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EMPIRICAL RELATIONSHIP BETWEEN MECHANICAL PROPERTIES OF HIGH VOLUME FLY ASH ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

This study is aimed to investigate compressive strength, flexural strength and shear strength of engineered cementitious composites (ECC) with high volume fly ash by replacing cement with Class F fly ash in the range of 40%, 60%, 80%, and 100% respectively. The experimental results shows that compressive strength and flexural strength decreased at 28 days as the percentage of high volume fly ash increased, but when the curing was increased to 90 days, 40% and 60% high volume fly ash engineered cementitious composite exhibited lesser but similar compressive and flexural strength compared to ECC without fly ash. The shear strength decreased as the percentage of high volume fly ash increased in ECC at 28 days. However, the rate of reduction of shear strength decreased when the curing was increased to 90 days. Based on the experimental results, an empirical relationship (exponential) is proposed between shear strength, compressive strength and flexural strength to predict shear strength from compressive and flexural strength at 28 and 90 days respectively. The percentage difference between the experimental and predicted shear strength from the empirical relationship was observed to be lesser than 14% for both 28 and 90 days, thus exhibiting the degree of accuracy for the proposed relationship.

Keywords: Cementitious composites, Compressive strength and flexural strength, Empirical relationship, Shear strength.

1. Introduction

Engineered cementitious composites (ECC) are high ductile fiber reinforced cementitious composites, generally consisting of cement (binder), fine aggregates and fibrous material (maximum of 2% by the weight of cement) as their constituents without coarse aggregates [1]. ECC exhibits a unique strain hardening behavior unlike other concrete, thereby increasing its load carrying capacity. The mixture design of ECC is based on micro mechanics design principle. ECC has higher cement content compared to conventional cement mortar [2]. The several beneficial properties of ECC that enabled its application in various fields are due to its excellent energy absorption [3], self-healing property [4-5], repair and rehabilitation of concrete structures [6]. Several other applications of ECC also includes exposure to adverse weather condition to couple structural elements [7].

The higher cement content in ECC leads to the excessive hydration rate and associated risks of plastic shrinkage cracks. Several investigations were also reported on the use of high volume fly ash in engineered cementitious composites on self-healing and strain hardening properties. On the other hand the annual generation of fly ash is being increased every year in India. In 2015 nearly 180 million tons of fly ash was generated and approximately only 60% of fly ash was utilized [8]. Utilization of fly ash in ECC will not only reduce higher cement content but also reduces heat of hydration and environmental pollution. The incorporation of fly ash enhances the mechanical properties in ECC when the optimized level of fly ash was used with the increase in the curing age [9]. The addition of high volume fly ash in ECC mixtures generally reduces the compressive strength at 7 and 28 days respectively. Several results have been reported by reusing fly ash in fiber reinforced concrete and composites [10] However, investigations on the shear strength of ECC have not been focused due to the complexity in testing equipment.

A simple and a modified testing method suggested by Bairagi and Modhera [11] was adopted in this study to find the shear strength of high volume fly ash engineered cementitious composite. Similar testing method was also adopted by Senthil Kumar and Baskar [12] to find the shear strength of concrete with E-waste as aggregates. The test results revealed that shear strength decreased due to the poor bonding of E-waste aggregates and cement.

In this study the compressive strength, flexural strength and shear strength of ECC with high volume fly ash (HVFA) is investigated. HVFA is used as both partial and complete replacement for cement in ECC.

2. Materials and Methods

The materials used in ECC includes Ordinary Portland Cement (OPC) of 53 grade conforming to IS: 12269 [13]. Cement was replaced with high volume fly ash with 40%, 60%, 80% and 100% based on volume of cement. The fly ash used in the study was Class F fly ash conforming to IS: 3812 [14] obtained from Ennore Thermal Power Station, Tamil Nadu, India. The fine aggregate used was locally available river sand passing through 1.18 mm sieve with specific gravity of 2.65 conforming to IS: 383 [15]. Ordinary potable water was used for both mixing and curing. To maintain fixed water binder ratio and to increase the workability, high range water reducing admixture was used based on IS: 9013 [16].

