STUDY ON MECHANICAL PROPERTIES OF HYBRID FIBER REINFORCED ENGINEERED CEMENTITIOUS COMPOSITES

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This paper describes an experimental study on the behavior of engineered cementitious composites (ECC) accompanied by compressive, flexural and uni-axial tensile strength. In this experimental program, six sets of ECC mixtures with 2% total volume fraction of fibers were produced for each set of mixture and was proportioned to have the same material quantity such as silica sand, micro-silica and cement in order to determine the optimal percentage of polyvinyl alcohol (PVA) and steel fibers (SF). ECC mix proportion is designed experimentally by adjusting the amount of micro-silica and silica sand by conducting four-point bending, compressive and uni-axial tensile strength test of the ECC specimens. The test results emphasize that there is an improvement in ultimate flexural strength and ultimate tensile strength of the hybrid fiber reinforced cementitious composites with the addition of 1.5% of PVA and 0.5% of Steel fibers. High tensile strain capacity of about 25% has attained for the addition of 2% of PVA fibers, which indicates a superior ductility behavior of ECC specimens. Furthermore, the experimental results emphasize that there is a good correlation between flexural deflection capacity and tensile strain capacity.

Keywords: *Hybrid fiber, four-point bending, uni-axial tensile, PVA, ECC*

1. Introduction

The class of ultra-ductile fiber which is reinforced with cementitious composites ably known as engineered cementitious composite (ECC) was originally invented in the early 1990s at Michigan university [1]. It is apparent that, hybrid fiber reinforced engineered cementitious composites (HFRECC) is produced to have high improved toughness and ductility and it will depend on the micromechanical design which exhibits a remarkable tensile strain capacity, although it uses only short fibers with a moderate volume fraction of typically around 2% or less [2]. The strain hardening behavior of ECC can also be taken into consideration in the design of ECC members under bending moments [3]. The striking characteristic feature of ECC is its tensile ductility, with strain capacity varying from 3-7% [4]. In addition, when compared with normal concrete, ECC exhibits 500-600 times higher strain capacities [5]. Furthermore, upon comparison with normal concrete, coarse aggregates will be eliminated thereby resulting in the utilization of higher cement content [6]. Generally, high cement content leads to high rate of hydration, higher shrinkage and cost. For the purpose of reducing the quantity of cement in ECC mixture, micro-silica or any cementitious material can be added. But in doing so, immense care has to be taken to ensure that the mechanical properties are not varied especially the ductility shouldn't be changed [7]. In [8], the utilization of recycled concrete fines as a partial replacement of natural sand in concrete was investigated to show that the strength at early ages was marginally lower. The feasibility of utilizing recycled concrete fines together with recycled coarse aggregates for self-compacting concrete has been studied by Ceprak and was achieved high performance by using 25-50% recycled concrete fines as replacement of river sand [9].

Unlike normal fiber reinforced cementitious composites, the robust nature of ECC is that, it possesses an ultra-high tensile ductility of several percent. This is due to the fact that, even after the first matrix cracking, it exhibits metal like pseudo strain-hardening behavior due to progressive formation of multiple cracks [10-12]. In generality, the tensile characteristics play a major role in deciding the flexural properties of cement [13], whilst, the tensile ductility of ECC is reflected by its flexural response also [14]. In this context it can be claimed that, for plasticity under tension ECC can exhibit a flexural strength as high as 10-15Mpa, a degree of 2 or 3 times high when compared with normal concrete [15]. It is interesting to note that, the crack width of ECC can be limited to 100μm by ensuring perfect control of the fiber-matrix interface properties as well as fiber bridging [16]. Much more relevant research work in the literature focuses on the behavior of cement based material reinforced by mono fibers based [17] and hybrid fibers with two different fibers or more [18,19]. As a result, ECC attains a higher flexural strength and it takes place to the maximum deflection of hardening zone [20]. Therefore, it can be claimed that, strain hardening is a vital property of ECC and moreover, it does not rely on geometry. Consequently, it can be figured out that, flexural characteristic is the most prominent part which decides the overall performance of ECC [21]. The aim of using hybrid combinations is to generate synergetic interaction

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between fibers that may invigorate the advantages those cannot be achieved by mono-fibers. Even though, huge amount of research is carried pertaining to the behavior of ECC as a material, however, to the best of the authors knowledge there is a lack of information elucidating the performance of ECC structural members while employing hybrid fibers such as polyvinyl alcohol (PVA) and steel fibers (SF). Therefore, this work evaluates, the mechanical properties of hybrid fiber reinforced cementitious composites incorporating polyvinyl alcohol and steel fibers.

2. Experimental Program

In order to examine the behavior of hybrid fiber reinforced cementitious composites, six types of mixtures with different percentage variation of mono and hybrid fibers have been investigated in this present study. And the experimental program has been mainly focused on the influence of different percentage variation of fiber volume fraction such as PVA and Steel fibers content on the mechanical properties including compressive strength, flexural strength and uni-axial tensile strength.

