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Experimental investigation of the mechanical properties of Engineered Cementitious Composites (ECC)

MUSTAFA KAMAL[1], SAJJAD WALI KHAN[1], KHAN SHAHZADA[1], MUHAMMAD ALAM[2]
[1]Department of Civil Engineering, University of Engineering &Technology, Peshawar, Pakistan
[2]Department of Civil Engineering, Abasyn University, Peshawar Campus, Peshawar, Pakistan
Email: mustafakamalswat@gmail.com, drsajjadwalikhan@uetpeshawar.edu.pk

Abstract: The primary aim of this research was to study the mechanical properties (i.e. compressive, tensile and flexural strengths) of the engineered cementitious composites (ECC). To achieve the aim of the project, an experimental study was carried out to investigate the properties of ECC mix with varying fiber contents (poly vinyl alcohol) at different maturation time of 14 & 28 days respectively. The effect of different fiber contents (0, 0.5, 1, 1.5 and 2%) on compressive, flexural, and tensile strengths as well as ductility was experimentally investigated. 45 Cylinders and 30 beam specimens were casted according to ASTM standards, whereas 15 thin strips of 1.5 inch thickness were casted for checking its ductile behavior. A large body of experimental results was obtained by testing these specimens in Universal Testing Machine (UTM) in material testing laboratory of the Department of Civil Engineering, UET, Peshawar. Furthermore, the effect of increasing PVA fiber contents on the properties of fresh ECC (workability and density) was also studied. The test results showed improved compressive, flexural and tensile strengths at higher content of fibers. The compressive and flexural strengths of ECC was found to be maximum at a fiber dosage of 2% and 1.5 % respectively. Similarly, increasing PVA fibers increased the tensile strength of the ECC as well. However, workability of concrete was found to decrease with increasing fiber contents in ECC.

Keywords: *Engineered Cementitious Composites, Poly Vinyl Alcohol, Mechanical Properties, Fiber content.*

Introduction:

Concrete is the most widely used man made construction material in the world [1]. The consumption in such a large scale is due to its various properties (i.e. durability, availability, cost, and mouldability). In addition to these properties, concrete has some shortcomings (i.e. low ductility and tensile strength, low strength to weight ratio [2]. In order to overcome these shortcomings; an ultra-ductile material with improved properties has been developed by Victor Li in 2001 [3]. This material was named as engineered cementitious composites (ECC). Small hair like fibers, in case of ECC is added into the mix, which totally change the crack pattern of the concrete. ECC is a high performance fiber reinforced composite material of cement mortar. As suggested by V.C. Li, the amount of fibers in ECC is generally less than 2% by volume [4-5-6].

Unlike the fiber reinforced concrete, ECC has superior structural properties; tensile, compressive and flexural [4-7]. The small volume of fiber contents (0-2%) makes it economical too compared to normal fiber reinforced concrete [8]. Furthermore, due to strain hardness after cracking, ECC have high fracture toughness and therefore damage tolerance is very high. Due to the interaction between fibers and cementing matrix, many micro cracks with a very specific width are developed instead of few very large cracks, making ECC very ductile [9]. This micro cracking behavior makes it corrosion resistive as well as helps in the self-healing of the cracks [10-11]

Experimental study:

In order to thoroughly investigate the effect of fiber contents in the mix on the mechanical properties of ECC, five different volumetric ratios of (0, 0.5, 1, 1.5, and 2% by volume) were used. A large number of samples were casted and tested in the material testing laboratory of the Department of Civil Engineering UET Peshawar.

Selection of materials:

The first step was to select the suitable materials for the preparation of ECC. In addition to other materials, the fibers used in ECC play an important role in the overall behavior of ECC. It was reported, that PVA fibers were the most suitable material for reinforcing ECC [12]. Therefore, REC 15x8 mm (PVA) fibers as shown in Figure 1, were used in this study, which were supplied by the Kurary Corporation japan. These were very thin hair like and flexible fibers that were quite useful in reinforcing the micro cracks in concrete.

A low water to cement ratio (w/c) is always desirable to increase the strength of the ECC. Therefore a w/c ratio of 0.35 was chosen to be the best to keep balance between strength and workability. To achieve proper workability with a w/c ratio of 0.35, chemical admixtures (Poly-carboxylate) were used. Similarly, micro size sand (0-600 μm) was used for the preparation of ECC and Type-I ordinary Portland cement was used in this research.

Figure 1 *REC15x8mm PVA fibers*

Mix proportions and sample preparations:

On the basis of varying fiber content, five different mix proportions were used in this research work. The details of the mixture proportions are given in Table 1.

