INFLUENCE OF POLYMERIC AND NON-POLYMERIC FIBERS IN HYBRID ENGINEERED CEMENTITIOUS COMPOSITES

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In this study the mechanical performance of hybrid engineered cementitious composite using polymeric fibers and glass fibers are investigated. Nine different mixes are used in this study, in which three mixes with mono fiber and the remaining mixes are developed with hybrid fiber reinforcement. The hybridation with low and high modulus fibers are engaged to increase the mechanical performance of the engineered cementitious composite. This process has a notable achievement in the direct tensile strength and young's modulus of the ECC mix. The outcome revealed that, poly vinyl alcohol of volume fraction 0.65% and glass of volume fraction 1.35% displayed significant and reasonable characteristics than the other mixes.

Keywords: *ECC, Polymeric fibers, glass fiber, mechanical properties, micro structural studies*

1. Introduction

In the past few decades, for structural application high compressive strength concrete has been used. But, the brittleness number of the concrete increases as the compressive strength increases [1]. This poses a disadvantage to the high strength concrete, which leads to the limited usage of high compressive strength concrete in structural applications. Particularly for seismic resistant structures, concrete requires high ductility, as it makes a significant difference in the overall structure against the seismic response. Hence there is a need to increase the yielding zone of concrete structure using high ductility cementitious materials. The Engineered Cementitious Composites (ECC) developed by Victor Li at the end of twentieth century, showed unique properties of high strength concrete that exhibited excellent strain hardening properties, multiple cracking and fiber bridging properties which in turn increase the ductility of structure. ECC is a cement matrix based composite material reinforced with short random fibers of maximum volume fraction 2.0%. It can also be called as Ultra-High Toughness Cementitious Composite (UHTCC). ECC mixes are generally developed with adding Polyvinyl Alcohol (PVA) fiber, polypropylene (PP) fiber and polyethylene (PE) fiber. The introduction of fibers is to minimize the damages in the concrete structure that is subjected to seismic and impact effects [2-4].Initially, this material was applied for the repair and retrofitting purpose due to their characteristics like high performance, flexible processing, short fibers at moderate volume fraction and isotropic properties. Due to the above unique properties, ECC was widely applied in various structural elements since the last decade.

In the past few years, considerable research works have been carried on to improve the performance of ECC through various strategies and technical approaches. It was noted that the ingredients used in the ECC were similar to the fiber reinforced concrete, except the coarse aggregate. Initially various fibers were used to develop the ECC mix, however in particular ECC developed with PVA fibers showed significant characteristics in terms of self-consolidation, mechanical performance, durability, minimum equipment force and various other field applications. The Performance attribute of ECC is attained by micro mechanism based composite optimization. This optimization technique provides guidance in determining the type, size and quantity of ingredients to be present in the ECC mixes [5,6]. The application of ECC is emerging at present in various infrastructures. Significant applications include link slab in bridges [7], mitaka dam retrofit [8], tunnel linings [9], dampers [10], retaining wall and via duct [11], shear resistance [12], ECC strips in RC slab [13], beam-column joint [14] and retrofit for masonry wall [15]. In recent days, technological development in various varieties of fibers has provided us exceptional platform for new opportunities for the development of fiber reinforced composite materials [16]. Fibers with different geometric properties, material properties and nature of behavior are used in hybrid

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composites, which in turn increases the material properties of fiber reinforced cementitious composites [17-21]. In this research work, to enhance the properties of the composite an attempt is made to use two fibers of different nature in the same composite mix. The aim of the research work is to design a new composite material with enhanced tensile strength and flexural strength by taking into account the combined contribution of low modulus and high modulus fiber as an advantage.

2. Research significance

In the present scenario, application of ECC has extended over to various applications in construction industries and it may be extend further in the near future. However there are few limitations in the applications of ECC with mono fibers which in turn creates a need to improve the mechanical properties of the ECC with mono fiber. The Hybridation in the ECC with low and high modulus fiber exhibits notable improvement in the mechanical properties [1 - 4]. In this research, an attempt is made to develop a hybrid cementitious composite by incorporating low modulus PP fiber and high modulus glass fibers with PVA fiber to improve the compressive strength, direct tensile strength and the flexural behavior of ECC. For determining the various characteristics, hybridation is developed by replacing PVA fibre by PP fiber with 0.65%, 1.00% and 1.35% volume fraction and similarly replacement of PVA fibre by glass fiber with 0.65%, 1.00% and 1.35% volume fraction. ECC with 2.0% volume fraction of PVA fiber is kept as a reference mix.