2.1. Constituents of materials

The standard ECC mix proportion was derived from the aforementioned research work and it has been used and modified in the present experimental investigation [22]. An ordinary Portland cement (OPC) of 53 grade (according to Bureau of Indian Standards) with a surface area of 340m^2/kg and a specific gravity of 3.15 was utilized. In order to replace the cement, locally available micro-silica was used as the supplementary cementitious material with a constant micro-silica to cement ratio of 0.26. Maximum and average grain sizes of silica sand used in the mixtures are of 0.5mm and 0.2mm respectively, in order to replace fine aggregates. In order to attain proper workability in fresh ECC mortar matrix after the addition of fibers, polycarboxylate ether based super-plasticizers (HRWRA-High range water reducing admixture) and Hydroxypropyl methyl cellulose (VMA-Viscosity modifying agent) were used according to ASTM standard code [23]. Hybrid fibers (PVA and steel) were used at a total volume fraction of mortar as 2% in composite matrix. Table 1 illustrates the physical and mechanical properties of hooked end steel and PVA fibers and their typical views are displayed in Fig 1 and Fig 2, respectively. In this experimental work, six different ECC mixtures were cast by incorporating various dosages of mono and hybrid fibers. All the specimens were cast with the same water-cementitious ratio of 0.3 by varying the fiber dosages from 0 to 2%. In the first test mixture, ECC mortar specimens were cast in order to assess the strength without the addition of fibers and it has been used as reference for all the other five mixtures. In the second and third mixtures, the effect of adding 2% of PVA fibers and 2% of steel fibers by total volume fraction were investigated, respectively. And in the last three mixtures, the combined effects of hybrid fiber dosages (i.e. 1-1, 1.5-0.5, 0.5-1.5 PVA-SF by total volume fraction of 2%) on the performance of mechanical properties have been determined. The mix proportion of mono and hybrid fiber reinforced cementitious composites is shown in Table 2.

2.2. Mixing and Casting Procedures

All ECC mixtures were mixed with the same procedure. Initially, the matrix materials were first mixed including cement, micro-silica and silica

Table 1.

Mechanical and physical properties of PVA and steel fibers

Type of fibers	Shape of fibers	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Modulus of elasticity (GPa)	Density (kg/m^3)
PVA	Straight	12	0.04	300	1600	41	1290
Steel	Hooked-end	35	0.5	70	1100	210	7850

Fig 1 - Typical view of hooked-end steel fibers.

Fig 2 - Typical view of PVA fibers.

Table 2

Mix proportion of mono and hybrid fiber reinforced cementitious composites

Mixture series	Designation of the mixture	Cement (kg/m^3)	Micro-silica (kg/m^3)	Silica sand 0.5mm (kg/m^3)	Silica sand 0.2mm (kg/m^3)	Water (kg/m^3)	HRWRA (kg/m^3)	HPMC (kg/m^3)	Total V_f (%)	PVA (%)	SF (%)
1	ECC-Control	1	0.26	0.42	0.28	0.3	0.7	0.0087	0	0	0
2	ECC0-2	1	0.26	0.42	0.28	0.3	0.7	0.0087	2	0	2
3	ECC2-0	1	0.26	0.42	0.28	0.3	0.7	0.0087	2	2	0
4	ECC1-1	1	0.26	0.42	0.28	0.3	0.7	0.0087	2	1	1
5	ECC1.5-0.5	1	0.26	0.42	0.28	0.3	0.7	0.0087	2	1.5	0.5
6	ECC0.5-1.5	1	0.26	0.42	0.28	0.3	0.7	0.0087	2	0.5	1.5

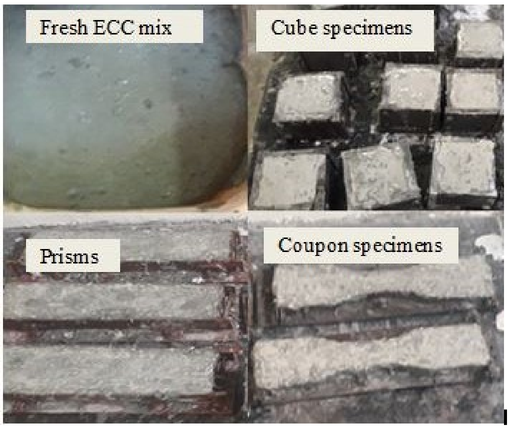
Note* Content of steel and PVA fibers are expressed as volume fraction of the mix, while all the other ingredients are expressed as weight parts of cement content.

Table 3

Slump flow and compressive strength of Hybrid fiber reinforced cementitious composites

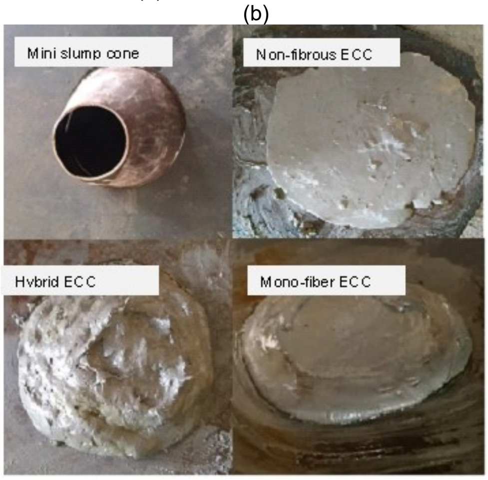
Mixture series	Designation of the mixture	Mini-slump flow diameter (cm)	Compressive strength 7 days (MPa)	Compressive strength 28 days (MPa)
1	ECC-Control	29.0	38.46	51.28
2	ECC0-2	25.2	38	57.01
3	ECC2-0	23.4	36.10	54.148
4	ECC1-1	22.6	42.04	59.135
5	ECC1.5-0.5	21.4	45	61.95
6	ECC0.5-1.5	22.2	38.7	58.05

