Experimental Investigation on Engineered Cementitious Composites

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Abstract
Cement-based composite materials like Engineered Cementitious Composites (ECCs) are applicable in the strengthening of structures because of the high tensile strength and strain. Proper mix proportion, which has the best mechanical properties, is so essential in ECC design material to use in structural components. In this paper, after finding the best mix proportion based on uniaxial tensile strength and strain, the correlation between these parameters were calculated. Since material properties depend on the content ratios, six mixtures with different Fly Ash (FA) content were considered to find the best ECC mixture called Improved ECC (IECC). Also, the influence of local fine aggregates and FA on the tensile behavior of ECC was considered to introduce IECC which has the best tensile properties. The results show that the effects of FA and fine aggregates on tensile behavior are considerable.

***Keywords* -** Engineered Cementitious Composites, Experimental Study, Local Admixtures, Mechanical Properties

1. INTRODUCTION

ECC material, known as a type of HPFRCC invented about 25 years ago, has special properties such as ultra-high ductility and tensile strength [1]. Although there are several specs introduced in the literature, common ductility for ECC is more than 0.03, and the width of cracks is about 60 μm. Figure 1 shows that unlike normal concrete, these properties of ECC and strain-hardening should be met in the tensile stress-strain curve [2]. Interaction between matrix and fiber and their interfaces makes high tensile strain and ductility in ECC material [3]. ECC is widely used in structures to retrofit the elements such as RC members, especially in retrofit to improve their seismic behavior [4-6]. ECC is made of several materials like cement, FA, fine aggregates, water, fiber and superplasticizer. So, the mechanical properties of ECC depend on these parameters, mix proportions and type of them. Finding the effects of each of these materials is difficult. However, finding a relationship between one of them and mechanical properties of ECC is valuable and applicable in composites. There is much study on ECC and using it in structural elements. However, few works have been conducted on the effect of each parameter and estimation of each parameter on mechanical properties of ECC. Especially using artificial models and numerical methods can be applicable to predict the tensile behavior of ECC. Considering a special material like FA or fiber, which are so effective on ECC material properties is so important, since the main difference between ECC and other common materials such as concrete and mortar is the use of FA and fiber. These parameters make ECC distinguished material among the others. Thus, using them and their mix proportions and types affect on ECC behavior, especially tensile strain and strength.

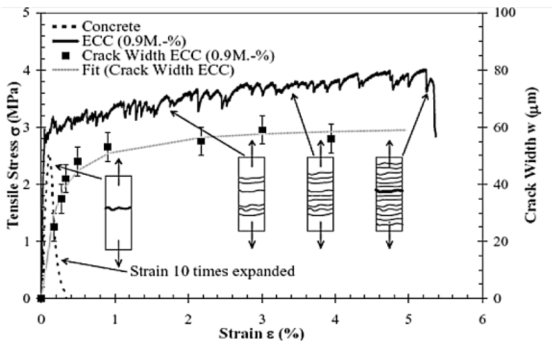


Figure 1. Comparison of the tensile behavior of concrete and ECC [2]

Fiber dispersion is one of the most effective parameters on the tensile behavior of ECC to achieve strain-hardening in the tensile stress-strain curve. The type of aggregate is affected on this parameter whether coarse aggregates cause poor dispersion like plain concrete or fine and appropriate aggregates enhance tensile behavior and ductility like ECC [7,8]. Moreover, cement content and its quality play a noticeable role in hardening of the strain of ECC as the most valuable specs of ECC that should be met with experimental results. Previous works show that the performance of ECC is better than regular concrete in tension due to utilizing very fine aggregates [9,10]. Using fine sands without any coarse aggregates increases the price of ECC material and makes it more expensive. However, using a suitable gradation of aggregates economize the mixture.

Previous researches show that Fly Ash (FA) affects on the tensile behavior of ECC like sustainability, tensile strength and strain, and toughness. Few works show that how FA affects of ECC behavior and how to find the best mix proportion. Since this material is expensive in the local area, find a solution and numerical model to predict this influence is so valuable. Also, finding an artificial model is applicable for practical engineering because ECC design is a complicated process.

Li and Wang investigated that if FA content increases sustainability performance will be improved whereas matrix toughness will be reduced [11]. Tosun et al. have shown that utilizing proper FA affects on ECC properties in fresh and hardened states directly by using two types of FA [12].