The fibers used in ECC were crimped (undulated) steel fibers of length 50 mm and diameter of 1mm; polypropylene fibers of 12 mm length with 200 to 300 microns in diameter were used. The fibers used were 1% steel and 1% polypropylene fibers based on volume of binder.

2.1. Compressive strength

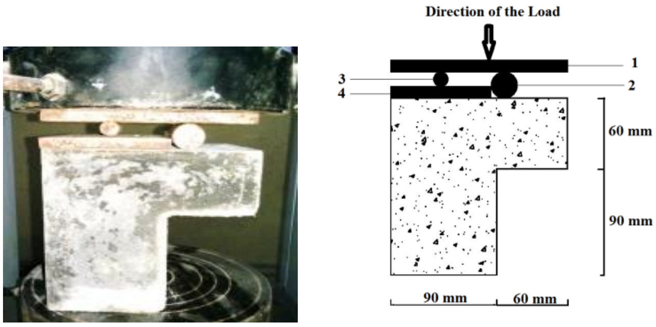
The compressive strength of ECC with and without high volume fly ash were tested by using cube molds of size 50 mm based on IS: 4031 Part 7 [17]. The compressive strength tests were performed at 7 days, 28 days, 56 days and 90 days respectively.

2.2. Flexural strength

The flexural strength test was performed on prism molds of size 40 mm × 40 mm × 160 mm based on ASTM C 348 [18]. The flexural strength of ECC with and without HVFA were tested at 28 days and 90 days respectively.

2.3. Shear strength

The specimens tested for shear strength were prepared as L shaped in 150 mm mold by placing wooden block of cross section 90 mm × 60 mm. The test setup consisted of two steel plates, one with 150 mm × 110 mm × 10 mm and other with 150 mm × 85 mm × 10 mm with two rollers of 12 mm and 22 mm in diameter with the length of both rollers as 150 mm were used to transfer the load. The shear plane is formed below the center of 22 mm roller as shown in Fig. 1. This test set up was based on Bairagi and Modhera [11] and Senthil Kumarand Baskar [12].



1-150 mm × 110 mm × 10 mm, 2-22 mm dia mild steel ball, 3-12 mm dia mild steel ball, 4- 150 mm × 84 mm × 10 mm

Fig. 1. Shear strength testing set up.

3. Results and Discussion

The results of compressive, flexural and shear strengths of ECC with and without fly ash are discussed below;

3.1. Compressive strength

The compressive strength results of high volume fly ash engineered cementitious composites are shown in Fig. 2. The compressive strength of ECC without HVFA increased from 43 MPa to 60 MPa when the curing was increased from 7 days to

90 days. The compressive strength of ECC with HVFA decreased as the percentage of fly ash increased. The compressive strength of ECC with 40% fly ash attained 28 % lesser than ECC without fly ash with 33 MPa at 28 days, but when the curing was increased to 90 days the compressive strength was only 6% lesser than ECC without fly ash. Similarly the ECC with 60%, 80% and 100% fly ash attained lesser compressive strength at 28 days but when the curing was increased to 90 days, the rate of gain of compressive strength increased. The increase in the rate of gain of compressive strength is due to the pozzolanic action of high volume fly ash and increase in the curing period. The compressive strength results are similar to the results of the previous researchers [9].

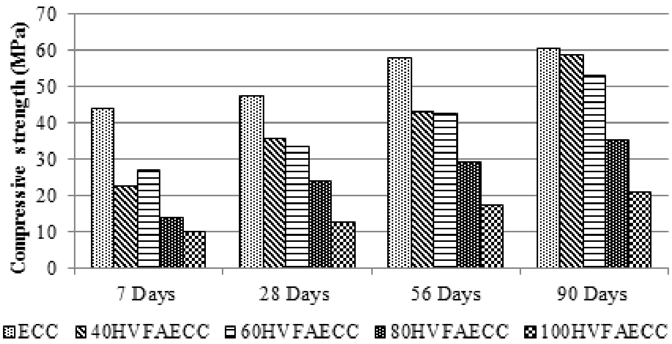


Fig. 2. Compressive strength (MPa).