sand in a mixture machine for one minute at low speed. Then, in order to ensure the occurrence of homogeneous mortar, the dry ingredients were mixed with the water which has been already assorted with HRWRA (super-plasticizers) for another three minutes. And then, the non-metallic PVA fibers and metallic steel fibers were added to achieve further mixing process until the fibers were dispersed uniformly based on visual inspection. Then, the fresh ECC mortar was poured into the steel molds of standard sizes without compaction and also into the mini-slump cone in order to evaluate the workability of fresh ECC mortar mix. A truncated cone mold with a bottom diameter of 92.08mm and a top diameter of 43.5mm and height of 75.78 mm has been used to evaluate the workability of each set of mixtures. The cone was kept in the horizontal base plate and the fresh mortar has been poured and tamped lightly to bleed off any entrapped air pockets, and the cone was then lifted gently. The slump flow deformation was defined as the dimension of the spread when the mortar stops flowing [24]. The mini-slump flow diameter for each ECC mixtures is illustrated in table 3. All the specimens were demolded after 24hrs and then cured in water for another 28 days before testing at a temperature of 20 to 27 degree Celsius and at a relative humidity of 90% to 95%. Fig 3 displays the fresh mortar mix of ECC specimens.



(a) Fresh ECC mortar mix

(b)



(c) Mini-slump cone test

(d)

Fig 3 - Fresh mix of ECC mortar matrix.

2.3. Test Methods

To study the behavior of hybrid fiber reinforced cementitious composites for different percentage variation of mixtures, the specimens were prepared for compressive strength, flexural strength under four point bending and uni-axial tensile strength test.

2.3.1. Compressive strength test

To investigate the composite behavior of hybrid fiber reinforced cementitious composites, three cubes of size 70.6mmx70.6mmx70.6mm [25] for each mixture were cast and tested in universal compressive testing machine with the capacity of 3000kN at a loading rate of 6kN/min under load control processor after 28 days of its curing period in accordance with bureau of Indian standard code [26]. Fig 4 displays the typical view of compressive strength test set up.

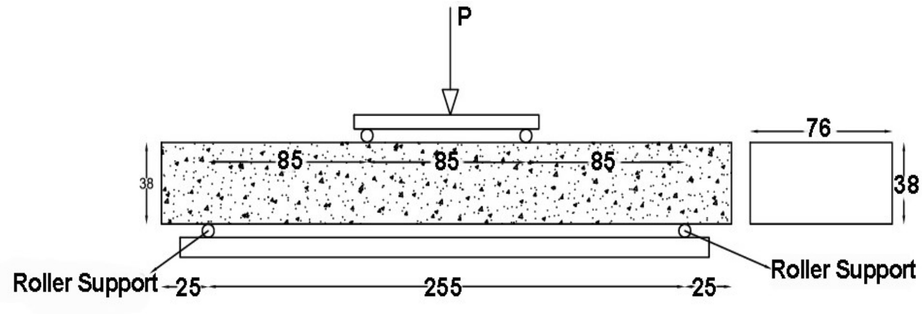
Fig 4 - Typical view of compressive strength test set up.

2.3.2. Flexural strength test

To characterize the deflection behavior of non-fibrous, mono-fiber and hybrid fiber reinforced cementitious composites; four-point bending tests have been conducted after 28 days of curing period. The beam of size (305mmx76mmx38mm) was used in the present study. Effective length of the beam was kept as 255mm with the third point loading distance of 85mm and support distance was of 25mm. All prismatic specimens have been tested according to the test procedure recommended in ASTM standard code [27] and its experimental and schematic views are shown in Fig 5. Using a dynamic UTM (Universal testing machine) with a capacity of 1000kN, all prismatic specimens have been tested under displacement control at a loading rate of 0.25mm per minute until failure. The resulting load versus displacement data has been recorded while testing and also the load versus deflection curves were plotted automatically for every twenty seconds.

2.3.3. Uni-axial tensile strength

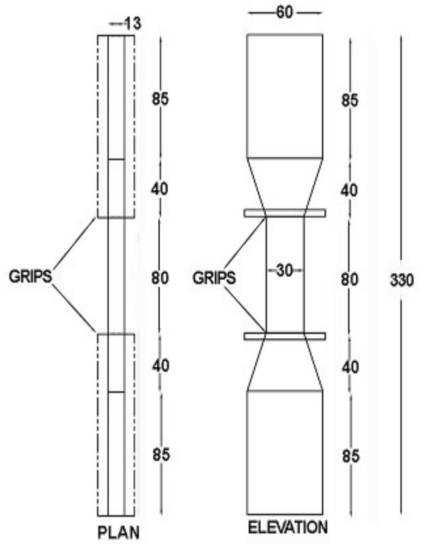
A uni-axial tensile test was developed to evaluate the behavior of tensile properties of ECC specimens with and without hybrid fibers. The uni-axial tensile coupon specimens (Dog bone shape) of gauge length 80mm and cross-section of 30mmx13mm were cast and tested for each mixture. Three dog bone shape specimens of aforementioned size were cast and tested in universal testing machine after the curing period of 28 days. Initially the specimen was fixed using steel plates in both the sides which has been manufactured according to its size and was tightened with bolts in all the four corners in order to diminish eccentrical load transformation. Eventually, the specimen was held to the machine with the help of two J-rings provided in the top end as well as in the bottom end for applying pulling force. The gauge length of the specimen is of 80mm which has been left without any connection in order to examine the crack pattern at first cracking load. All the specimens have been tested under displacement control at a loading rate of 0.15mm per minute. The tensile properties of the coupon specimens including first cracking and ultimate tensile strength were directly evaluated from a data analysis system which is connected to the universal testing machine and the resulting