Zhu et al. showed that FA ratio affects on the flexural strain of the specimen so that by increasing FA ratio from 50% to 80%, the deflection has increased 100% in four-point bending test [13]. Also, Wan et al. have represented FA ratio effects on the tensile strain of ECC to find the best mixture. In ratios 50% to 75% FA content, 75% has the highest tensile strain and 50%, and 65% have the lowest values [14]. Moreover, the authors represented the influence of FA content on ECC performance under tensile loads using five different mixtures. It was concluded that the best tensile strain and strength belong to 1:1.5 and 1:0.5 C: FA ratios respectively [15].

There are some researches about using slag in ECC to achieve high ductility and strength in tension. These studies showed that FA was necessary to enhance the tensile behavior of ECC [16-18]. In the previous study, the authors evaluated two types of aggregates and concluded that utilizing fine aggregate shows the ductile performance of ECC in tension [15].

Although all studies in the literature represent the ECC behavior and material properties, few researches work on ECC design and how to find the best mechanical properties using numerical models. Also, none of them carried out experimental and numerical studies on local materials and effect of FA with different mix proportions. In this study, two kinds of aggregates and several FA contents were used to exhibit the influences on the tensile behavior of ECC. Different mix proportions affected on tensile strain and strength.

Since the authors use ECC in the retrofit of masonry infill walls, finding the best ECC mixture which has the highest tensile strength and strain is extremely significant. So, many parameters which include the type of aggregates, FA, cement contents, and mechanical parameters were considered to find the best ECC called IECC. Using local aggregate and achieve the best ECC behavior are the main purpose of this paper. Local materials make structural design economic and high-ductile behavior of ECC in tension causes to select this material in the retrofit.

2. Experimental Investigation

2.1. Material Properties

This section is about the assessment of six ECC mixtures to find the best tensile behavior called IECC. In this investigation, aggregates and binders in two and three types respectively were used to produce ECC. The aggregates include sand and quartz powder, and binders consist of cement, FA and SL. Based on previous studies, mix proportions were opted [5,6]. The other materials were the same like PVA fiber, water, and superplasticizer. The characteristics of the aggregates and fiber were shown in Figures 2 and 3. PVA fiber used in previous researches by the authors has 8 mm long and diameter, elongation and density are 39 µm, 6% and 1.3 g/cm3 respectively. Also, the tensile strength of fibers is 1600 MPa and their Young's modulus is 42.8 GPa.

TABLE 1. The ratios of the weight of ECC matrix

Mixture	Binder		Aggregates			Superplastisizer
	Cement	FA	Sand	Quartz Powder	Aggregate Type	
FA-ST1	1	2	0.35	0.35	I	0.012
FA-ST2	1	2	0.35	0.35	II	0.012
FA-0.5	1	0.5	0.35	0.35	II	0.012
FA-1	1	1	0.35	0.35	II	0.012
FA-1.5	1	1.5	0.35	0.35	II	0.012
FA-2.5	1	2.5	0.35	0.35	II	0.012
FA-3	1	3	0.35	0.35	II	0.012

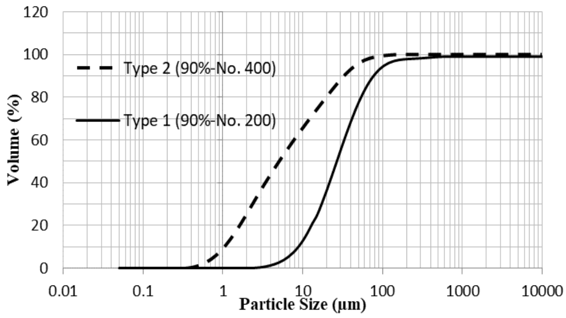


Figure 2. Gradation of fine sands [15]

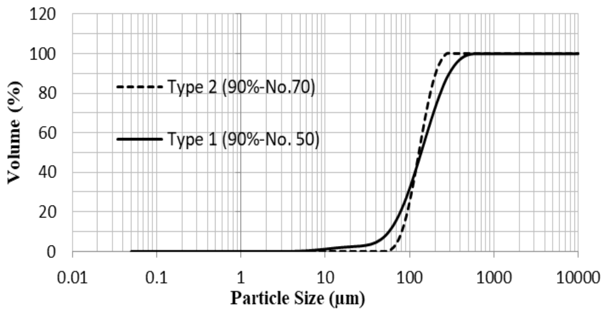


Figure 3. Gradation of quatz powder [15]

As seen in Figures 2 and 3, two kinds of aggregates were evaluated to make ECC more ductile with better mechanical properties. More than 90% of particles of sand type I and type II were smaller than 300 µm and 212 µm. Also, more than 90% of particles of quartz powder type I and type II were smaller than 75 µm and 38 µm [15]. As noted, utilizing good aggregates and limitation of the size and the weight of aggregates enhance the ductility of ECC and fiber dispersion. This consideration controls the material properties to make IECC.

