 2.5% for the third large-scale trial), suggesting possible improvements as a result of increased mixing experience. These improvements may continue as more large-scale mixing experience is accumulated and more rigorous ECC quality assurance and quality control standards are adopted.

Comparing the ECC compressive strength gain (Fig. 5) with the tensile first cracking and ultimate strengths (Fig. 6), the magnitude of strength gain from early age (4 days) up to full strength (28 days) is significantly different. This difference highlights the vastly different failure modes of ECC (or concrete) in compression and tension throughout hydration. Independent of age, the tensile first cracking strength and ultimate tensile strength of ECC are governed by crack initiation from defect sites and fiber bridging failure, respectively. Compression failures in ECC are governed by the crushing strength of the material, which is low at early age and rises significantly with time (as seen in Fig. 5).

DISCUSSION

The ultimate goal of this research is to advance large-scale ECC materials processing technology to a stage at which engineers can begin to design confidently with these new materials, and material contractors can provide this material with consistently high quality. To undertake design with HPFRCC materials, a small number of material parameters must be established as minimum design values that can be used with appropriate confidence. Together, these parameters form a constitutive model for use in structural design. Initially for use in design, this model may be an assumed elastic-perfectly-plastic model without accounting for pseudo-strain-hardening behavior. The major difference between an elastic-perfectly-plastic model and pseudo-strain-hardening behavior is the assumption of no increase in strength with increased deformation in the elastic-perfectly-plastic model (Fig. 7), which ignores the demonstrated hardening behavior of ECC in tension (Fig. 1 and 7). Ultimately, this assumption results in a reserve of material and, therefore, structural, load capacity as deformation increases, thereby providing higher actual load capacity than anticipated in design. Such conservatism is appropriate when introducing new materials into the engineering design community.

To properly define such a model, six parameters are needed (Fig. 7). These parameters are the elastic modulus in tension and compression, E_t and E_c; tensile strength f_t; ultimate tensile strain capacity ε_{tu}; compressive strength f_c'; and ultimate compressive strain capacity ε_{cu}. Within this work, statistical information from large-scale trial mixtures was gathered to determine three of these six variables: tensile cracking strength, ultimate tensile strain capacity, and compressive strength. Ultimate tensile strength was also recorded. Instrumentation and data collection for closely monitoring elastic modulus in compression or tension, along with compressive strain capacity, was not performed in this investigation for a significantly large sample set of specimens to allow for faster testing of ECC coupons and cylinders to keep pace with MDOT construction schedules for projects implementing ECC material. Therefore, only three of the parameters are characterized within this study. For design, deterministic values of tensile and compressive modulus, and ultimate compressive strain capacity can be taken for ECC-M45 from the literature.[18-20] For the three parameters studied, minimum values for appropriate confidence levels were determined for use in design. As a larger body of test data develops, confidence levels should be developed for ECC elastic moduli and ultimate compressive strain capacity.

To develop confidence levels for these material parameters, the appropriate distribution capturing material variability was identified. Whereas the number of compressive and tensile specimens tested throughout these trials (36 and 72, respectively) represents a statistically meaningful sample size, a larger set of material test data accumulated from ECC-M45 laboratory tests was used to identify the appropriate material variability distributions. These laboratory sample sets were used only to characterize the type of distribution pertaining to ECC-M45 material properties and not determine large-scale ECC-M45 material properties.

Four material parameters—first cracking strength, ultimate tensile strength, ultimate tensile strain capacity, and ultimate compressive strength—were gathered for 112 tensile and 110 compressive laboratory tests conducted at 28 days. Plotted on a normal probability scale (Fig. 8(a) to (d)), these material parameters exhibit a normal distribution with proportions of explained variation (R^2 factors) of 0.95, 0.93, 0.96, and 0.99 for first cracking strength, ultimate tensile strength, ultimate tensile strain capacity, and ultimate compressive strength, respectively. Additionally, results from the Kolmogorov-Smirnov normality fitness test[21] confirm with over 99% confidence that each of these four distributions can be approximated normally. Therefore, a normal distribution was used to model material variability for these ECC material properties.

Using large-scale test data presented previously, a set of minimum material parameters was based on appropriate statistical confidence levels. Within the ACI Building Code,[22] a 99% confidence level is required for reaching 90% of compressive design strength for any individual test result. ACI 318 further requires that for materials with a compressive strength over 34 MPa (5000 psi), a 99% confidence level is required for 100% of design strength among any set of three material test results. These confidence levels are expressed in Eq. (5) and (6), respectively

Table 6—Design values for ECC material from large-scale processing (99% confidence)

Parameter	Test mean f'_{cr}	Test standard deviation σ	Design value (99% confidence)
Compressive strength, MPa (psi)	64.20 (9.31)	2.72 (0.40)	60 (8.7)
First crack strength, MPa (ksi)	4.79 (0.70)	0.32 (0.05)	4.35 (0.63)
Ultimate tensile strength, MPa (ksi)	5.94 (0.86)	0.50 (0.07)	5.25 (0.76)
Tensile strain capacity, %	2.2	0.17	2.0

$$f'_{cr} = 0.90 f'_c + 2.33\sigma \quad (5)$$

$$f'_{cr} = f'_c + 1.34\sigma \quad (6)$$

where f'_{cr} is the mean compressive strength of the material tested, f'_c is the compressive strength used in design calculations, and σ is the standard deviation of measured material compressive strengths.

