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PRELIMINARY FINDINGS ON SIZE EFFECT IN ECC STRUCTURAL MEMBERS IN FLEXURE

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ABSTRACT

This article examines the presence of size effect in ECC structurally sized members in flexure. High tensile strain capacity, fracture toughness, and characteristic length make ECC an ideal material for preventing brittle failures responsible for size effects present in concrete members. This study primarily focuses on the structural implications of size effect in ECC and steel reinforced ECC (R/ECC) members. Three series of beam specimens fabricated of reinforced concrete, ECC, and R/ECC are tested in flexure to determine the presence and severity of size effect. Preliminary test results of structurally sized members, currently up to 1.4 meters in length, are presented. Correlations between size effect in brittle and quasi-brittle materials and material characteristic length are also discussed.

Keywords
Engineered Cementitious Composite, ECC, Size Effect, Flexural Strength, Toughness, Characteristic Material Length

INTRODUCTION

Current trends in civil engineering are leading towards larger structures with increasing performance demands, however, existing construction materials may not be able to meet these higher requirements. The use of oversized building elements made of high strength concrete to overcome high load requirements in large structural applications illustrates this scenario. While the strength of the building elements, as computed based on material strength, may be adequate, the high brittleness of the members, due to both limited material properties and large member size, may lead to alternative failure modes, ultimately lowering load capacity. The dependence of structural brittleness, specifically upon member size, is of great concern as structural applications grow larger and require higher strength capacity.

It is well established that the flexural and shear strength of members made with quasi-brittle materials is not constant with specimen geometry or size, but rather diminishes as specimen size grows larger. This is largely due to fracture failure of the material. This phenomenon, referred to as the size effect, was first quantified in concrete by Hillerborg, et al [1] by the definition of the brittleness ratio. This quantity, based on specimen material properties and geometry, first captured the effect of specimen size on flexural strength. Further quantification of size effect in concrete was achieved by Bazant et al [2,3] through the introduction of the generalized size effect formula. This non-linear fracture mechanics based theory relates concrete size effect to a characteristic material length, most commonly nominal aggregate size in concrete. Similar results have been found by others, including Carpenteri et al [4].

While brittleness is the primary cause for the presence of size effect in most cementitious materials, Engineered Cementitious Composites (ECC), a class of ultra ductile fiber reinforced cementitious composites, exhibit very high fracture energy, up to 34 kJ/m^2 [5]. This high toughness, comparable to the toughness of aluminum, is achievable through the addition of discontinuous short length fibers and a micromechanics based design approach. The design methodology features constituent tailoring and optimization to attain material properties such as high fracture toughness, large tensile strain capacity, and small crack widths. All of these characteristics are achievable due to the formation of closely spaced microcracks, which allow for the formation of large fracture process zones and tensile pseudo-strain hardening of the material.

As mentioned, the primary cause for size effect in cementitious materials is brittleness. With a fracture energy roughly 3000 times that of hardened cement paste, the resistance of ECC to fracture failure may lead to a significant reduction or elimination of size effect in ECC when compared to concrete. This effect was demonstrated by Kuneida et al [6] through investigation of ECC flexural members ranging from 0.4 meters to 1.2 meters in length. While inconclusive in determining size effect on flexural strength, promising experimental and analytical results were obtained for small-scale ECC members. High fracture energy, in combination with the initial data from Kuneida et al's small scale element studies, suggest as a minimum a slight reduction of size effect in ECC when compared to plain concrete and quasi-brittle fiber reinforced concrete materials.

Analytical work in this regard was performed by Li et al [7] on ECC material containing polyethylene fibers. Numerical analysis performed on concrete and various ECC materials demonstrated that in concrete, size effect is dominated by the matrix properties, while for fiber reinforced composites, size effect is increasingly dependent on fiber properties and fiber bridging relationships. As the structural brittleness number decreased for various specimen sizes, the severity of size effect also diminished. For specimens ranging in depth from 2 cm to 10 cm, negligible size effect was seen from ECC while the size effect in concrete specimens of similar size and geometry exhibited a significant reduction in strength.