Table 1*: Mix proportion for ECC*

Item	Formulation (kg/m3)	Remarks
Cement	1000	Ordinary Portland cement
Water	350	w/c = 0.35
Sand	700	1:0.7
Coarse Aggregate	0	Mortar based
PVA fibers	0 - 26	REC15 x 8 mm
Additives	2-4	Super plasticizer

After selection of proper materials and mix proportions, the mixing of material was done with the help of electric motor mixer to obtain a homogenous mix. In order to achieve the desired properties of true ECC, proper sequence of adding the constituents was strictly followed. First the aggregates and ordinary Portland cement were mixed for 40-60 seconds without the addition of water. After dry mixing, the water was then added followed by super plasticizers to get a uniform mix. Finally, fibers were dispersed in the mixture and mixed for 60 seconds.

Before pouring of the concrete into the molds, the concrete molds were oiled with mixture of kerosene oil and diesel. After proper mixing, the mixture was then placed in the molds as shown in the Figure 2. Tamping was continuously done during the pouring of the concrete with the help of tamping rod, to minimize the honeycombing. Levelling of the concrete surface was done and the samples were then left in the molds to set for 24 hours. After 24 hours the specimens were removed from the molds and were put in the curing tank. The curing was done for 14 and 28 days respectively in the tank.

Figure 2*: Pouring of ECC into the molds*

Tests Performed:

Fresh ECC: The properly mixed true ECC has a creamy texture as shown in Figure 3. Therefore, the slump cone test was performed in a slightly different method from ordinary concrete. To check workability, slump cone was filled with ECC material and emptied on glass. The ECC spread like a pancake as shown in the Figure 4. The two orthogonal diameters of the pancake were measured and the deformability was calculated by the fallowing equation.

$$\Gamma = \frac{(D_1 - D_0)}{D_0} \quad (1)$$

Where D_1 is the average of the two orthogonal diameters of the pancake and D_0 is the diameter of the base of the slump cone. The value of Γ should be not less than 2.75 [6]. Density of the mixes were calculated according to standard test method of ASTM C138. Determination of the density is the measure of the light weightiness of the concrete. As PVA fibers has less weight in a specific volume. Therefore, it was confirmed that the addition of PVA fibers into the mixes lead to a light weight concrete [13].

Hardened ECC:

Compressive, flexural and tensile strengths tests were conducted according to ASTM standards. Compressive strength of the specimens was determined according to the ASTM C39 standard test method by crushing the cylindrical specimens. This is one of the quality test method used to determine the compressive strength of the concrete. Cylindrical specimens were prepared. The diameter and depth of the cylinders were 6 inch and 12 inch respectively. Before testing, capping of the cylinders were done to provide smooth surfaces to the jaws of UTM machine. The test was conducted at dried surface condition. The upper platen of the UTM was allowed to move at constant speed to apply an axial compressive load on the surfaces of the cylinder. The UTM machine gives an optimum value of compressive load (P) at failure. The compressive strength can be calculated by the given equation.

***Figure 3**: Creamy texture of ECC*

***Figure 4**: Pancake shape of ECC*

$$\text{Compressive strength} = \frac{P}{\pi r^2} (2)$$

Whereas, the flexural strength tests were performed in accordance with the ASTM C78 standard test method using three point loading. For such purpose, beams specimens of all the mix proportions were casted in especially prepared molds. The dimensions of the beams samples used for finding the flexural strength was 30"x6"x6". The loading apparatus was prepared for three point loading test, as described in ASTM C78. For test setup the span length between the supports were divided into three equal parts, implies that loadings were applied at a distance of one third from the support. When the fracture develops at the tension face within middle one third of the beam span length. The modulus of rapture can be calculated as:

$$MOR = \frac{PL}{bd^2} (3)$$

Where P is the applied load, L is the effective length of the beam, b & d width and depth respectively.

In case the fracture generates at the tension face outside the middle one third of the beam span length.

$$MOR = \frac{3Pa}{bd^2} (4)$$

In order to check the tensile strength of ECC, split cylinder tensile tests were performed according to the ASTM C496 standard test method using molded cylindrical specimens. The samples were prepared in the same way, as prepared for compressive strength. The dimensions of the cylinders were kept constant, for both tensile and compressive strength. A diametric compressive force was applied over the entire length of the cylinder. These compressive forces generate tensile stresses on the plane containing applied load. The cylinders failed in tension rather than compression. The tensile strength was calculated from the ultimate load (P) noted at the time of failure. The equation used to determine the tensile strength is given below.

$$T = \frac{2P}{\pi lD} (5)$$

In order to check the ductility of ECC, it was difficult to observe ductile behavior of the material for a thick cross-section of 6x6 inch beam, therefore, thin strips of about 1.5 inch thick, 6 inch wide and 30 inch long were casted and tested. These were the dimensions for the ductility test of true ECC that had already been used [14]. The loading conditions and testing assembly was similar as selected for calculation of flexural strength, but, only the thickness of the strips was minimized. This enables us to observe the noticeable amount of bending with a slight increase in the load. The same Arduino software was used for reading the deflection values with respect to increasing applied load from UTM machine with built in load-displacement curves. The curves were then compared with each other to check the effect of PVA fibers on ductility.