3. Experimental investigation

3.1. Materials and mix preparation

The OPC 53 grade cement and Class F fly ash from Mettur thermal power plant, Tamilnadu, India are used in this study. PVA fibers, PP fibers and glass fibers are used to develop the hybrid ECC, Table 1 and Table 2 shows the chemical composition of cement and flyash and characteristics of fibres respectively. Table 3 shows the different ECC mixes used in this investigation. Chloride free conplast SP430 water reducing agent is added in the ECC mix to meet the flexibility in fresh state of ECC mix. River sand is used as a fine aggregate with specific gravity of 2.66 and fineness modulus of 2.85. Mixes are named as M1 for ECC mix with PVA mono fiber reinforcement, PP and glass fibers reinforced ECC mixes as M2 and M3 respectively. Mixes M4, M5 and M6 are made with hybridation of PP fiber against PVA fiber in volume fraction of 1.35%, 1.00% and 0.65% respectively. Similarly, mixes M7, M8 and M9 are made with hybridation of glass fiber against PVA fiber in volume fraction of 1.35%, 1.00% and 0.65% respectively. Hybridation process is made to improve the mechanical characteristics and ductility nature of ECC mix. Mixer machine is used to prepare the ECC mixes. Initially powdered ingredients such as cement, fly ash and sand are added and are allowed to mix for minimum five minutes. Then, the water and super

Table 1

Chemical composition of cement and fly ash

	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Alkalines (%)
Cement	63.71	22.30	4.51	3.39	1.77	2.59	1.73
Fly ash	5.31	55.37	29.74	7.88	1.48	0.22	--

Table 2

Physical and mechanical characteristics of fibre

Fibre	Diameter [μm]	Length [mm]	l/d ratio	Density (g/cm3)	Nominal tensile strength [MPa]	Elongation at break [%]	Young's modulus [MPa]
PVA	39	12	308	1.3	1600	6	42.5
PP	37	10	270	0.91	400	23	2.5
Glass	17	10	588	2.55	2200	3.5	81.0

Table 3

Mix design of ECC

Mix ID	Cement	Fly ash	Sand	Water/Binder ratio	Super Plasticizer [%]	PVA Volume [%]	PP Volume [%]	Glass Volume [%]
M1	1	0.43	0.71	0.35	1.0	2.0	--	--
M2	1	0.43	0.71	0.35	1.0	--	2.0	--
M3	1	0.43	0.71	0.35	1.0	--	--	2.0
M4	1	0.43	0.71	0.35	1.0	0.65	1.35	--
M5	1	0.43	0.71	0.35	1.0	1.0	1.0	--
M6	1	0.43	0.71	0.35	1.0	1.35	0.65	--
M7	1	0.43	0.71	0.35	1.0	0.65	--	1.35
M8	1	0.43	0.71	0.35	1.0	1.0	--	1.0
M9	1	0.43	0.71	0.35	1.0	1.35	--	0.65

plasticizer are added in the dry mix and allowed for 5 to 7 minutes prior to which the proper stirring and mixing of super plasticizer with water is essential. This preparation ended shortly by adding fibers to the wet mix and 3 to 5 minutes was given to the wet mix to distribute the fibers to spread evenly. The advantage in preparing mix for more than 15 minutes is to reduce the thixotropy effect of the ECC mix [26].

3.2. Test methods

3.2.1 FTIR analysis

Fourier Transform Infra-Red spectroscopy (FTIR) analysis has been used to examine the chemical composition at the surface of the fibers. The analysis was performed using the Nicolet 6700 FTIR spectrometer (from thermo fisher scientific, USA).

3.2.2. Compressive Strength and Young's Modulus

To determine the compressive strength of ECC mixes, 70.7 x 70.7 x 70.7 mm size cube specimens are used. Tests conducted after 3 days, 7 days, 14 days and 28 days curing according to IS 4031- Part 6: 1988 [27]. Compression testing machine of 200 kN capacity is used to test the specimen, three specimens are casted and tested for each mix, average strength value is taken in to account. Cylinder with 100 mm in diameter and 200 mm in length specimen is used to determine the young's modulus.