2.2. Mix Proportions

The ratios of the weight of ECC matrix ingredients (cement, fine aggregates, water, superplasticizer, and PVA) are given in table 1 as below. PVA fiber proportion is 2% in volume in all mixtures. At first, cement, FA and aggregates as dry components were mixed using a mini mixer as shown in figure 4 for one minute. To produce the flowable and viscose mortar, water and superplasticizer were added to the dry components and mixed for 4 minutes. Good viscosity of mortar helps the fibers to be dispersed uniformly after adding them to the mortar and mixing about 3 minutes.

After producing standard ECC with two different types of aggregates, the purpose is to evaluate the mechanical properties of seven different ECC mixtures. Total weight of binder is fixed. However, the binder consists of cement and FA in six mixtures.

2.3. Testing Plan

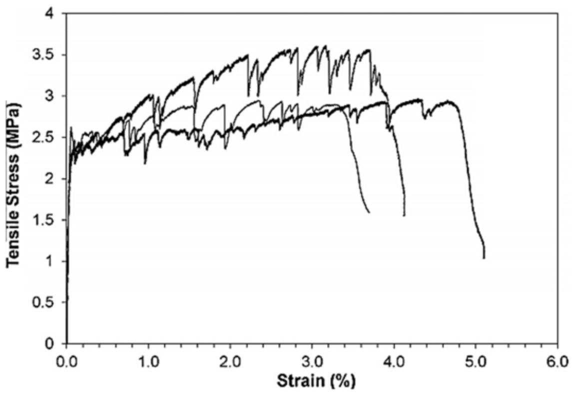
The last purpose of this paper is using IECC, which has high tensile strain and strength, in the strengthening of masonry infill walls. To determine IECC properties, 7-day dog-bone samples were examined under uniaxial tensile forces. The tensile stress-strain curves can be determined based on these tests which show mechanical characteristics of ECC like hardening and cracks. Another important parameter is workability determined using the slump test which is about 35 cm for standard ECC (FA-ST2). Figure 4 shows test set-up of ECC specimens and uniaxial tensile tests results respectively. The uniaxial tensile tests were done seven days after casting ECC in the dog-bone mold and curing in this period. The displacement control loading rate applied to the specimens was 0.015 mm/s

Figure 4. Test set-up and uniaxial tensile test results

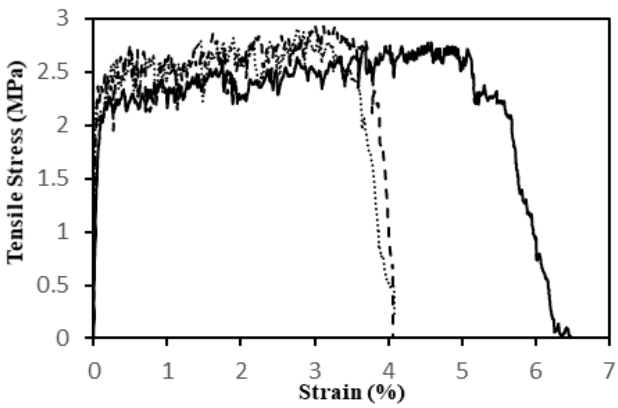
3. Results and Discussion

In Figure 5, an extensometer was used in the middle of the specimen to read the relative deformation and calculate the tensile strain. Also, the ratio of average force to the area in the failure zone was utilized for stress determination. Each figure shows the tensile stress-strain curves of 3 specimens in experimental studies.

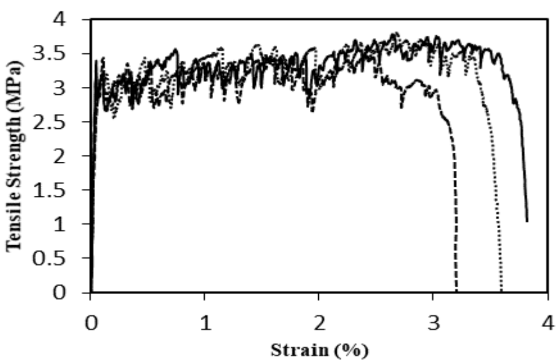
Some significant mechanical characteristics of ECC which include tensile strength, tensile strain, fracture energy, and toughness index, were calculated to exhibit the comparison of different types of aggregates and binder. The definition of the mechanical properties of ECC is represented in Figure 6.