Using a normal distribution model, a set of minimum design values meeting these confidence levels is shown in Table 6 for ECC-M45 first cracking strength, ultimate tensile strength, ultimate strain capacity, and compressive strength, along with the statistical parameters used in the calculations. Whereas the 99% confidence levels assumed in Eq. (5) and (6) are recommended for compressive strength within the ACI Building Code, identical confidence levels are adopted for tensile properties for ECC-M45 as well. Based on 28-day test data from large-scale mixing trials, design compressive strength values, design tensile strength values, and design ultimate strain capacity values for ECC-M45 mixed in large-scale transit mixing trucks should be set at 60 MPa (8.7 ksi), 4.35 MPa (630 psi), and 2.0%, respectively. If a more advanced material constitutive model was used that incorporated strain hardening after first cracking, as proposed by the active RILEM Technical Committee on High Performance Fiber Reinforced Cement Composites (TC-HFC),[23] an ultimate tensile design strength could also be assumed as 5.25 MPa (760 psi) with 99% confidence. In the case of TC-HFC,[23] a linear strain-hardening model is assumed from the point of first cracking up to the stage of crack localization and load drop.

CONCLUSIONS

Within this work, the design and optimization of ECC materials for large-scale commercial batching and transit mixing was completed. The three large-scale trial mixtures of 0.75, 1.5, and 3 m^3 (1, 2, and 4 yd^3) verified that large-scale mixing of ECC material is possible and can result in a material that is both high performing by retaining overall ductility and mircocracking behavior, and commercially capable of production using large-scale batching and truck-based mixing operations. Additionally, enough material testing has been carried out to determine statistically significant minimum design values with appropriate confidence levels for ECC-M45 materials batched and mixed using commercial equipment and facilities.

Prior to large-scale mixing, grain size distribution analysis was conducted, and preliminary small-scale test mixtures in gravity-based paddle-type drum mixers (capacity of 200 L [7 ft^3]) were completed. This preliminary theoretical and experimental work established a material design methodology

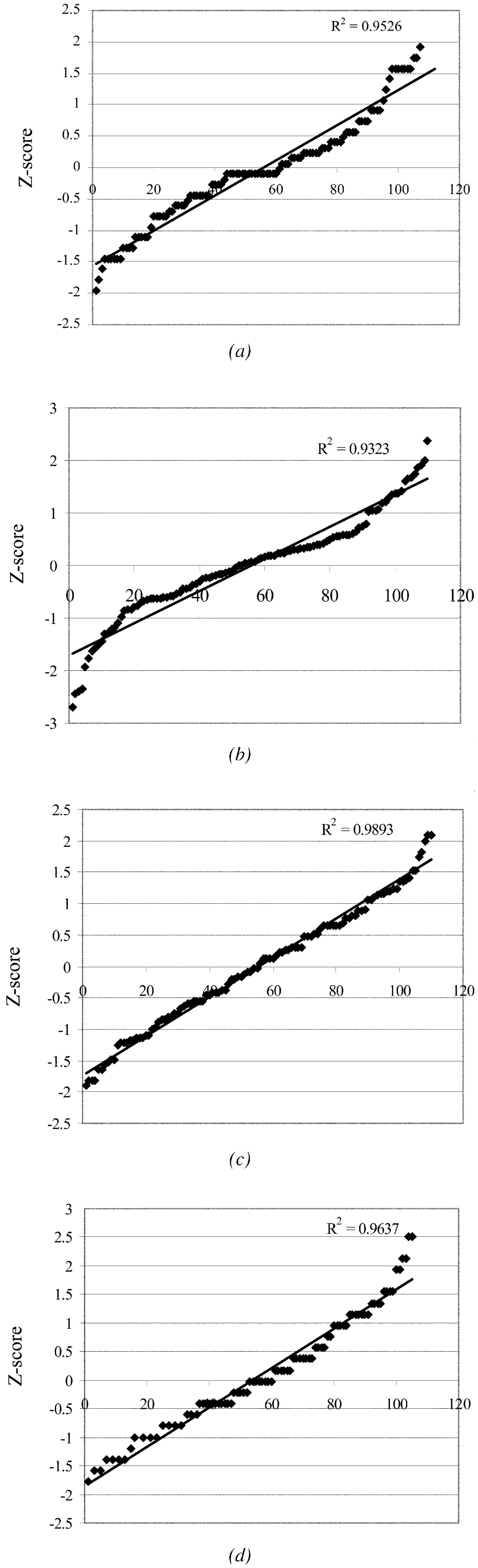

Fig. 8—ECC material parameters plotted on normal probability scale for 112 uniaxial tension tests and 110 compression tests: (a) first cracking strength; (b) ultimate tensile strength; (c) ultimate compressive strength; and (d) ultimate tensile strain capacity.

and batching sequence for large-scale ECC processing. A commercial concrete batching plant and concrete transit mixing trucks were used to perform a series of trial mixtures to process three trial batches of ECC material, each increasing in total volume up to 3 m^3 (4 yd^3). These trial mixtures provided meaningful lessons on large-scale mixing of ECC-M45 material in conventional transit truck mixers. Using the predetermined batching sequence, the overall mixing of ECC-M45 material resulted in a fresh material that was homogeneous, flowable, and rheologically stable. Further, the ECC-M45 material retained these fresh properties up to the 60-minute time limit required for transit time by the Michigan Department of Transportation.

Testing of ECC-M45 mechanical properties has shown that the compressive strength gain of material processed at large scales is similar to that of laboratory mixtures. The tensile performance, however, does exhibit a reduction from that typically seen in laboratory-grade ECC-M45 material. Using a dataset of large-scale ECC material test results, minimum values of ECC-M45 design parameters for compressive strength, tensile strength, and ultimate tensile strain capacity are set with a 99% confidence level. These values are 60 MPa (8.75 ksi), 4.35 MPa (630 psi), and 2.0%, respectively, for ECC-M45 material mixed in large-scale commercial concrete batching plants and mixed using transit mixing concrete trucks.

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