3.2. Flexural strength

The flexural strength of ECC with and without HVFA is shown in Fig. 3. The flexural strength of ECC without HVFA attained14 MPa and 16 MPa at 28 and 90 days of curing, whereas ECC with varying percentage of fly ash (40%, 60%, 80% and 100%) attained 14% to 70% lesser flexural strength compared to ECC without fly ash at 28 days. ECC with 40% and 60% fly ash attained flexural strength similar to ECC without fly ash (6% and 8% lesser) when the curing was increased to 90 days, whereas the flexural strength of ECC with 80% and 100% fly ash were 20% and 65% lesser than ECC without fly ash. The engineered cementitious composites with high volume fly ash attained lesser flexural strength at both 28 and 90 days, but there was a noticeable increase in the rate of gain of flexural strength similar to compressive strength results.

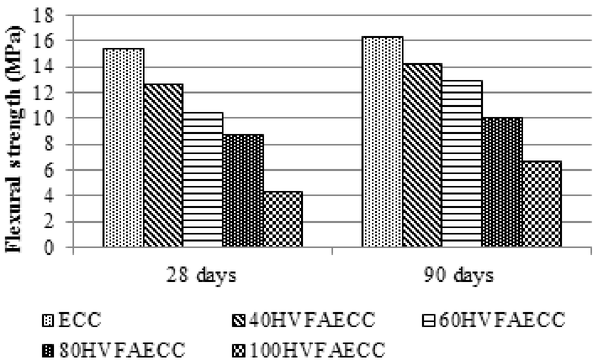


Fig. 3. Flexural strength (MPa).

3.3. Shear strength

The shear strength specimens were tested at 28 and 90 days of curing in the compressive strength testing equipment as shown in Fig. 1. The shear strength results of ECC with and without fly ash are compared as shown in Fig. 4. The shear strength of ECC without fly ash were 10.4 MPa and 12.3 MPa at 28 and 90 days respectively. Similarly the shear strength of ECC with high volume fly ash attained lesser shear strength compared to ECC without fly ash at 28 days, but when the curing was increased to 90 days the shear strength of HVFAECC attained higher shear strength compared to its 28 days.

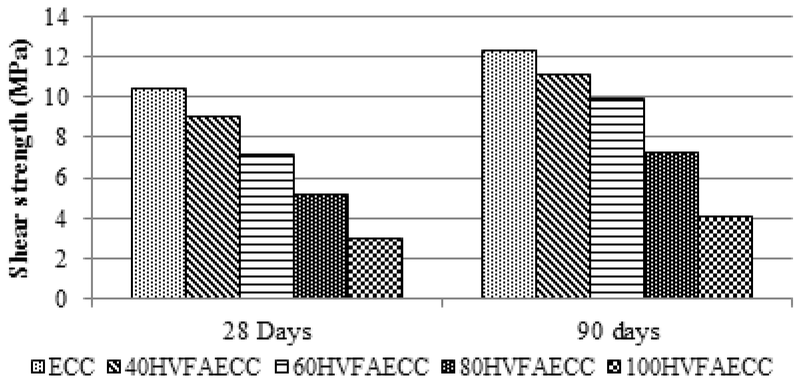


Fig. 4. Shear strength (MPa).

The HVFAECC exhibited similar but lesser shear strength compared to ECC without fly ash. Moreover, the shear strength test also revealed that micro cracks were formed when the load was applied but the crack propagation was minimized when the specimen attained failure load. This was observed both in ECC with and without fly ash due to the incorporation of steel and polypropylene fibers.

3.4. Rate of reduction of shear strength

The shear strength results clearly revealed that incorporation of steel and polypropylene fibers increased the tendency of changing the brittle behaviour to ductile behaviour in ECC with and without HVFA that was noticed during testing and it is shown in Fig. 5. Based on the shear strength results the rate of reduction of shear strength of HFVAECC with respect ECC without fly ash was analysed for both at 28 days and 90 days of curing. The rate of reduction of shear strength of HVFAECC compared to ECC without fly ash will also provide behaviour of fibers under shear. The result from the shear strength is a clear evident that as the fly ash increased the shear strength decreased but the rate of reduction of shear strength decreased as the curing age was increased. The shear strength of cementitious composites with 40% fly ash was 13% lesser at 28 days but when the curing was increased to 90 days the reduction in shear strength was reduced to 10%. Similarly HVFAECC with 60% fly ash showed 30% reduction in shear strength at 28 days and 19% at 90 days compared to ECC without fly ash. The shear strength reduction for 80% and 100% fly ash exhibited similar trend compared to ECC without fly ash.