(a) Schematic view of flexural strength test-set up

(b) Typical view of flexural strength test-set up

Fig 5 - Flexural strength test set up.



(a) Schematic view

(b) Typical view

Fig 6 - View of uni-axial tensile strength test set up.

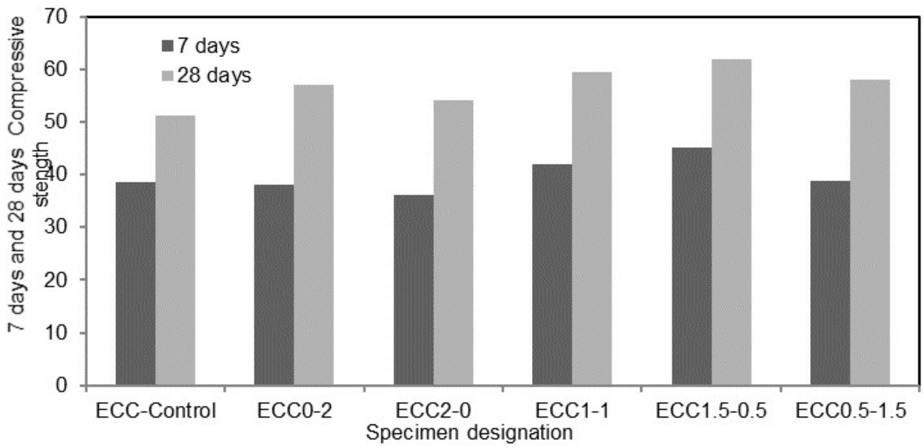


Fig 7 - Compressive strength of mono and hybrid fiber reinforced cementitious composites.

stress versus strain curve has been plotted automatically while testing. Fig 6 shows the typical and schematic view of uni-axial tensile strength test set up.

3. Results and Discussion

3.1. Compressive strength

Table 3 illustrates the acquired compressive strength results at the age of 7 days and 28 days of hybrid fiber reinforced cementitious composites along with mini-slump flow test results. The magnitude of each specimen's compressive strength recorded in the table is an average of three cubes tested in UTM with the capacity of 3000kN. Compared to the ECC-Control specimens, ECC mixtures with mono fibers such as steel and PVA fibers (ECC-SF and ECC-PVA) maintains the same level of compressive strength between 38MPa and 36.1MPa at the age of 7 days, whereas at the age of 28 days, the compressive strength increased by about 11% and 5.5% for ECC-SF and ECC-PVA composites, respectively. Reason might be imputed due to the self - cementing properties of micro-silica or silica sand to attain 38.46MPa at the age of 7 days for non-fibrous cementitious composites and because of the inclusion of PVA and steel fibers to the mortar matrix for mono fiber composite mixtures. The effect mono-fibers in the ECC mixture is the adverse direction and the reduction of compressive strength was perceived at the end of 7 days when compared with non-fibrous ECC mix, whereas the compressive strength at the age 28 days has been effectively increased for both mono-fiber composites. The effect of hybrid fibers is comparatively better than that of the mono and non-fibrous cementitious composites.

Fig 7 illustrates the compressive strength of different percentage variation of mono and hybrid fiber reinforced cementitious composites. From the graph, it was observed that the compressive strength of ECC mortar incorporated with hybrid fibers (ECC0-2 and ECC2-0) had attained two-third strength at the age of 7 days when compared the same with 28 days compressive strength, whereas for ECC-Control mixture, the compressive strength of 38.46MPa has attained at the 7 days which is of three-fourth of its 28 days compressive strength. The combination of ultra-fine particles in the cementitious composites is the reason for the resistivity of micro-voids present in the matrix and hence the micro filler effect will lead for the enhancement of strength characteristics. And also, because of the exclusion of fibers, in which micro-silica produces more interfacial transition zones; fine micro-silica and silica sand introduces higher content of un-hydrated cement particles, which further enhances the interface transition zone of the resulting ECC-Control specimens which leads to enhance the early compressive strength. ECC1.5-0.5 mixture has attained higher compressive strength at the age of 7 days as well as at the age of 28 days and the reason may be ascribed due to the combined effects of hybrid fibers.

3.2. Flexural Strength

The behavior of flexural strength test has been examined through four-point bending test using a prismatic specimen of aforementioned size in terms of first cracking flexural strength, ultimate flexural strength and mid-span deflection at ultimate stress.

