Matrix Design of High Strength Engineered Cementitious Composites (ECC) Incorporating Alccofine and Synthetic Fibers

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Abstract

Next to the concrete, mortar plays a major role in the construction industry. For the past few decades mortar is used as a repair and retrofitting material after doing few modifications. These kind of cement mortars used in the textile reinforced concrete, engineered cementitious composites, ferrocement etc along with the different types of fibers. This paper deals with the matrix designing based on compressive strength, tensile strength and matrix toughness of the cement mortar incorporating Alccofine (1203) and . Alccofine is the specially processed ultra fine material used as a supplementary cementitious material in this paper. In this paper Alccofine is added to the matrix in 0%, 20%, 40%, 60%, 80%, 100% to find the optimum content of Alccofine to add in the mortar to check its compressive strength, tensile strength and matrix toughness to prepare matrix for the engineered cementitious composites. It is found that up to 80% addition of Alccofine shows increasing trend in all three properties whereas at 100% it shows higher toughness and almost same compressive strength. Relatively less matrix toughness is highly recommended for the ECC hence it was found that 80% Alccofine as an optimum addition in the mortar. River sand was replaced by the coarse quartz sand to check the performance of ECC. Polyvinyl alcohol fiber and Polypropylene fiber had been added to the above matrix and tested under compressive, Flexural and Uniaxial tensile strength and compared the performance.

Keywords: Matrix, Alccofine, Toughness, ECC, Polypropylene Fiber, Polyvinyl Alcohol Fiber.

1. Introduction

Engineered cementitious composites are also known as strain hardening cementitious composites. It is a class of high performance fiber reinforced cementitious composites having tight crack width control. Mortar is the material used widely in the construction industry after the concrete. In olden days mortar is made up of limestone and mainly used for the plastering works. Recent findings show that mortar can be used as a repair and retrofitting material when fibers added to it. To prepare such composites, matrix has to be designed on the basis of matrix toughness. Using mortar along with the fibers for the plastering work effectively reduce the crack width. Supplementary cementitious material also can be added in the mortar as like in concrete. It will effectively reduce the utilization of cement, which leads to reduce the production of cement. Ultimately reduces the CO_2 emission during the manufacturing process of the cement.

Many research works have been taken place in the past decades to replace cement by several industrial byproducts such as fly ash, GGBS, Silica fume, Nano silica etc. Alccofine is a new generation material specially processed product based on slag of high glass content with high reactivity obtained through the process of controlled granulation [1].

1.1 Review of literature

ECC designed based on micromechanics to design the components of the matrix, fiber and fiber matrix interface to design the mode of failure, tensile strain capacity and elongation of the ECC. Usually in cementitious material three types of tensile failure have been encountered Brittle, Quasi-Brittle, and Strain Hardening failure [2]. Supplementary cementitious material increases both mechanical and durability properties when it mixed with steel fibers give better results as we expected. Regular ECC is with cement, fly ash, microsillica, sand, PVA fibre. But Ismail et al. studied the performance by replacing silica sand with limestone sand and gravel sand (Size ranges from 1.19 to 2.38 mm). ECC were made using slag, silica fume, flyash, and metakaolin in various percentages. Slag boosted 7 days strength in higher levels than 28 days strength compared to the regular ECC whereas Silica fume gives better results in both 7 and 28 days but metakaolin gives maximum compressive strength. Splitting tensile strength also shows the same trend as like compressive strength [3]. HSHD-ECC's ductility was largely achieved by much wider crack opening due to absence of interfacial chemical bond and higher ultimate tensile stress, rather than preferred saturated micro cracks. In previous studies, this issue was addressed by incorporating small amount of artificial flaw or increasing the volume of inert filler in matrix. This will lead to a more homogeneous defect system or reduce matrix fracture toughness in ECC, and thereby impart saturated multiple-cracking behaviour to the ECC [4]. Compared to the ECC with steel fibers perform well in both compressive and direct tensile strength than ECC with synthetic fibers such as polyvinyl alcohol fiber and polypropylene fiber. Regarding flexural strength synthetic fibers behave well compared to the steel fibers [5]. Addition of steel fibers along with the synthetic fibers in engineered cementitious composites does not affect the mechanical properties instead It contribute to the enhancement of those properties [6]. By increasing the reinforcing index more than 800, first crack load starts increasing because of the influence of the PVA fibers. Regarding deflection, by increasing reinforcing index more than 800 deflection values at failure also increased and bending ability of the ECC slabs before failure also get increased [7]. Size of the sand particle also plays a major role in the pseudo strain hardening property. Compared to the coarse sand ECC (size ranges from 2.36 mm) Fine sand ECC with maximum size of 0.3 mm enhances the pseudo strain hardening property. Coarse sand ECC exhibits high fracture toughness and less young modulus compared to the fine sand ECC [8]. Relationship between compressive strength and flexural strength was found, and flexural strength is underestimated and it leads to the strain hardening behaviour of ECC. But in the relationship between compressive strength and elastic modulus, elastic modulus is overestimated due to the absence of coarse aggregates [9].