3.2.3 Direct Tensile Strength

Dog bone specimen of size 330 mm x 60 mm x 30 mm [5 - 7] with gauge length of 80 mm and a cross section of 30 mm x 30 mm has been used to examine the direct tensile strength of ECC mixes after 7days, 14 days and 28 days curing. The uniaxial direct tensile test is carried out using universal testing machine of capacity 100 kN. Figure 1 shows the test setup and dog bone specimen details for direct tensile test.

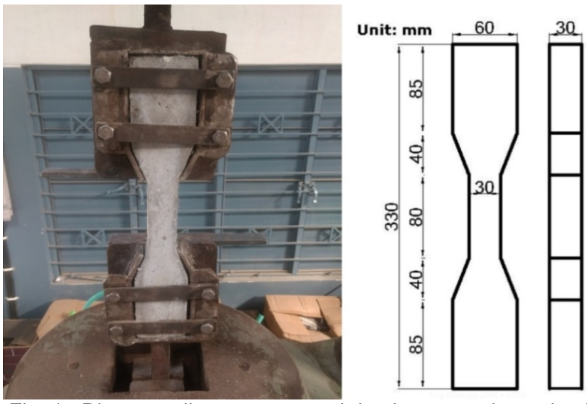

Fig. 1 - Direct tensile test setup and dog bone specimen detail.

3.2.4. Field Emission Scanning Electron Microscopy Analysis

Field emission scanning electron microscopy (FESEM) analysis is made on the ECC specimens after direct tensile test to determine the

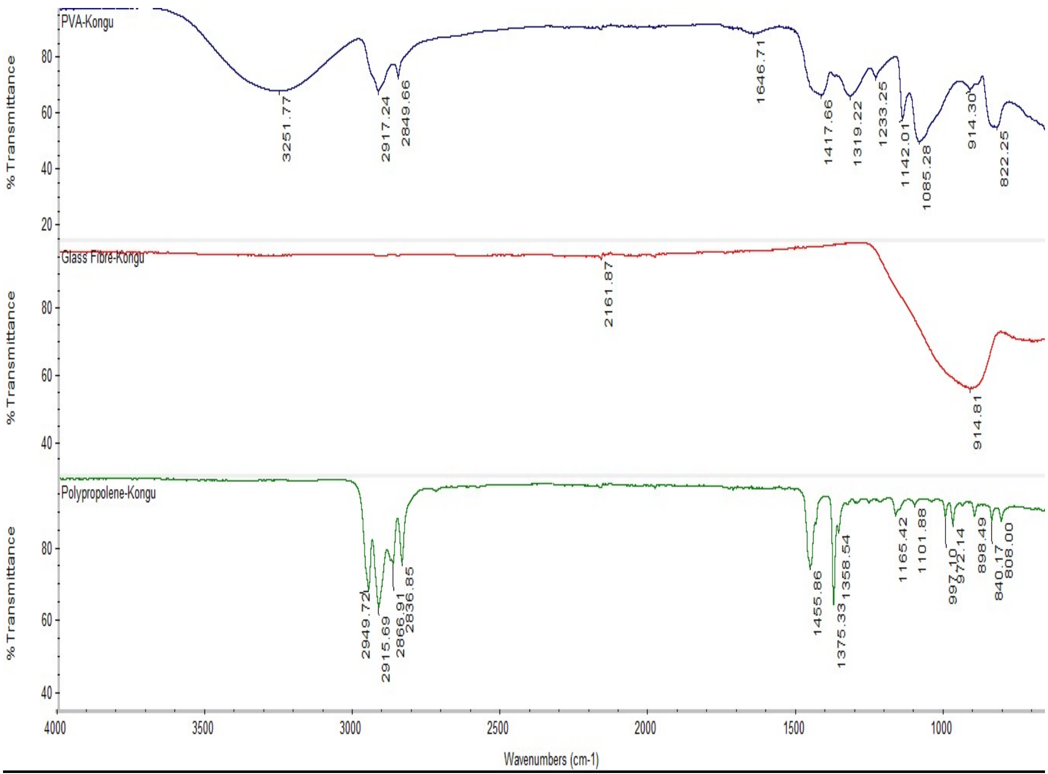

Fig. 2 - FTIR Test on Fibers.

surface morphology of cementitious particle, fiber orientation and bond between cement composite and fiber. Zeiss sigma make with a resolution of 1 nm @ 15kV with HD was used for FESEM Analysis.