Fig. 5. Shear strength test specimen after failure with crack in the shear plane.

4. Empirical Relationship Between Shear Strength, Compressive Strength and Flexural Strength

Based on the experimental results of compressive strength, flexural strength and shear strength of the high volume fly ash engineered cementitious composites, an empirical relationship between the shear strength, compressive strength and flexural strength is performed. Since a simple experimental method was suggested to find the shear strength of the composites, this empirical relationship will also predict the shear strength based on the experimental results of compressive strength and flexural strength at 28 days and 90 days respectively.

4.1. Relationship between shear strength and compressive strength

The relationship between shear strength and compressive strength were performed and it is shown in Fig. 6. The relationship between shear strength and compressive strength resulted in the exponential function with the equation of $y = 2.059e^{0.0369x}$ with $R^2 = 0.948$ at 28 days and $y = 2.5513e^{0.0259x}$ with $R^2 = 0.9658$ at 90 days respectively. The function y represents the shear strength and x represents the compressive strength of the mixtures in Fig. 6.

The experimental and predicted values of shear strength from compressive strength are given in Table 1. The percentage differences between the experimental and predicted values are also calculated to find the degree of accuracy of the proposed relationship. The percentage differences between the experimental and predicted values are lesser than 14% for both 28 and 90 days respectively.

Table 1. Predicted shear strength from compressive strength.

Mix	28 days Shear Strength		% Error	90 days Shear Strength		% Error
	Experimental	Predicted		Experimental	Predicted	
ECC	10.40	11.80	13.45	12.33	12.16	-1.41
40HVFAFECC	9.03	7.71	-14.59	11.07	11.68	5.47
60HVFAFECC	7.18	7.13	-0.74	9.96	10.04	0.84
80HVFAFECC	5.19	4.96	-4.38	7.22	6.32	-12.45
100HVFAFECC	3.03	3.31	9.14	4.07	4.41	8.44

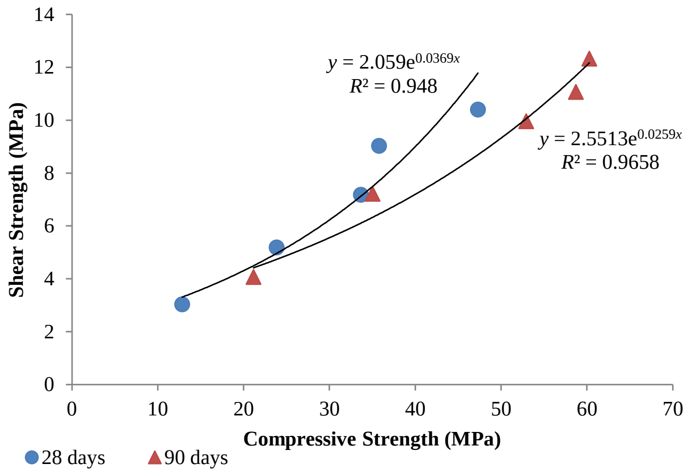


Fig. 6. Shear Strength and compressive strength.

4.2. Relationship between shear strength and flexural strength

Similar to the proposed relationship between the shear strength and compressive strength, the relationship between the shear strength and flexural strength were also determined and it is shown in Fig. 7. The resulted exponential equations are $y = 1.9197e^{0.1165x}$ with $R^2 = 0.968$ at 28 days and $y = 2.0532e^{0.1162x}$ with $R^2 = 0.9569$ at 90 days respectively. The function y represents the shear strength and x represents the flexural strength of the mixtures in Fig. 7.

The experimental and predicted values of shear strength from the proposed exponential relationship is given in the Table 2. The percentage difference between the experimental and predicted shear strength values are lesser than 11%.