3.2.1. Flexural first cracking strength

In general engineered cementitious composite material shows an elastic and plastic behavior under flexural loading. Load versus deflection curve tends to be linearly elastic with the flexural loading till the first crack occurs, after that there was a little sudden drop in stress caused by the cracking of cementitious composites as well as yielding of fibers. The flexural strength of the mono and hybrid fiber reinforced cementitious composites is tabulated in Table 4. Fig 8 displays the flexural first cracking strength and ultimate flexural strength of mono and hybrid fiber reinforced cementitious composites. The results emphasized that the percentage variation of PVA fibers strongly affected the workability of fresh mortar and it has also influenced the first cracking strength at the age of 28 days. For the mixture without fiber content, the first cracking strength has been reduced by about 29.5% when compared with ECC1.5-0.5 (1.5% of PVA and 0.5% of steel fibers combination) specimens and for the mixtures with mono fibers such as ECC0-2 (2% of steel fibers) and ECC2-0 (2% of PVA fibers) the first cracking strength decreased by about 17.6% and 11.5% respectively, when compared the same with ECC1.5-0.5 which has the highest value of flexural first cracking strength amongst all the

Table 4

Flexural strength of hybrid fiber reinforced cementitious composites

Mixture series	Designation of the mixture	Flexural first cracking strength (MPa)	Deflection at first crack (mm)	Ultimate flexural strength (MPa)	Deflection at ultimate flexural stress (mm)
1	ECC-Control	6.26	0.25	8.15	0.65
2	ECC0-2	7.31	0.29	10.10	0.62
3	ECC2-0	7.85	0.56	10.87	0.96
4	ECC1-1	8.23	0.52	11.25	0.84
5	ECC1.5-0.5	8.88	0.44	12.68	1.22
6	ECC0.5-1.5	6.96	0.75	10.36	1.35

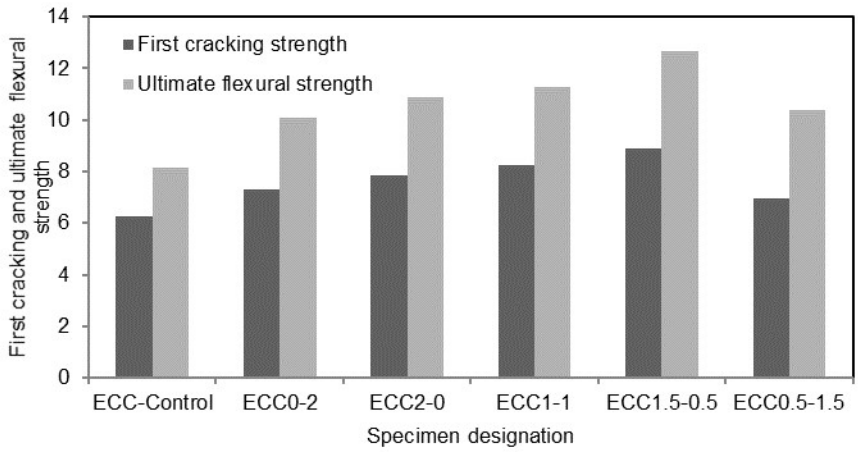


Fig 8 - Flexural strength of mono and hybrid fiber reinforced cementitious composites.

other five mixtures considered in this experimental work. This may be attributed due to dilation effect which is engendered by silica sand or micro-silica content and also due to the unpresence effect of fibers. The maximum first cracking strength of 8.88MPa was obtained for hybrid fiber reinforced engineered cementitious composites with 1.5% of PVA and 0.5% of steel fibers. It has been recognized from Fig 9 (displays the flexural stress verses mid-span deflection), the ultimate stress resulting at post cracking behavior for all the specimens are completely influenced with the percentage variation of fiber content, where the maximum ultimate flexural strengths for all composite specimens ranged from 8.15MPa to 12.68MPa for ECC-Control and ECC1.5-0.5, respectively. It can be observed from the results; 5.46kN is the highest value of ultimate load at post cracking for hybrid fiber reinforced cementitious composites ECC1.5-0.5.

3.2.2. Flexural deflection capacity

The flexural stress versus mid-span deflection of hybrid fiber reinforced cementitious composites with different percentage variation of PVA and steel fibers are displayed in Fig 9. In the flexural load versus deflection curves, the maximum flexural stress is defined as the flexural strength, and the corresponding deflection is defined as the flexural deflection capacity. The flexural deflection capacity of an ECC beam reflects the material ductility. From the figure, it has been clearly observed that the deflection capacity of non-fibrous specimen is having different trend compared with hybrid fiber reinforced cementitious composites and this is due to the continuous evolution of fiber matrix and fiber matrix interface properties. The optimal balance of these aspects of ECC material leads to peak deflection capacity at the age of 28 days. Flexural strength result depicts, all fiber reinforced cementitious composites evinced deflection hardening behavior after 28 days of curing and flexural deflection capacity reaches 0.62mm and 1.35mm for non-fibrous and ECC0.5-1.5 mixtures respectively, at the ultimate level of flexural strength. From the experimental results, for all fiber reinforced cementitious composites, as the percentage of fiber content varies, the flexural deflection capacity increases when compared with non-fibrous ECC mixture. The mid-span deflection increases, because of the volume of hybrid fibers. From the flexural test results, all the fiber reinforced cementitious composite mixtures exhibited more strain and deflection hardening behavior when compared with non-fibrous cementitious composites. The addition of hybrid fibers to cementitious composites caused an increase in the ultimate flexural load and deflection. The ECC-SF and ECC-PVA composites show higher improvement than that of the non-fibrous cementitious composites. The improvement in flexural strength is attributed to the reinforcing effect created by the PVA and steel fibers. The mixture that contains 1.5% of PVA and 0.5% of steel fibers has remarkable strain hardening and crack arresting behavior compared with mono-fibers and non-fibrous cementitious composites. The flexural strength of the hybrid reinforced ECC imputes, with the increase of load, the stress at the tip of the crack starts to be lower than the bridging stress across the crack resulted, on account of the mixture of individual fiber volume fraction. The flexural stress and deflection increased with the combination of PVA and Steel fibers, it is due to the fiber bridging ability of micro-cracks. From the experimental results, higher flexural deflection capacity is accompanied with the increase of ultimate flexural strength as well as first cracking strength of hybrid fiber reinforced ECC. The volume of steel fibers increases, the flexural deflection capacity reduces in the mixture ECC0.5-1.5, as a result, combination of lower volume of metallic steel fiber and higher volume fraction of non-metallic PVA fiber enhances the effects on flexural deflection capacity. Fig 10 shows the failure pattern of ECC prisms.