Result and Discussions:

It was found that the workability of ECC decreases with the increase in the fiber volume. The calculated values of deformability factor (Γ) for true ECC are given in the Table 2. The values of Γ for 0%, 0.5%, 1% and 1.5% are above the specified value, whereas, for 2%, the value is slightly lower than the specified value but within the acceptable range.

***Table 2**: Deformability factors for various fiber volume fractions*

Volume of REC 15 x 8 mm in ECC/Mortar	Γ
0%	4
0.50%	3.45
1%	3.1
1.50%	2.82
2%	2.70

The determination of the densities are actually the measure of the light weightness of the mix. Thus an inverse relationship was found between the density and fiber contents i.e the density decreased as the volume fiber contents increased as shown in Figure 5. This decrease was consistent till 2% fiber volume was added. The decrase in weight was about 5%.

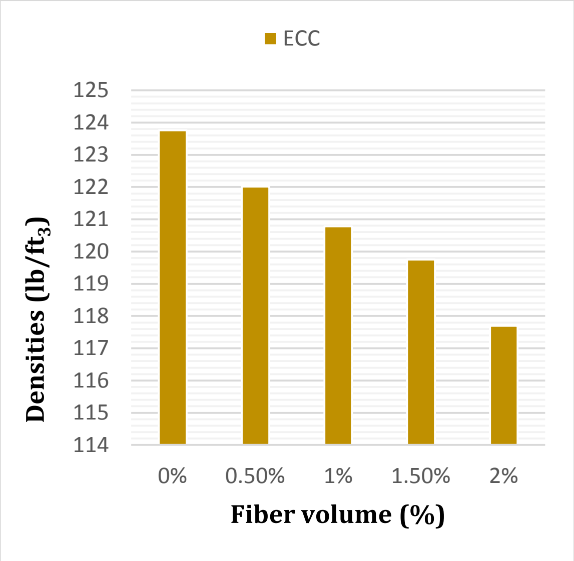

Figure 5:*Densities of Mixes with varying fiber contents*

Figure 6 presents the compressive strength of the moulded cylinderical specimens which were cured for 14 and 28 days. Each bar of the graph shows compressive strength of three samples. It can be seen in the Figure 6 that the compressive strengths varies between 4449.3 Psi and 6175.3 psi, depending on the fiber volume and age of testing.

For the mortar having REC 15x8, the increase in compressive strength was directly related to the fiber contents, i.e., as the fiber volume was increased, the compressive strength of composites also increased. This increase in compressive strength was significant by adding PVA fibers from 0 to 2%. The compressive strength reached a maximum value of 6175.28 psi at 2% fiber content. In comparison with control mix (having zero fibers), increase in the compressive strength was about 31% for 28 days. Similarly, for 14 days strength this increment was 34%. From Figure 6, it can be concluded that composites having fibers can resist high compressive loads as compared to plain mix with no fibers.

It was also observed that the age effect was more prominent for low volume fibers and as the volume of fiber contents increased the difference in the compressive strength regarding the age was found to decrease. For example, the compressive strength difference between the 0.5% PVA content mixtures having age of 14 days and 28 days was approximately 16.75%. On the other hand, this difference for 1.5% and 2.0% PVA content mixtures was 2.7%.