Based on the proposed relationship between the shear strength, compressive strength and flexural strength it is observed that shear strength can be predicted for this composites based on the experimental values of compressive strength and flexural strength with the good degree of accuracy (error lesser than 11%). This will also enhance the concrete investigators to have a clear idea on the behaviour of composites in shear without performing the test.

Table 2. Predicted shear strength from flexural strength.

Mix	28 days Shear Strength		% Error	90 days Shear Strength		% Error
	Experimental	Predicted		Experimental	Predicted	
ECC	10.4	11.55	11.01	12.33	13.69	11.06
40HVFAFECC	9.03	8.35	-7.52	11.07	10.75	-2.86
60HVFAFECC	7.18	6.47	-9.88	9.96	9.21	-7.49
80HVFAFECC	5.19	5.33	2.63	7.22	6.6	-8.57
100HVFAFECC	3.03	3.19	5.17	4.07	4.46	9.68

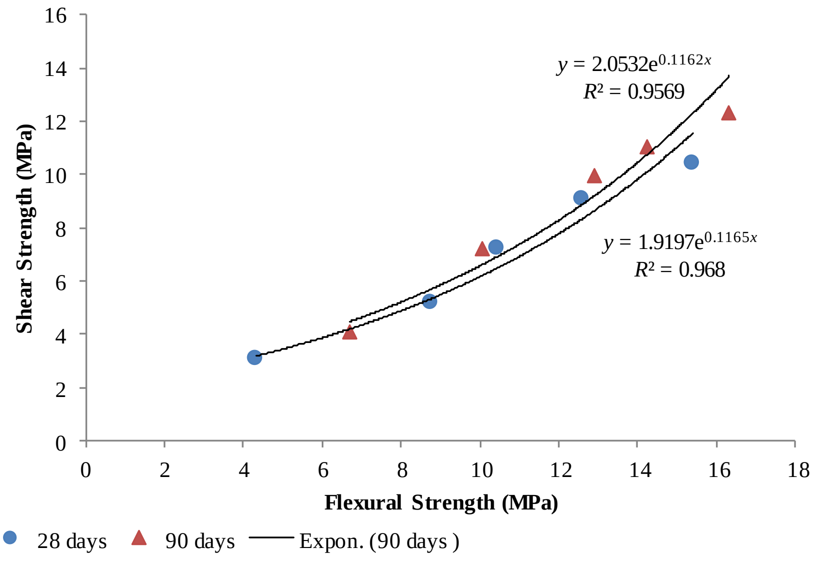


Fig. 7. Shear Strength and flexural strength.

5. Conclusions

The effect of high volume fly ash in engineered cementitious composites on the mechanical properties such as compressive, flexural and shear strengths were investigated in this study. The structural application of high volume fly ash in ECC needs to be further investigated in the future to not only increase the service lifetime but also towards sustainable development under different conditions. Based on the experimental investigation and the relationship between compressive, flexural and shear strengths of high volume fly ash engineered cementitious composites the following conclusions can be made;

- The compressive strength of ECC with high volume fly ash exhibited lesser strength at 28 days but when the curing was increased to 90 days 40% and 60% fly ash attained lesser but similar strength compared to ECC without fly ash.
- The flexural strength of ECC with 40% and 60% exhibited similar results compared to ECC without fly ash when the curing was increased to 90 days.
- The shear strength decreased as the percentage of high volume fly ash increased.
- The rate of reduction of shear strength decreased as the curing age increased.
- Based on the experimental results of shear strength, compressive strength and flexural strength an exponential relationship was proposed to predict shear strength from compressive strength and flexural strength at 28 and 90 days.
- The predicted shear strength from compressive strength and flexural strength exhibited good degree of accuracy with the error lesser than 14% and 11%.

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Nomenclatures

R^2	Coefficient of determination

Abbreviations

ASTM	American Society for Testing and Materials
ECC	Engineered cementitious composites
ENVIS	Environmental information system
HVFA	High volume fly ash
HVFAECC	High volume fly ash engineered cementitious composites
IS	Indian standards
OPC	Ordinary Portland Cement

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