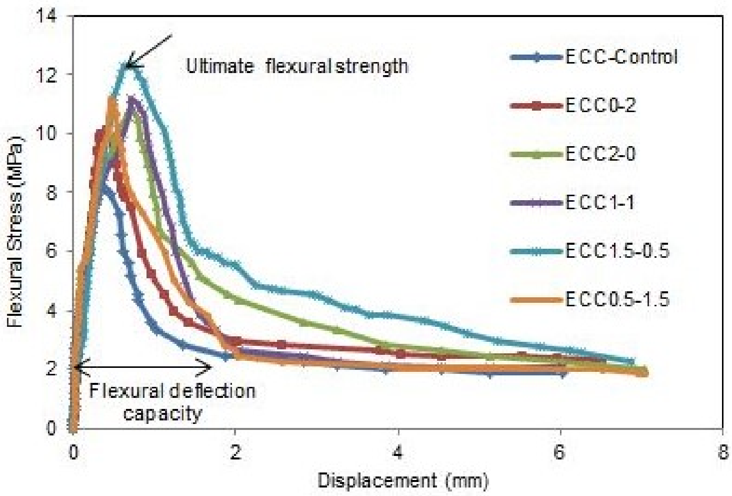


Fig 9 - Flexural stress versus mid-span deflection of hybrid fiber reinforced composites.


Fig 10 - Failure patterns of ECC prisms.

Table 5

Tensile strength of hybrid fiber reinforced cementitious composites

Mixture series	Designation of the mixture	Tensile first cracking strength (MPa)	Ultimate tensile strength (MPa)
1	ECC-Control	5.02	6.65
2	ECC0-2	5.96	7.88
3	ECC2-0	6.94	8.20
4	ECC1-1	7.46	8.45
5	ECC1.5-0.5	7.84	9.45
6	ECC0.5-1.5	6.32	8.55

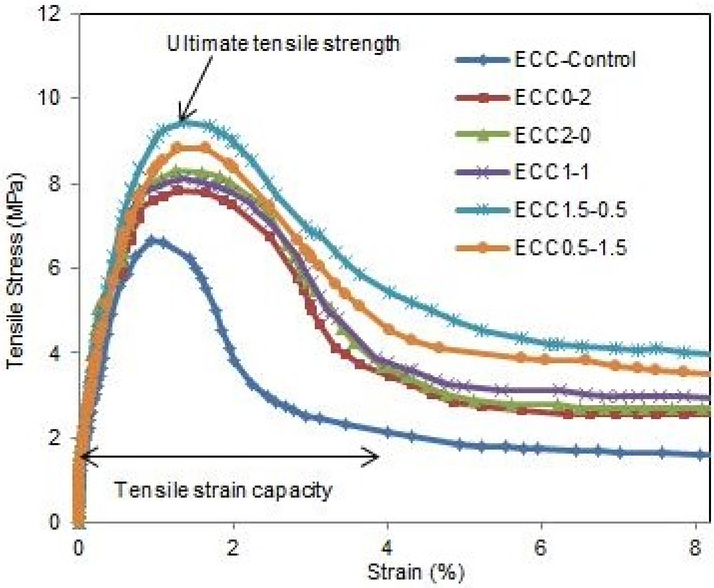


Fig 11 -Tensile stress versus strain % of hybrid fiber reinforced cementitious composites.