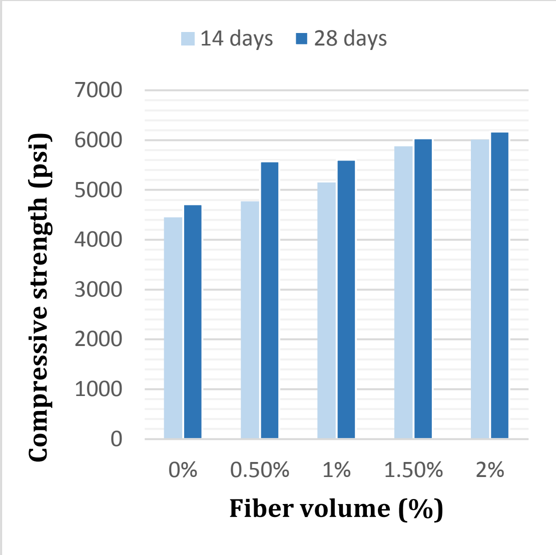

Figure 6: *Compressive strength of ECC at 14 and 28 days*

As shown in the Figure 7, the flexural strength of true ECC increases with increasing fiber contents in the mix. This increase is consistent for 14 days strength, but in case of 28 days, the maximum flexural strength was achieved at 1.5% volume fiber. Although, this strength is not as higher (approximately 1.48%), when compared with 2% at 28 days, but still 1.5% is consideredto be the optimum value of fiber contents for 28 days strength. At 28 days strength, the increment in the flexural strength for 1.5% PVA fiber (optimum value) with respect to 0% fibers (control specimen) is about 70%. Whereas, at 14 days testing, the difference is 90% for 0% (control specimen) and 2 % (shows maximum flexural strength at 14 days).

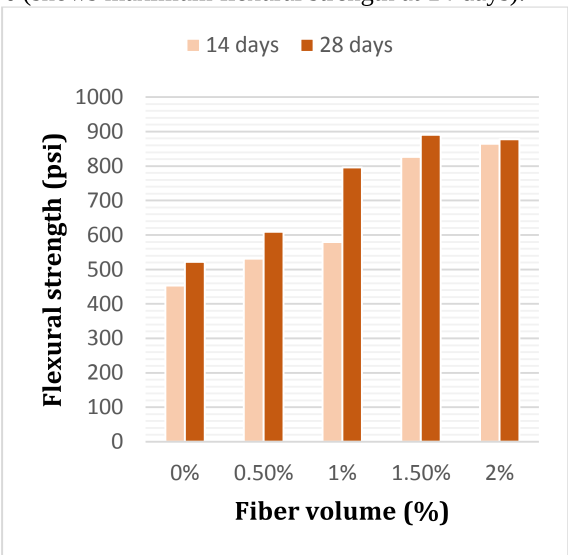

Figure 7: *Flexural strength of ECC at 14 and 28 days*

The split tensile strength of true ECC having variable volumetric ratios (0-2%) of PVA (REC 15x8) fibers was determined at the age of 28 days. It was found that cylinders having high dosages of PVA fibers (1.5% and 2%) can resist high tensile stresses as compared to cylindrical specimens with no fibers. The tensile strength showed by the samples with 0% fibers was about 435 Psi. As expected, by adding PVA fibers at 0.5%, the tensile strength started to increase and reached to 551 Psi. At 1% fiber content, the increase in tensile strength was about 50%. The tensile strength reached maximum value of 720 psi at 1.5% fiber content. In comparison with control mix, increase in the tensile strength was about 65.5% for 28 days. A little drop in tensile strength was noticed at 2% fiber content. But still, the tensile strength of the specimens with 2% fibers by volume was 63.3% more than the control specimens.

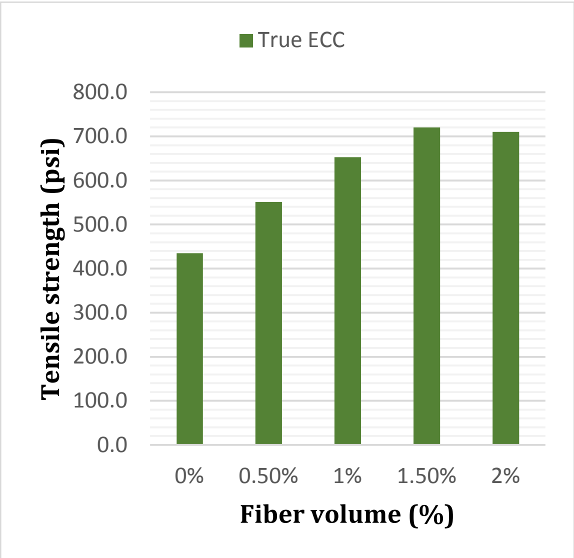

Figure 8*: Split tensile strength of ECC with REC 15X8 at 28 days*

During the testing of the beams for flexural strength, the load–deflection curves were also drawn as shown in Figure 9. In comparison to strips, there was less amount of deflection at mid span of the beams. This is because ductility decreases as the depth of the beam increases, due to increase in the stiffness. As shown in Figure 9, deformations increase with increase in fiber contents and is therefore maximum for 2% fiber contents.

