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# An Experimental Investigation on Fracture Parameters of Concrete Beams Made of Engineered Cementitious Composites (ECC)

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**ABSTRACT:** Due to the existence of cracks in concrete structures, the conventional strength criteria may not be able to predict their failure. It has been shown that the theories of fracture mechanics can predict the behavior of these structures appropriately. In this experimental and analytical study, by using fracture mechanics theories, fracture parameters of flexural different specimens made of Engineered Cementitious Composites (ECC) are investigated. 24 flexural specimens with the notch at their mid-length were manufactured and tested. Six of these specimens with the dimensions of 350×100×100 mm were conducted under Work of Fracture Method (WFM) and other 18 specimens with the dimensions of 190×70×70 mm, 380×140×70 mm and 760×280×70 mm were studied under Size Effect Method (SEM). The materials used for ECC included polypropylene fibers, cement, iron furnace slag, silica fume and stone powder. Two ratios of fibers (1% and 2%) were used in different mixtures of ECC. It was observed that by increasing fibers from 1% to 2%, the amount of flexural strength, fracture energy and fracture toughness ($K_{IC}$) of the specimens increased. On the other hand, compressive strength, characteristic length ($L_{ch}$) and brittleness number of specimens decreased. The Bažant's size effect law was also discussed for the ECC specimens.

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## 1- Introduction

The Engineered cementitious composite (ECC) is a particular class of high-performance fiber-reinforced concrete (HPFRCC) and has an important Characteristic of strain hardening [1]. This property causes high energy absorption in the ECC [2]. Fracture energy in materials with strain hardening behavior can be divided into two parts, an off-crack-plane matrix-cracking component that include the expanded area of the microcracks, which surrounds the crack tip before the crack spreads, and an on-crack-plane fiber-bridging component, that is the mechanism of bridging the fibers.[4-3]. In this study, due to the lack of adequate laboratory studies on ECC fracture parameters, the fracture toughness and fracture parameters of ECC were investigated by using WFM and SEM from various available methods in fracture mechanics [5-9].

## 2- Materials and Methods

Contrary to the initial mixing of ECC provided by Li [10], local materials were used to produce ECC. In this study, two mix designs ECC 1-10 and ECC 2-10 with 1% and 2% fiber content, were produced (Table 1). To evaluate the mechanical properties of ECC, compressive strength, tensile strength and flexural strength, 100 × 100 mm cubic specimens, 100 × 200 mm cylindrical specimens and 300×100×50 mm prismatic specimens were prepared, respectively. According to ASTM 1609 [11] and RILEM TC 89 [12], ECC notched beams were prepared to study WFM and SEM, respectively (Figure 1). The notch depth in beams for WFM was 33 mm. For SEM, in three beam sizes, the notch depths were 14, 28 and 56 mm. Also, the width of the notch of beams in WFM and SEM was equal to 3 mm. The details of the experiment are shown in Figure 1.

## 3- Experimental Results and Discussion

Increase of the fiber content from 1% to 2% decreased the compressive strength and elastic modulus and increased the flexural strength of ECC. In WFM, fracture energy ($G_F$) and characteristic length ($L_{ch}$) were calculated based on RILEM 50-FMC [13] and the area under the load-displacement relationship of the notched beam. Xu and Zhu [14] state that as the tail of load-displacement relationship is flat, the test is usually finished when the displacement of the beam center reaches a certain value. In this study, due

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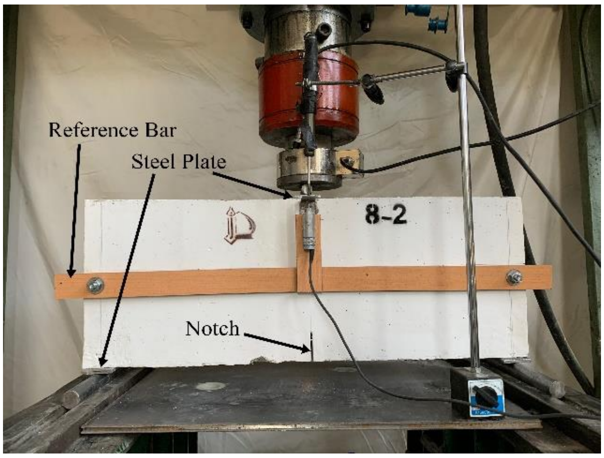