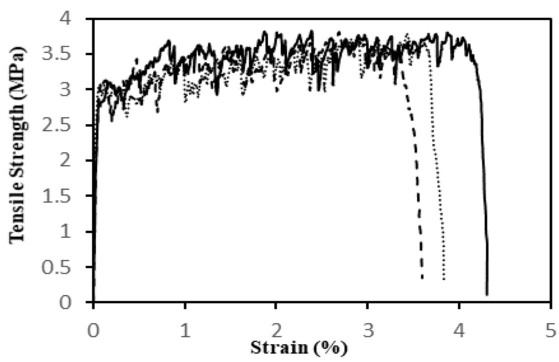
(a) FA-ST1



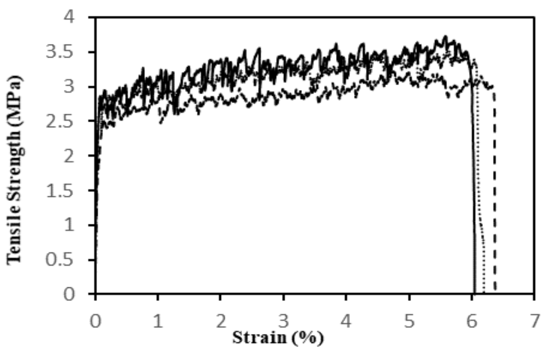
(b) FA-ST2



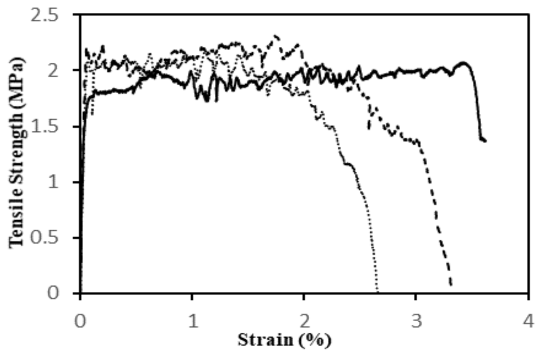
(c) FA-0.5



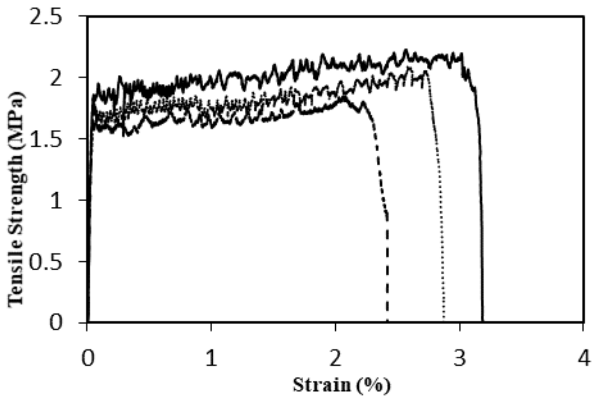
(b) FA-1



(c) FA-1.5



(b) FA-2.5



(g) FA-3

Figure 5. Tensile behavior of ECC with different admixtures

As seen, the tensile behavior of different mixtures of ECC mentioned in table 2, were obtained in stress-strain curves to compare the effect of each part which includes FA, SL or aggregates. All strength values in table 2 are the maximum strength of the specimen before failure, and the ultimate tensile strain is the value before large degradation in the curve. Since the mixture FA-ST2 has better performance than FA-ST1, the other mixtures produced using aggregates type 2 presented above. Among the different ratios of FA, the best tensile behavior of ECC belongs to specimen FA-1.5 which has tensile strength 3.4 MPa and tensile strain of 6.1% averagely. These values are more than standard ECC characteristics which are 2.84 MPa and 4.15% respectively. Thus, Mixture FA-1.5 is called IECC due to ductile performance. To compare all tensile properties of specimens, include tensile strength and strain table 2 and Figures 7 are determined to show mean and standard deviation values of results in bar charts.