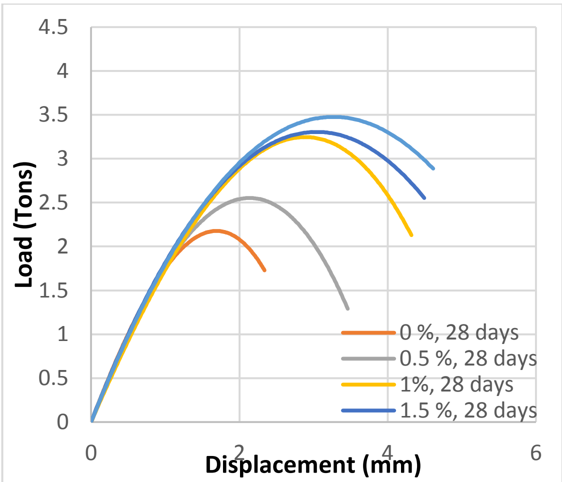

Figure 9*: Load to displacement curves of ECC beam samples at 28 days*

To check the ductility of ECC, the displacement at mid span of the thin slabs were measured with respect to maximum load. The displacement plots below shows the deflection of the specimens at ultimate load. As shown in Figure 10, the displacements of the ECC specimens shows 5 to 8 mm of deflection at ultimate load. It is observed that at ultimate load, as the failure starts, these samples were still able to take load and a maximum deflection of 10 mm was achieved till rupture. It was also noticed that there was a brittle failure in the specimens having 0% fibers.

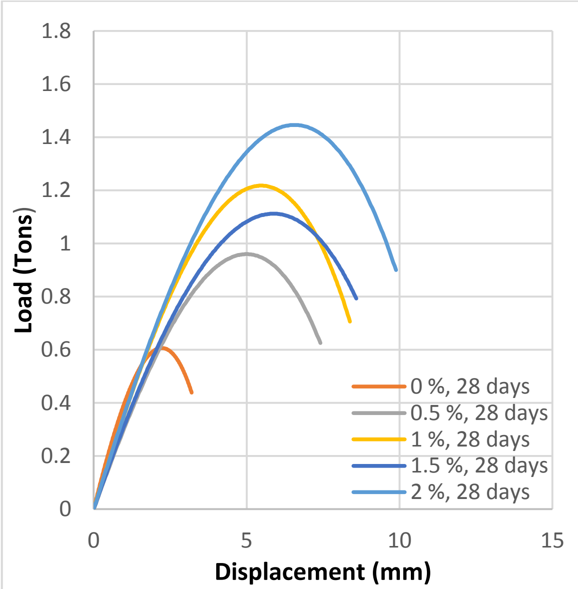

Figure 10*: Load-deflection curves of ECC slab specimens under the application of load*

One of the property of ECC is the formation of microcracks because of the dispersion of fibers in the mix, and thus the cracks formed after failure do not become widened. As predicted, instead of one large crack, number of microcracks were developed. Due to these microcracks ECC exhibits the property of strain hardening and failed specimen were still able to take some load. Which lead to ductile behaviour in ECC. During this study, it was found that in strips of ECC , micro cracks were developed as shown in the Figure 11.

Figure 11*: Picture shows micro cracks generated in ECC*

Conclusions:

- The addition of PVA fibers was found to greatly affect the mechanical properties of ECC.
- From the experimental results obtained, the optimum value of fiber volume fraction is 1.5%.
- The compressive strength of ECC was observed to increase up to 30% at optimum value of fiber content (1.5%).
- Similarly tensile and flexural strengths were found to increase up to 66% and 70% respectively at 1.5% fiber content.
- For both compressive and flexural strengths, age effect is more for low volume for fibers, whereas, the difference in strengths was found to decreasefor high dose of PVA fibers.
- The ductility of ECC was found to increase with the increase in the fiber content in the mix.
- The amount of PVA fibers greatly influenced the workability of ECC. The workability decreased as the amount of fibers increased.
- ECC was lighter in weight when compared to plain concrete.
- The cracks formed in ECC specimens with no fibers under loading were large and jagged in tension, due to which the specimens were divided in two parts. On the other hand, micro-cracks were generated in beams and strips having PVA fibers.

List of symbols:

Γ	Deformability factor
D_1	Average of the two orthogonal diameters of the pancake and
D_0	Diameter of the base of the slump cone
P	Ultimate applied load by UTM
r	Radius of the cylinder
L	Span length of the beam sample in inches
b	Average width of the beam specimen at fracture surface in inches
d	Beam average depth at fracture in inches.
a	Horizontal distance between the fracture and the nearest support.
l	Length of the cylinder
D	Diameter of the cylinder

List of abbreviations:

ECC	Engineered Cementitious Composites
PVA	Poly Vinyl Alcohol
ASTM	American Society for Testing Material
UTM	Universal Testing Machine
MOR	Modulus of Rupture

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