**Fig. 1. Details of Fracture Test**

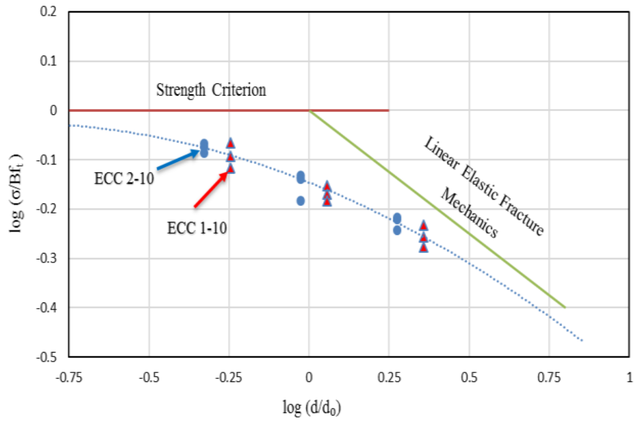


**Fig. 2. Size effect of ECC specimens with various Fibers content**

to the large displacement of ECC notched beams, the area of the load-displacement relationship was calculated up to the displacement of 11 mm at the beam center. Test results show that ECC has a larger $G_F$ compared to other concretes such as ordinary concrete [15] and self-compacting steel fiber reinforced concrete [16]. The values of $G_F$ in ECC 1-10 and ECC 2-10 were 3059 N.m and 3749 N.m, respectively. Fracture parameters in SEM were calculated based on RILEM TC 89 [12] and the existing statistical parameters were in accordance with the criteria of this standard. The results show that by increasing the fibers content, the fracture energy ($G_f$), the length of the fracture process zone ($C_f$) and the fracture toughness ($K_{IC}$) increased. According to Figure 2, it can be seen that the data obtained for ECC are in accordance with the Bažant's size effect curve, which means that the specimen size is effective in ECC and is in accordance with the nonlinear fracture mechanics (NLFM). In addition, the brittleness number ($\beta$) of ECC 1-10 and ECC 2-10 indicates that these two mixtures follow the principles of nonlinear failure mechanics and $\beta$ of these two mixtures was between 0.1 and 10.

## 4- Conclusions

An increase in fiber content from 1% to 2% decreases the compressive strength by about 12.5%, increases the tensile strength by about 29.4% and increases the flexural strength by about 72%.

The increase of fiber content by 1% increased $G_F$ by 22.5% and $G_f$ by 69.6%. Also, $L_{ch}$ decreased by about 36%. The other fracture parameters such as $C_f$ and $K_{IC}$ increased by 21.4% and 21.3%, respectively.

The $G_F / G_f$ ratio for notched beams made with ECC 1-10 and ECC 2-10 were 171.9 and 124.1, respectively. According to previous studies, this ratio for ordinary concrete was approximately 2.5. The large values of $G_F / G_f$ in the case of ECC are due to the large displacement of ECC specimens.

By Considering the test results of ECC notched beams in SEM, it can conclude that the size of specimen is effective in ECC and the principle of nonlinear fracture mechanics should be used to analyze the fracture in ECC.

**Table 1. Mix proportions**

| Mix | Mix proportions of ECC mixes (kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cement | Silica fume | Limestone powder | Blast furnace slag | Fibers (%) | Water | Superplasticizer |
| ECC 1-10 | 496 | 264 | 596 | 132 | 1 | 452 | 21 |
| ECC 2-10 | 496 | 264 | 596 | 132 | 2 | 452 | 25 |

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