4. Results and discussion

4.1. FTIR analysis

The PVA, PP and glass fibers were characterized by FTIR analysis based on their chemical structure. Figure 2. shows the chemical structure of all fibers. In general, PVA fiber has a relatively simple chemical structure. PVA polymer is produced by the polymerization of vinyl acetate to poly vinyl acetate, followed by the hydrolysis of PVAc to PVA [8]. From the figure, it can be incurred that for PVA fiber peak band was observed at 3251 cm-1 and was vibrant between 2917 cm-1 to 2849 cm-1. An infra-red spectrum for PP fiber has the peak band at 2949 cm-1 to 2836 cm-1 and 1455 cm-1 to 1358 cm-1 , both peaks are vibrant. It was compatible with the earlier research findings [32]. From the wave number of PVA fiber, the main chemical group in polymer structure is OH stretching groups and for PP fiber C-H symmetrical stretching groups [33]. An infra-red spectrum for glass fiber has the peak band at 914 cm^{-1}, which is a non-vibrant band. The wave length parameter was lost due to the purification of un wanted impurity bonds (Ge–Te–Se) in the glass fiber, and thus it provides the clear transmission window up to 1200 cm^{-1} , which is fairly related to the previous research result on purified glass fiber [34]. The main chemical group in polymer structure is C-OH ring and side group vibrations.

4.2. Compressive Strength

Totally nine different mixes were tested to determine the compressive strength of the ECC after 3, 7, 14 and 28 days of curing. For each mix, three specimens were tested and an average compressive strength was taken in to account. Figure 3. shows the variations in the compressive strengths of different ECC mixes after curing in different stages. 51 MPa, 47.5 MPa, 53.71 MPa, 53.2 MPa, 50.85 MPa, 48 MPa, 53.1 MPa, 52.7 MPa and 52.6 MPa are the 28 days compressive strength of M1, M2, M3, M4, M5, M6, M7, M8 and M9 ECC mixes respectively. From the results, it can be noted that there is concomitant increase in the compressive strength. After completion of 3 days, the compressive strength of concrete with ECC mixes is in the range of 18.5% to 20.0 % of the 28 days compressive strength. Similarly after 14 days, the compressive strength is observed as 91.2%, 93.7%, 93.5%, 92.7%, 92.2%, 95.4%, 91.1% and 89.6% for M1, M2, M3, M4, M5, M6, M7, M8 and M9 ECC mixes respectively. Hence, from the results, it can be observed that the fiber hybridation does not create any major vital impact on the compressive strength. Cube specimen fails with typical ductile failure pattern after the compressive load. It is clearly observed that the ECC mixes are more ductile; and this is owed to the fiber bridging effect, as a result the fragments are stuck around the cubes [32].

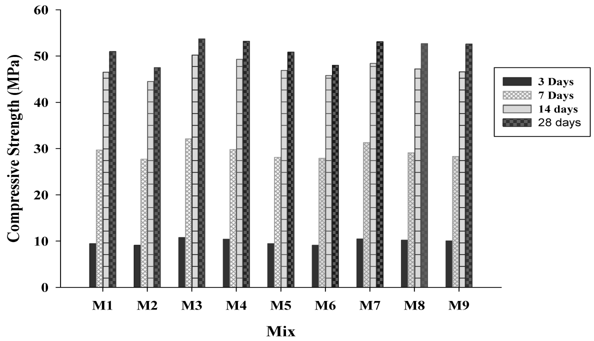

Fig. 3 - Compressive strength of ECC mixes.

4.3. Young's Modulus

The average Young's modulus of ECC specimens after 3, 7, 14 and 28 days are shown in Figure 4. From the figure, it can be clearly observed that the young's modulus of all the mixes exhibit similarity after 3 days curing. After 7, 14 and 28 days, there is a reasonable variation in the young's modulus values. Among all the mixes, M2 exhibits lower Young's Modulus value of 22.1 GPa due to the presence of polypropylene fiber. This ensures the presence of polypropylene fibers in hybridation process affects the young's modulus value. Mix M3 shows the better performance than the other mixes as it displayed 26.3 GPa due to the presence of high modulus glass fiber. PVA fiber based mono ECC produced notable achievement in the Young's modulus properties which is 0.9 times of the M3 mix.

