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 (RECC) members. Three series of beam specimens fabricated of reinforced concrete, ECC, and RECC 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 leaning 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 defined as aggregate size in concrete. Similar results have been found by others, including Carpinteri 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/m² (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 improve 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 Kusmland 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 Kusmland 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, 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 ± 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Concrete</th>
<th>Aggregate</th>
<th>Sand</th>
<th>Fly Ash</th>
<th>Water</th>
<th>Superplasticizer</th>
<th>Methyl Cellulose</th>
<th>Fiber (Volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
<td>0.45</td>
<td>0.01</td>
<td>0.0</td>
<td>0.02</td>
</tr>
<tr>
<td>ECC</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
<td>0.45</td>
<td>0.01</td>
<td>0.0</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 1. Tensile Stress-Strain Curve of ECC Material

Concrete used in this study for comparison purposes was composed of cement, coarse aggregate (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 stress of 0.2%, ultimate strength of 520 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 bar used in larger specimens.

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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 1.5% 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](image)

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, 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

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Notation</th>
<th>Test Number</th>
<th>Span Length, s (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td>RC-2</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>RC-3</td>
<td>2</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>RC-4</td>
<td>3</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>RC-5</td>
<td>4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

In Table 2, MOR values are shown for each series.

![Figure 3. Early Tensile Strain Capacity Development of ECC](image)

**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>
<thead>
<tr>
<th>Series</th>
<th>MOR (MPa)</th>
<th>Series</th>
<th>MOR (MPa)</th>
<th>Series</th>
<th>MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC-1</td>
<td>19.76</td>
<td>ECC-1</td>
<td>12.52</td>
<td>R/ECC-1</td>
<td>14.92</td>
</tr>
<tr>
<td>RC-2</td>
<td>22.92</td>
<td>ECC-2</td>
<td>12.84</td>
<td>R/ECC-2</td>
<td>16.83</td>
</tr>
<tr>
<td>RC-3</td>
<td>22.97</td>
<td>ECC-3</td>
<td>12.58</td>
<td>R/ECC-3</td>
<td>15.49</td>
</tr>
<tr>
<td>RC-4</td>
<td>9.68</td>
<td>ECC-4</td>
<td>12.81</td>
<td>R/ECC-4</td>
<td>16.35</td>
</tr>
<tr>
<td>RC-5</td>
<td>13.45</td>
<td>ECC-5</td>
<td>11.56</td>
<td>R/ECC-5</td>
<td>16.79</td>
</tr>
<tr>
<td>RC-6</td>
<td>13.78</td>
<td>ECC-6</td>
<td>12.27</td>
<td></td>
<td>14.76</td>
</tr>
<tr>
<td>RC-7</td>
<td>13.78</td>
<td>ECC-7</td>
<td>12.27</td>
<td></td>
<td>18.77</td>
</tr>
<tr>
<td>RC-8</td>
<td>13.78</td>
<td>ECC-8</td>
<td>13.54</td>
<td></td>
<td>19.45</td>
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<tr>
<td>RC-9</td>
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<td>ECC-10</td>
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<td>RC-11</td>
<td>13.78</td>
<td>ECC-11</td>
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<tr>
<td>RC-12</td>
<td>13.78</td>
<td>ECC-12</td>
<td>13.54</td>
<td></td>
<td>16.23</td>
</tr>
</tbody>
</table>

Typical load versus midpoint displacement curves for ECC specimens is 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.

![Load vs Displacement Curves of ECC-3 Specimens](image)

**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 increases, 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.

![Load versus Displacement Curves of R/ECC-3 Specimens](image)

**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.

![Presence of Size Effect in Reinforced Concrete, ECC, and R/ECC Specimens](image)

**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
where $a$ is the crack length, $K_{IC}$ is the critical fracture toughness, and $E$ is the Young's modulus.

The dependence of $K_{IC}$ on $a$ can be expressed by a power law relation:

$$K_{IC} = C a^{n}$$

where $C$ is a constant and $n$ is a constant exponent.

The effect of the material size on the fracture toughness is significant, as it reduces the effective size of the crack-tip region and hence the stress concentration. This effect is often quantified by the size parameter $1 - L/2a$, where $L$ is the specimen thickness.

The size effect is more pronounced in materials with lower fracture toughness. In materials with higher fracture toughness, the size effect is less significant due to the larger crack-tip region.

CONCLUSIONS

Based on the experimental results and theoretical analysis, it can be concluded that the size effect on fracture toughness is significant and should be considered in material design and selection.

The size effect can be minimized by using materials with higher fracture toughness and by increasing the specimen thickness. Furthermore, the use of fracture mechanics models that account for the size effect is essential in predicting the fracture behavior of materials under different conditions.

Figure 2: Graphical representation of the size effect on fracture toughness for different materials.
With the current set of member sizes tested, it is not possible to determine whether ECC will follow current NEPM 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 failure, or are rather subject to other forms of size effect, such as those arising from material variability.

REFERENCES