The objective of this study is to clarify experimentally the size effect of structurally sized members made with ECC material. While the value of small-scale studies cannot be underestimated as a basis for larger work, until the phenomenon of size effect is studied in large size components, closer to the scale of building members, its impact on the engineering and construction community cannot be ascertained. This study, and the preliminary results discussed in this article, is focused on the examination of both small and large flexural members fabricated with both un-reinforced and reinforced ECC to examine the effect of size on flexural strength both with and without main reinforcement. The results presented and discussed herein are preliminary and serve as a beginning of larger testing series to follow.

EXPERIMENTAL PROCEDURES

Materials

This study utilized an ECC comprised of 2% by volume poly-vinyl-alcohol (PVA) fibers in random orientation along with standard mortar matrix components, cement, fine aggregate (0.1 mm nominal grain size), water, and various admixtures to improve the fresh properties of the mixture. Mixing proportions are detailed in Table 1. Mechanical properties determined by uniaxial tension testing demonstrated an average first cracking strength of roughly 2.8 MPa at 0.06% strain, an ultimate tensile strength of 4.0 MPa, and a tensile strain capacity of 4.9% (Figure 1). The ductility of this ECC in terms of tensile strain capacity is therefore approximately 500 times that of concrete or normal fiber reinforced concrete (FRC). The ultimate compressive strength of the ECC material was 60 MPa.

Table 1. Material Mix Proportions by Weight for Concrete and ECC

	Cement	Aggregate	Sand	Fly Ash	Water	Superplasticizer	Methyl Cellulose	Fiber (Volume)
Concrete	1.0	2.0	2.0	0.0	0.45	0.01	0.0	0.0
ECC	1.0	0.0	1.0	0.1	0.45	0.02	0.0015	0.02

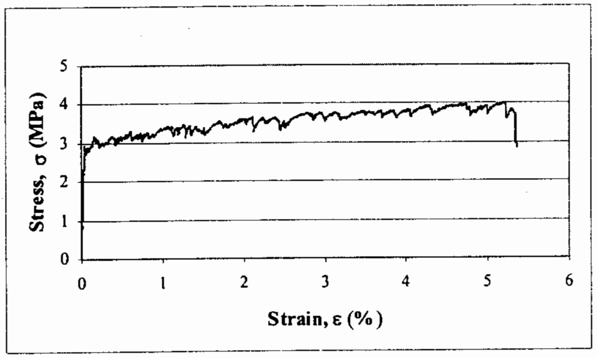


Figure 1. Tensile Stress-Strain Curve of ECC Material

Concrete used in this study for comparison purposes was composed of cement, coarse aggregates (10 mm nominal grain size), fine aggregate, and water. Various admixtures were used as needed to optimize fresh concrete properties. The mix proportions of concrete are also reported in Table 1. While tensile testing was not carried out on concrete specimens, the tensile strength and ultimate strain capacity may be assumed equal to or slightly lower than the first crack strength and first crack strain of ECC, respectively. The compressive strength of concrete used in reference specimens was 45.0 MPa.

The longitudinal reinforcement in reinforced ECC specimens consisted of deformed steel reinforcing bars with a yield strength of 410 MPa, yield strain of 0.2%, ultimate strength of 620 MPa, and ultimate strain of approximately 14%. The reinforcing ratio for all specimens was kept constant, however, due to the small size of some specimens, conventional steel reinforcing bars could not be used. In this case, smooth steel rods of comparable strength and strain capacity were used after being mechanically deformed to more realistically simulate the conventional bars used in larger specimens.

Specimen Configuration
Three series of flexural specimens were tested in mid- point bending (Figure 2) to determine the load-deflection curve for each specimen, and ultimately the modulus of rupture (MOR). The three series consisted of reference concrete, ECC, and steel reinforced ECC (R/ECC). Each series consisted of a set of beams with subsequently doubled size for most specimens, e.g. each beam was scaled twice as large as the previous beam. Specimen geometries were sized in two dimensions, beam depth and span, while the beam width was kept constant for all specimens at 0.075m. Test beam sizes are further detailed in Table 2. For R/ECC specimens, the reinforcement ratio was kept constant at 1.6% for all specimen sizes and at a depth of 85% of overall specimen height. This reinforcement ratio was chosen for convenience as a result of beam dimensions used in this study and standard reinforcing bar sizes. In this article, results from the first four beam sizes for each series are reported. Ultimately, seven beam sizes are planned for testing, up to a beam length of 4.2 meters.