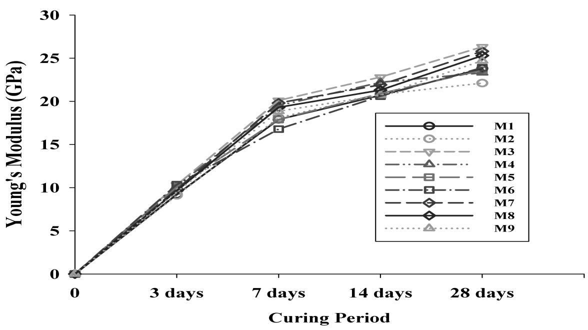

Fig. 4 - Young's Modulus of ECC Mixes.

In general ECC mixes shows very low Young's modulus value than the conventional concrete with equivalent compressive strength and this is because young's modulus of concrete is directly related to cement mortar and coarse aggregate, and due to the bond between them [35]. Hence, the absence of course aggregates in ECC mixes influences the young's modulus value.

4.4. Direct Tensile Strength

Application of ECC material in the construction industries have increased widely and it is vital to identify the role of ECC in different form of applications. Generally, ECC are developed to be used in the repair and rehabilitation of infrastructure and then due to their better performance, ECC is applied in various structural applications; one such significant characteristic is to improve the alleviation of crack damaged surface under tension. For this purpose, there is need to study the direct tensile strength of all ECC mixes. Tensile test has been carried out after 7, 14 and 28 days curing. Due to negligible strength attainment at 3 days, tensile strength value is ignored. ECC mix developed with glass fiber reinforcement exhibits maximum tensile of 7.98 MPa, 4.35 MPa and 2.12 MPa after 28, 14 and 7 days of curing respectively which is 1.53, 1.49 and 1.44 times greater than M1 mix. Mix M2 exhibits low strength of 1.23 MPa, 2.29 MPa and 4.55 MPa after 7, 14 and 28 days respectively. Similarly Mix M4, M5 and M6 displayed the tensile strength of 5.45 MPa, 5.09 MPa and 4.94 MPa respectively after 28 days curing and which is 31.7%, 53.0% and 59.7% less than the M3 mix. 6.93 MPa, 6.58 MPa and 6.45 MPa tensile strengths are exhibited by Mix M7, M8 and M9 respectively after 28 days curing. The Guideline recommended by Victor Li [36] for ECC mix based on the ultimate direct tensile strength after 28 days curing is to be limited around 4-12 MPa and the direct tensile strength of all the nine ECC mixes are within the particular range. Hence these mixes were used for different applications based on their role of application. In addition to that, the ultimate tensile failure crack pattern of dog bone specimen is occurred within the specified gauge length. Figure 5. Shows the direct tensile strength of ECC mixes.

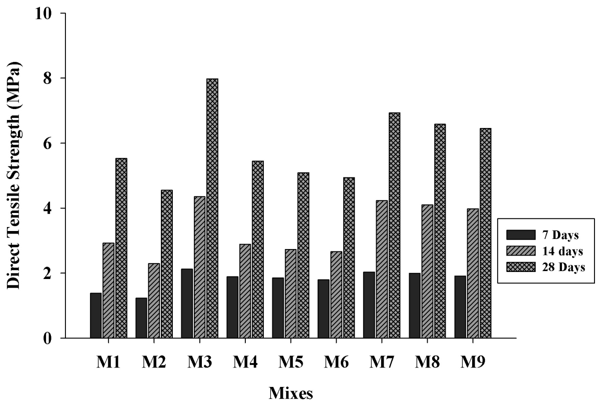

Fig. 5 - Direct Tensile Strength of ECC Mixes.

4.5. Micro Structure Analysis

Micro structural analysis of ECC with mono fiber specimen was viewed with the help of FESM. Core part of the dog bone specimen is taken in to account after tensile failure. Figure 6. shows the FESEM microscopes of ECC mix with PVA fiber of volume fraction 2.0% scanned with 500 magnification. From the figure, it is clear that the positive fiber dispersion in the cementitious matrix and dispersion surface produces smooth contact between fibers and cementitious matrix and further more micro fibers fail under rupture mechanism rather than the pullout failure which reflects the excellent adhesive bond between the fibers and cement matrix. [9]. Similarly Figure 7. shows the FESEM image of PP fibers with volume fraction of 2.0% and scanned with 5000 magnificence. From the image, it is clearly observed that the there is a noticeable change in the diameter of the fiber at the middle part of its length due to tensile stress applied on the ECC, more over PP is a strain hardening fiber and fails under notable yield after ultimate load, this instant increases the micro cracks and fiber bridging. Due to higher yielding nature than any other fibers used in this study, PP fiber fails with extent neck at the fracture. Glass fiber orientation with the cementitious matrix with the help of FESEM image is shown in Figure 8. It shows the similar results displayed by the PVA fiber at fracture and reflects excellent adhesion between the glass fiber and the matrix. This bonding effect between cement matrix and fibers guides to transfer the stresses and thus the improvement in the mechanical properties of ECC with glass fiber [10].