3.3. Uni-axial tensile strength

Tensile behavior was measured by direct uni-axial tension test which has been performed on coupon specimen and the results obtained are illustrated in Table 5. Fig 11 shows the typical stress versus strain percentage curves from the uni-axial tensile strength tests of hybrid fiber reinforced cementitious composites. In the tensile stress versus strain curves, the stress at the first drop associated with the first cracking strength and the maximum ultimate stress and its corresponding strain is defined as the tensile strain capacity. Obtained experimental results depict that there is an inherent increase in the tensile first cracking strength as well as ultimate tensile strength of mono fiber specimens such as ECC-PVA and ECC-SF compared to non-fibrous composites. After the occurrence of first crack, without any fracture localization the stress was continued to rise with in-elastic strain and then started to descend after reaching the ultimate load. For mono ECC-SF specimen, ultimate tensile strength has been increased about 19% compared with ECC-Control specimens. ECC mortar specimen reinforced with mono PVA fiber attained higher first cracking tensile and ultimate tensile strength than mono steel fiber reinforced ECC specimens. The achieved ultimate tensile strength for hybrid fiber reinforced cementitious composites ranged between 8.45MPa and 9.45MPa for ECC1-1 and ECC1.5-0.5 respectively, depending on the PVA and steel fiber content in the matrix. It was observed that the ultimate strength of hybrid fiber reinforced cementitious composites specimens (ECC1.5-0.5) increased about 20% and 42%, respectively when compared with ECC-SF and ECC-Control. Predominantly, PVA fiber has more superior dominant than steel fiber in terms of

Fig 12 - Failure patterns of ECC coupons specimens for different percentage variation of fibers.

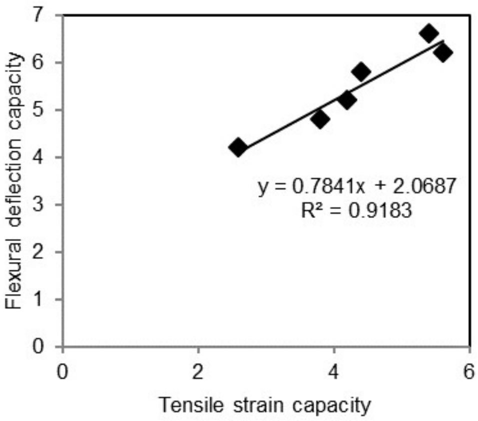


Fig 13 - Correlation between tensile strain capacity and flexural deflection capacity .

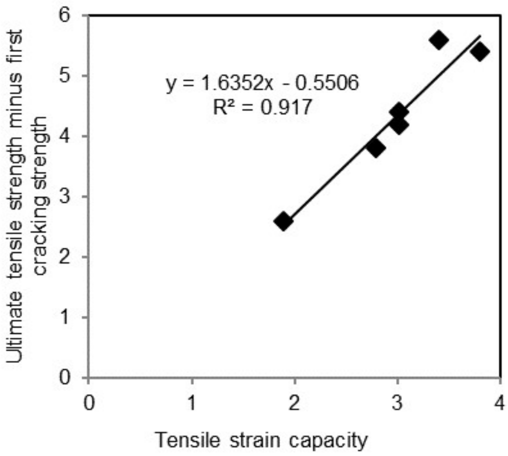


Fig 14 - Correlation between tensile strain capacity and the margin between the first cracking and ultimate tensile strength.

increasing the tensile strength of hybrid cementitious composites. In mono steel and PVA fiber ECC mixtures, as the load increases after the first crack, the stress continues to increase corresponding to the strain within the elastic region and then starts to descent after attaining the ultimate strength. Furthermore, from the experimental tensile test results, it can be clearly observed that the addition of PVA fiber enhances the tensile properties in the composite individually as well as with the combination of PVA and steel fibers. The PVA fibers aid in increasing the strain hardening portion for the hybrid fiber reinforced ECC and was able to maintain the load even after first cracking occurred. Failure pattern of ECC coupons specimens are shown in Fig 12.

3.4. Correlation between Flexural and Uni-axial tensile strength

Obtained test results from flexural strength and uni-axial strength depicts a linear correlation between flexural deflection capacity and tensile strain capacity of hybrid fiber reinforced cementitious composites and it is displayed in Fig.13. It is concluded that the newly developed uni-axial tensile test set up can give relatively consistent results and the material properties of ECC with micro-silica, silica sand and fibers such as PVA and steel fibers are relatively robust. The experimental results confirmed that, the tensile strain capacity shows a good relation with the difference between the ultimate tensile strength and first cracking strength as shown in Fig 14.

4. Conclusion

The behavior of hybrid fiber reinforced cementitious composites was experimentally investigated in this work accompanied by compressive strength, four point bending strength and uni-axial tensile strength. From the acquired experimental results, the following the conclusions have been drawn.

1. Increasing fiber content, improves the

deformability of cementitious composite mixtures as well as the mechanical properties such as compressive strength, flexural strength and uni-axial tensile strength. For the hybrid cementitious composite mixture contains 1.5% of PVA fibers and 0.5% steel fibers; compressive strength has been increased by about 20% compared with the non-fibrous composites.

2. In all cementitious composites, it was observed that, the tensile first cracking strength and flexural first cracking strength increase with the addition of hybrid fibers such as PVA and steel fibers compared with mono ECC-PVA and ECC-SF composites. The effect of percentage variation of volume fraction of two fibers ratio on the ultimate tensile strength corresponds similarly with its effects on the flexural first cracking strength. It has been observed that the ultimate tensile strength increased by about 42% and 20% for hybrid cementitious composites contains 1.5% of PVA and 0.5% of steel fibers when compared with non-fibrous and mono PVA composites, respectively.
3. Upon increase in the volume fraction of PVA, steel fibers and hybrid fibers, the flexural first cracking strength as well as deflection capacity of flexural failure possesses to increase. The increase in flexural deflection capacity is higher for 1.5% of PVA and 0.5% of steel fibers incorporation.
4. The addition of hybrid fibers resulted in an improvement in the ultimate tensile strength and tensile strain capacity of ECC composites than the mono PVA fiber (ECC2-0) and mono SF (ECC0-2). At the age of 28 days, higher tensile strain capacity has been attained for (ECC1-1) hybrid fiber reinforced cementitious composite specimens with the addition 1% of PVA fibers and 1% of steel fibers.