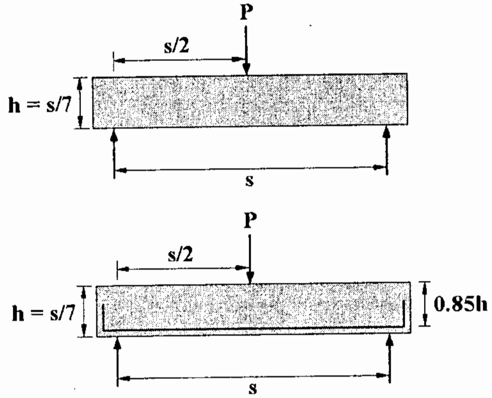


Figure 2. Test Specimen Geometry

Table 2. Test Specimen Dimensions and Notation

Test Series	Notation	Test Number (#)	Span Length, s (meters)
Reinforced Concrete	RC-#	1	0.175
ECC	ECC-#	2	0.263
Reinforced ECC	R/ECC-#	3	0.35
		4	0.7
		5	1.4

In order to examine the effect of the ductility of ECC on size effect most efficiently, beams were tested at the age of highest material performance. It can be seen from the micro-mechanical model used in the development of ECC material that a delicate balance exists among PVA fiber properties, the interfacial interaction between fiber and matrix, and the characteristics of the surrounding matrix [8]. While fiber properties are constant, as the matrix matures, the interfacial and matrix fracture properties vary, resulting in a slightly different performance in ECC material at early age. This is most evident in the first three weeks of curing. For testing purposes, optimal performance was assumed to be directly related to ultimate tensile strain capacity. This was determined through direct tension tests of

ECC plate specimens. The development of strain capacity with age is shown in Figure 3. From these tests, the optimal age for testing was determined to be roughly 10 days.

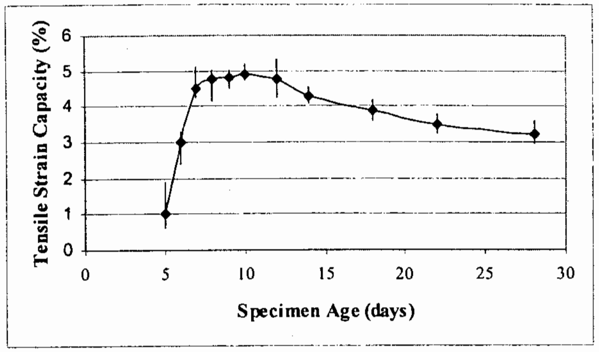


Figure 3. Early Tensile Strain Capacity Development of ECC

EXPERIMENTAL RESULTS

Experimental test results are summarized in Table 3. Reported is the modulus of rupture for each specimen. Experimental results from the reinforced concrete control specimens tested are as expected, showing the characteristic size effect seen in other studies of this nature. The failure mode of most concrete specimens was diagonal shear failure, however in the smaller specimens this failure mode was shared by bending failure. These results are similar to those seen by Bazant and Kazemi [9] while studying reinforced concrete beams of similar design.