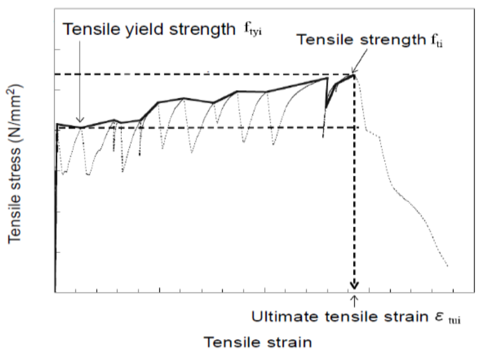


Figure 6. Definition of ECC characteristics

TABLE 2. Calculated ECC tensile parameters

ECC Mixture	Tensile Yield Strength (MPa)	Tensile Strength (MPa)	Ultimate Tensile Strain (%)
FA-ST1	2.4 ± 0.1	3.16 ± 0.25	3.92 ± 0.6
FA-ST2	2.3 ± 0.15	2.84 ± 0.23	4.15 ± 0.64
FA-0.5	3.25 ± 0.1	3.65 ± 0.1	3.35 ± 0.4
FA-1	2.95 ± 0.05	3.6 ± 0.08	3.7 ± 0.3
FA-1.5	2.65 ± 0.1	3.4 ± 0.14	6.1 ± 0.13
FA-2.5	1.9 ± 0.12	2.2 ± 0.13	2.7 ± 0.62
FA-3	1.76 ± 0.08	2 ± 0.175	2.67 ± 0.3

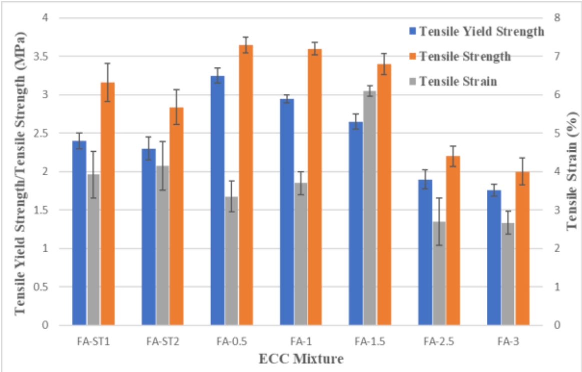


Figure 7. Comparison of ECC tensile behavior

Table 2 and Figures 8 show that the amount and the type of admixtures play an important role in material characteristics of ECC. Although FA increases the ductility of ECC and improve tensile behavior, its ratio is so important and effective in these parameters. As mentioned above, aggregate type II caused better tensile performance in ECC than aggregate type I. On the basis of table 3, compared to FA-ST2 as the standard mixture which contains FA, the tensile strain of FA-1.5 was increased 47%, and that of specimens with FA content 0.5, 1, 2.5 and 3 were decreased 19%, 11%, 35% and 36% respectively. Also, compared to FA-ST2, the tensile strength of specimens with FA content 0.5, 1 and 1.5 were increased 29%, 27% and 20% respectively and that of FA-2.5 and FA-3 reduce 23% and 30% respectively.

The results show that the effect of FA on increasing tensile strain was obvious. The comparisons noted above, represent that using FA instead of cement in binder caused increasing tensile strain and de-creasing tensile strength generally. However, the maximum value of tensile strain and strength belong to FA-0.5 and FA-1.5 respectively in mixture with two materials in the binder.

If FA ratio increases in ECC mixture, sustainability performance will be improved. However, tensile strength and matrix toughness will be decreased. Also, increasing FA content has positive effects on tensile strain of ECC in the specified range. In other words, in FA-0.5, FA-1 and FA-1.5 by increasing FA content, tensile strain is improved. More than FA-1.5 ratio this property is reduced. So, FA effects on tensile strain is not predictable in all conditions. However, numerical models can estimate this influence to predict tensile strain. Using FA decreases tensile yield strength and tensile strength generally. Thus, finding a customized mix proportion based on structural demands by considering these effects is so important in ECC design.

4. CONCLUSION

In this study, the best mix proportion of ECC was found based on tensile yield strength, tensile strength and tensile strain. All datasets can be used to find required ECC mixture for structural elements. The main results are summarized as follows:

- Two different types of aggregates in experimental studies showed that fine aggregates reduced tensile strength and increase tensile strain.
- The best mixture called IECC was FA-1.5 with FA: C=1.5:1 ratio. The tensile strength and tensile strain of this IECC were 3.4MPa and 6.1% respectively.
- FA-0.5 has the highest tensile strength with 3.65 MPa value averagely.

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