REFERENCES

[1] Victor C Li, From Micromechanics to Structural Engineering, Doboku Gakkai Ronbunshu., 1993, **21**, 1.
[2] Victor C Li, Engineered cementitious composites – material, structural and ductility performance, Concrete Construction Engineering Handbook 2007, CRC press.
[3] Recommendations for design and construction of high performance fiber reinforced cement composites with multiple fine cracks (HPFRCC). Concrete Engineering Series 82, 2008, Japan Society of Civil Engineering.
[4] X. R. Cai, B. Q. Fu, S. L. Xu, The apparent density, tensile properties and drying shrinkage of ultra-high toughness cementitious composites, Advanced Material Research, 2011, **261**, 223.
[5] Victor C Li, On engineered cementitious composites, Journal of Advanced Concrete Research 2003, **1**, 215.
[6] P. C. Hewlett, L. FM, Chemistry of cement and concrete, 4th edition, Oxford, Elsevier 2005.
[7] J. Chai, K. Kraiwood, T. Weerachart, S. Tirasit, Evaluation of the sulfate resistance of concrete containing palm oil fuel ash, Construction and Building Materials, 2007, **21**, 1399.
[8] R. S. Ravindrarajah, C. T. Tam, Recycling concrete as fine aggregate in concrete, International Journal of Cement Composites and Lightweight Concrete, 1987, **9**, 235.
[9] Y. Hasbi, Y. A. Huseyin, D. Iilami, S. Osman, D. Gokhan, Effects of the fine recycled concrete aggregates on the concrete properties, International Journal of the Physical Sciences, 2011, **6**, 2455.
[10] C. Zhitao, Y. Yingzi, Y. Yan, Quasi-static and dynamic compressive mechanical properties of engineered cementitious composites incorporating ground granulated blast furnace slag, Materials and Design, 2013, 44, 500.
[11] Victor C Li, S. Wang, C. Wu, Tensile-strain hardening behavior of PVA-ECC, ACI Materials Journal, 2007, **98**, 483-492.
[12] Z. Jian, Q. Shunzhi, M. Guadalupe, Y. Guang, V. B. Klass, Victor C Li, Development of engineered cementitious composites with limestone powder and blast furnace slag, Material and Structures, 2010, **43**(6), 803.
[13] M. Maaly, Victor C Li, Flexural/tensile strength ratio in engineered cementitious composites, Composite Structures, 2004, **6**, 573.
[14] M. Kumeda, K. Rakugo, Measurements of crack opening behavior with engineered cementitious composites under bending moment, Proceedings of the workshop of hybrid fiber reinforced cementitious composites in structural applications, 2006, Honolulu USA, p. 313.
[15] S. Quian, Influence of concrete material ductility on the behavior of high stress concentration zones, Proquest, 2007.
[16] Y. En-Hua, Y. Yingzi, Victor C Li, Use of high volumes of fly-ash to improve engineered cementitious composites mechanical properties and material greenness, ACI materials Journal, 2007, **104**, 303.
[17] P. S. Song, S. Hwang, B. C. Sheu, Strength properties of nylon and polypropylene fiber reinforced concrete, Cement and Concrete Research, 2014, **35**, 1546.
[18] K. T. Soe, L. C. Zhang, Impact resistance of hybrid fiber reinforced concrete composites, Composite structures, 2013, **104**, 320.
[19] W. Li, J. Xu, Mechanical properties of basalt fiber reinforced geo-polymeric concrete under impact loading, Material Science Engineering, 2009, **23**, 178-186.
[20] Y. Yang, X. Gao, H. Deng, P. Yu, Y. Yao, Effects of water-binder ratio on the properties of ECC, Journal of Wuhan Univ Technology, Material Science edition, 2010, **25**, 298-302.
[21] J. K. Kim, J. S. Kim, G. S. Ha, Y. Y Kim, Tensile and fiber dispersion performance of engineered cementitious composites produced with ground granulated blast furnace slag, Cement and concrete research, 2007, **37**, 1096.
[22] G. N. Maysam, N. Morteza, R. Mahmood, Behaviour of functionally graded reinforced concrete beams under cyclic loading, Gradevinar, 2015, **67**, 427.
[23] ASTM C494, Standard specifications for chemical admixtures for concrete.
[24] S. Mustafa, B. Zafer, O. Erdogan, K. E. Tahir, E. Y. Hasan, Mohamed L. Improving workability and rheological properties of engineered cementitious composites using factorial experimental design, Composites: Part B, 2013, **45**, 356-368.
[25] IS:10080-2004. Indian standard specification for vibration machine for standard cement mortar cubes.
[26] IS:4031(Part 6)-2005. Indian standard methods for determination of compressive strength of hydraulic cement.
[27] ASTM C78-94. Standard test method for flexural strength of concrete (Using simple beam with third-point load).

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