Table 3. Flexural Test Results of Reinforced Concrete, ECC, and R/ECC Beams

Series	MOR (MPa)	Series	MOR (MPa)	Series	MOR (MPa)
RC-1	19.76	ECC-1	12.52	R/ECC-1	14.92
	22.92		12.84		16.83
	22.07		11.28		13.49
			15.13		16.55
RC-2	Not Tested	ECC-2	9.88	R/ECC-2	12.88
			12.71		16.79
			16.31		18.47
RC-3	13.88	ECC-3	14.45	R/ECC-3	18.38
	12.72		11.54		13
	15.03		12.17		14.76
			18.77		19.4
RC-4	12.77	ECC-4	11.54	R/ECC-4	12.79
	11.88		13.17		14.99
	10.51		14.77		16.41
RC-5	8.62	ECC-5	11.54	R/ECC-5	13.75
	9.91		13.17		15.21
	9.70		14.77		18.23

Typical load versus midspan displacement curves for ECC specimens are shown in Figure 4. Similar to the tensile behavior of ECC specimens, the flexural specimens show an elastic pre-cracking regime followed by an extensive strain-hardening branch before ultimate failure. This strain hardening is accompanied by the formation of concentrated micro-cracks in beam sections of maximum curvature. After considerable deflection and development of micro-cracks, a single macro-crack finally localizes and load capacity drops. The failure mode for these specimens is primarily flexural with the macro crack forming near midspan and propagating upward ultimately to specimen failure.

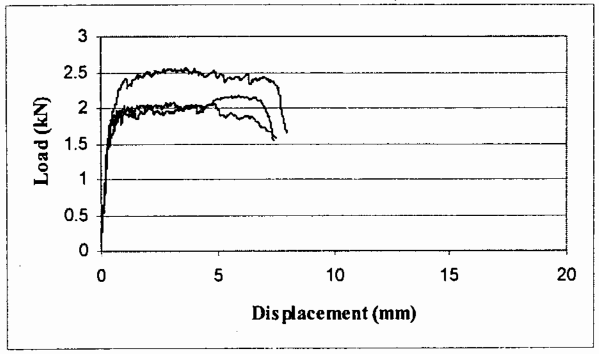


Figure 4. Load vs. Displacement Curves of ECC-3 Specimens

Typical load versus midspan displacement curves for R/ECC are shown in Figure 5. Analogous to ECC beams, the R/ECC specimens exhibit an initial elastic pre-cracking regime, which is slightly stiffer than seen in ECC beams. This elastic zone is followed by a strain-hardening behavior, together with formation of concentrated micro-cracking in the areas of highest curvature, and therefore maximum moment. While the formation of a localized macro-crack in ECC specimens was indicative of ultimate failure, the localized crack in R/ECC specimens propagated up to the level of reinforcement. After further load increase, slight yielding of the steel along with further extension of the localized macro-crack in shear-like failure was seen up to conclusion of the test at maximum allowable test deflections.

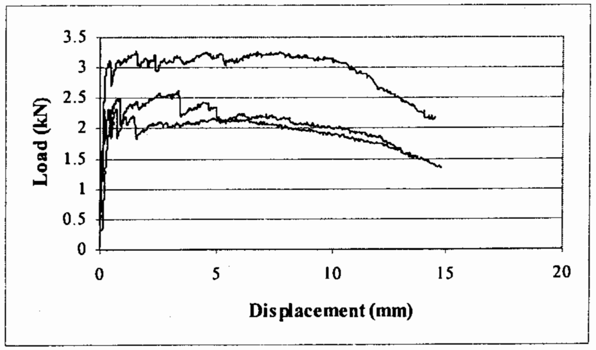
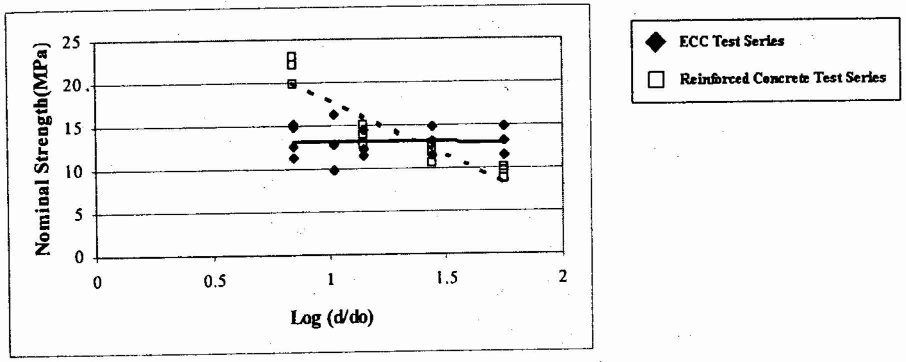