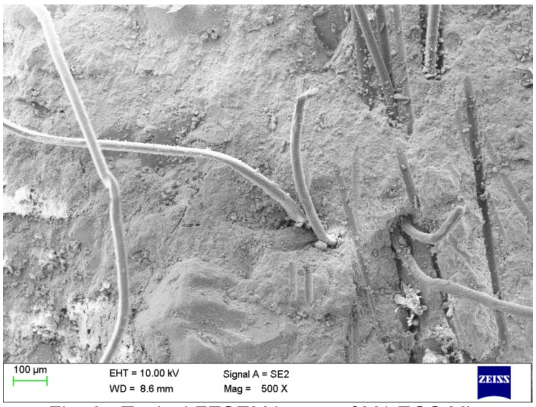

Fig. 6 - Typical FESEM image of M1 ECC Mix.

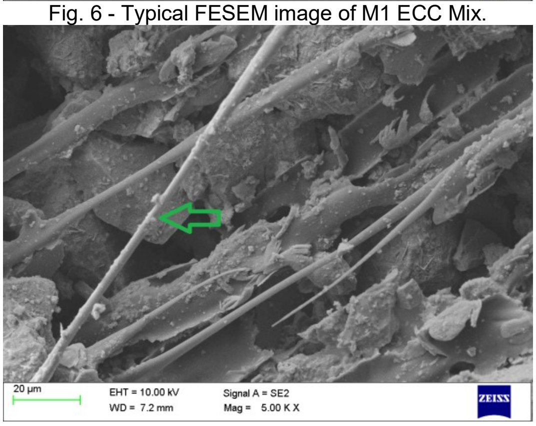

Fig. 7 - Typical FESEM image of M2 ECC Mix.

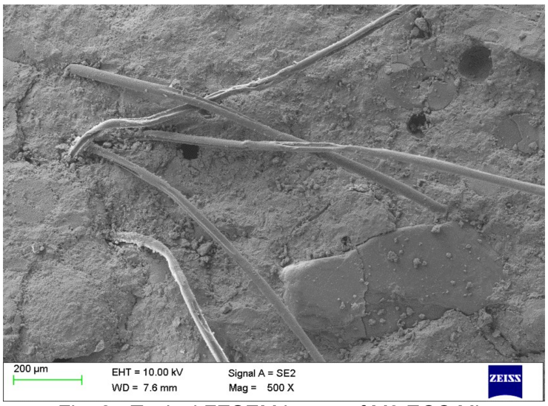

Fig. 8 - Typical FESEM image of M3 ECC Mix

5. Conclusion

Experimental investigation on the mechanical behavior and micro structural investigation on the ECC mixes were made and the following conclusions were arrived:

Hybridation of the fiber utilized caused no synergistic enhancement in the compressive strength of ECC mixes. ECC developed with glass fiber exhibit maximum ultimate strength but fail with minimum ductility due to their low modulus characteristics. Hybridation between PVA and glass shows notable performance in strength and ductility characteristics because of modulus of elasticity of PVA fiber and tensile strength of glass fiber. The results are similar in case of the young's modulus. Direct tensile strength of the hybrid ECC with PVA/glass fiber displayed promising results. If hybrid ECC mixes with high modulus fiber and low modulus fiber, the compressive strength and direct tensile strength were found to be more significant. However the ductility and multiple cracking decreased simultaneously. Similarly, hybridation with low modulus showed excellence in ductility and multiple cracking, despite the reduction in the compressive strength and direct tensile strength subsequently. A micro structural study reveals that a convincing bond between cement matrix and fibers used is achieved in the mix.

ACKNOWLEDGEMENT

PVA fibers used in this research work were funded by Kuraray pvt limited India.

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