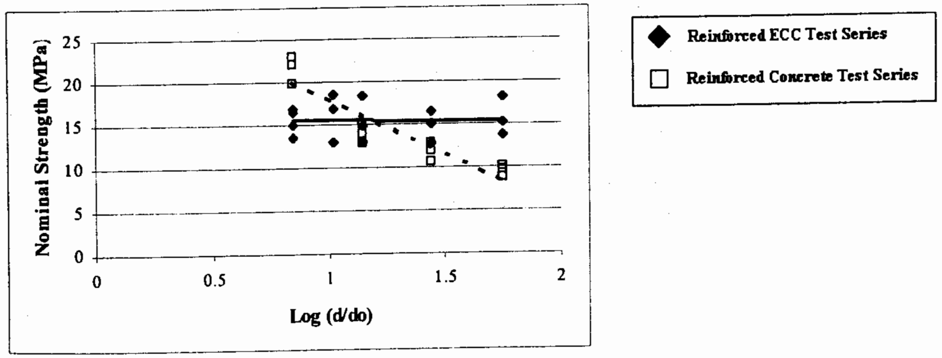
Figure 5. Load versus Displacement Curves of R/ECC-3 Specimens

The overall effect of specimen size on nominal strength is seen when the results from all flexural tests are assembled, as shown in Figure 6. The flexural strength is plotted versus

non-dimensional specimen depth. The non-dimensional depth is calculated by dividing the specimen depth by width, since the width is kept constant for all specimen sizes. From Figure 6 (a), the presence of size effect in ECC, when compared to reinforced concrete specimens is minimal. While the nominal strength of concrete specimens exhibits a significant decrease through the range of sizes tested, ECC specimens show a remarkably steady nominal strength throughout the range of sizes currently tested. This is also seen in the comparison between reinforced concrete and R/ECC specimens, shown in Figure 6 (b). While there is a considerable amount of variation in nominal strength among test specimens, even test specimens of the same size, the lack of size effect in this range of beam sizes made of both ECC and R/ECC material is evident.



(a) Reinforced Concrete and ECC Specimens



(b) Reinforced Concrete and R/ECC Specimens

Figure 6. Presence of Size Effect in Reinforced Concrete, ECC, and R/ECC Specimens

DISCUSSION

As mentioned above, the presence of size effect in ECC in comparison to concrete is minimal when dealing with the structurally sized members tested thus far. Over the range of specimens tested, on average, reinforced concrete specimens saw a significant reduction in nominal strength, while ECC and R/ECC specimens experienced a negligible drop in strength over the same range of beam sizes. While further testing of larger sizes is planned, similar results are anticipated. As structural member sizes increase, the severity of size effect in concrete will continue to become a larger problem, requiring the use of still larger member sizes to overcome lower strength while further exacerbating the problem. Through the use of higher toughness materials with less severe, or even negligible size effect, such as ECC and R/ECC, this continual enlarging of member size, or the need for compensating steel reinforcement, can be avoided.

Along with the preliminary establishment of the small severity of size effect in ECC material presented in this article, it must be determined whether these results coincide with existing size effect theories. Theories such as those proposed by Bazant or Carpenteri, mentioned eariler, are widely accepted for quasi-brittle materials, however the ductile nature of ECC may violate these theories, thus requiring a modification of existing theory, or complete development of new size effect theory. Current data indicates that a negligible size effect exists in both ECC and R/ECC flexural members. However, the present set of data is too limited to distinguish whether accepted size effect theories are violated, or this phenomenon is simply not exhibited in the range of sizes yet tested in the laboratory.

Current size effect theory is based upon three distinct types of fracture regimes which, when placed in a continuum, form the premise that with increasing size, nominal strength of brittle and quasi-brittle materials diminishes. The three regions which make up the overall size effect law are linear elastic fracture mechanics (LEFM), non-linear elastic fracture mechanics (NLEFM), and strength theory. The combination of these three regions into a continuum is shown in Figure 7.

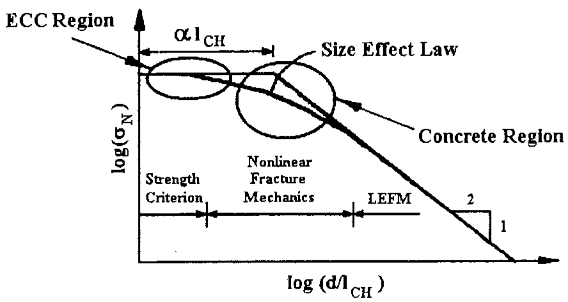


Figure 7. Generalized Size Effect Law Normalized by Characteristic Material Length

The portion of size effect theory which predicts the most severe effect is that developed according to LEFM, and corresponding to the largest member sizes. This theory, based upon a Griffith type crack, assumes that in relation to the surrounding material, the fracture process zone surrounding a crack tip is very small, often referred to as having the presence of a K-dominant zone. This allows for the assumption that all fracture energy is consumed at the crack tip, characterizing the material as ideally brittle. From LEFM theory, it can be seen that nominal strength is proportional to the square root of flaw size, and therefore proportional to the square root of specimen size. When plotted on a logarithmic scale, this is characterized by a size effect with a slope of -0.5, as seen in Figure 7.

Moving toward smaller member sizes, or less brittle materials, the size of the process zone at the crack tip becomes more significant in relation to overall member size. This results in a violation of the LEFM assumption that all fracture energy is consumed at the crack tip, and therefore the assumption of an ideally brittle material. Through the application of non-linear fracture mechanics, specifically theories developed by Hillerborg or Bazant such as the fictitious crack tip model, which take into account the larger fracture process zone surrounding the crack tip, a softening in the severity of the size effect is seen with decreasing member size. This dependence of size effect on overall brittleness of the material is captured through measures such as Hillerborg et al's characteristic length, mentioned earlier and shown in Equation 1

$$l_{ch} = \frac{E'G_f}{f_t^2} \qquad \text{(Equation 1)}$$

where E' is effective elastic modulus, G_f is fracture energy, and f_t is the tensile strength of the material.

As the brittleness of the material decreases and the fracture toughness increases, the magnitude of the process zone surrounding the crack tip increases proportionally. This enlargement of the process zone ultimately leads to a diminishing size effect with smaller member size. Due to large aggregates creating a significant fracture process zone, most commonly sized concrete members are within this region, highlighted in Figure 7.

As member size decreases further, or member ductility increases, NLEFM predicts negligible size effect. The high fracture toughness of ECC, nearly equivalent to aluminum as mentioned earlier, and extremely high value of characteristic length (~100m [7]), may suggest that ECC material lies in the upper left zone on the size-effect plot of Figure 7.

For a truly ductile material where the fracture failure mode is suppressed in favor of other types of failure modes (such as compression or buckling) in a structural member, the NLEFM theory of size effect loses meaning. In this case, structural members made with ECC or R/ECC may not show any size effect. If exhibited, however, the size effect will be governed by phenomenon other than fracture. The Weibull size effect or other concepts may be needed to explain this size effect. This situation remains a possibility for ECC structural members. In this limit, the concepts associated with fracture energy and characteristic length are no longer meaningful.

CONCLUSIONS

From the range of flexural specimens currently tested, there appears to be negligible size effect in ECC members when compared to reinforced concrete specimens. While reinforced concrete beams exhibited a significant reduction in flexural strength over a series of beams up to 1.4 meters in length, ECC and steel reinforced ECC beams showed no significant change in flexural strength. This phenomenon is due to the ductile nature of ECC material. ECC flexural specimens are highly unlikely to fail in a brittle manner negating brittle failure modes closely associated with size effect in concrete.

With the current set of member sizes tested, it is not possible to determine whether ECC will follow current NLEFM based size effect theory. While this theory may apply, it is plausible that ECC members exhibit no size effect due to the full suppression of fracture failures, or are rather subject to other forms of size effect, such as those arising from material variability.

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