2. Materials and Methods

2.1 Alccofine 1203

Alccofine 1203 is a patented, exclusive product (IP Patent No. 297735) that contains a mineral addition made of low calcium silicate. Unique particle size distribution emerges from controlled granulation. Its pozzolanic reactivity and latent hydraulic property lead to an improved hydration process. The packing density of the paste component is improved by the addition of Alccofine 1203. Because of this, the water need and additive dose are reduced, and the strength and durability characteristics of concrete at all ages are improved. Alccofine is a useful SCM combination for use in all grade concrete thanks to its precise balance of CaO_2, SiO_2, and Al_2O_3, as well as its distinctive patented PSD (Particle Size Distribution) design. Fig 1 shows Alccofine 1203.

Fig.1 Alccofine

2.2 Cement

Cement used in this work was OPC 53 grade conforming to IS: 12269 - 2013[12]. The chemical properties of cement are given in Table 1. Physical properties of the cement are given in Table 2.

Chemical composition, %	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	SO_3	Na_2O	LOI
Cement	21.80	63.56	5.12	3.20	0.80	0.75	3.22	0.55	1.00

Table 1. The chemical Analysis of Cement

Sl No	Properties	Values
1.	Specific Gravity	3.10

2.	Specific Surface Area	3710 cm^2/g
3.	Normal Consistency	31%
4.	Initial Setting Time	60 mins
5.	Final Setting Time	330 mins

Table 2. The Physical Properties of Cement

2.3 Fine Aggregate

The fine aggregate available naturally from river beds is used as per IS 383-1970[13]. Code conforming that, it is coming under Zone III. The particle size distribution curve for fine aggregate is shown in Fig 2. The Specific gravity of sand was found using specific gravity bottle as 2.61.

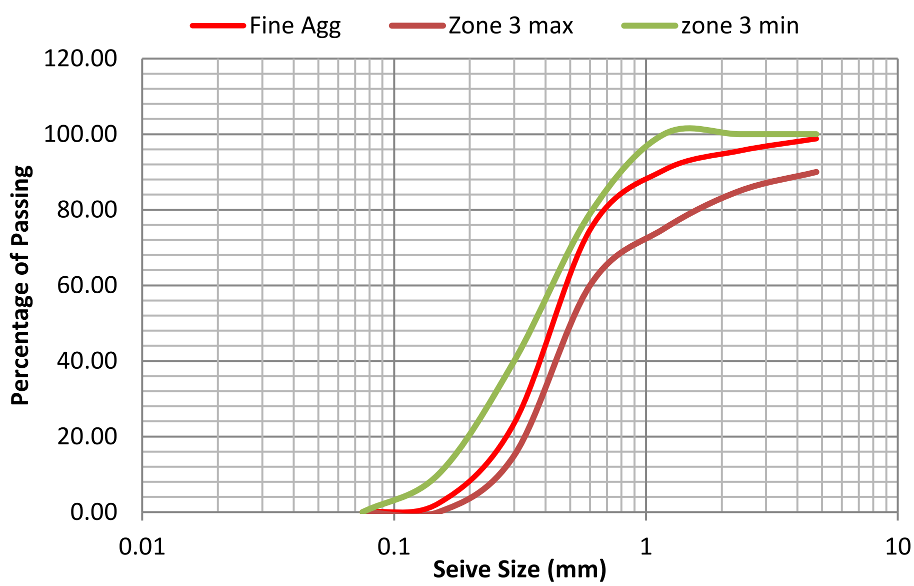

Fig 2. Particle Size Distribution Curve for Fine Aggregate

2.4 Quartz Sand

Quartz sand is also known as silica sand made up silica as a main element. The most common part of SiO_2 is quartz, which is a chemically inert and relatively hard material. When the magma cools, at different temperatures various minerals crystallize into a solid. Out of those one of the last mineral formed is known as Quartz. Fig 3 shows quartz sand. The particle size distribution curve for Quartz sand is shown in Fig 4, the curve falls under zone 1. The Specific gravity of quartz sand was found using specific gravity bottle as 2.56.

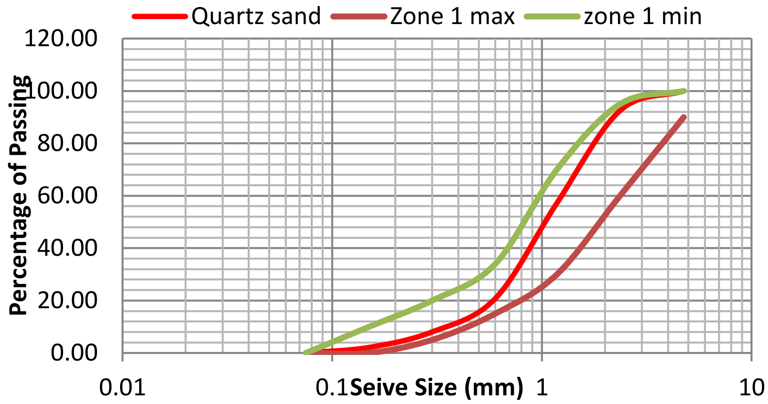

Fig 3. Quartz Sand **Fig 4. Particle Size Distribution Curve for Quartz Sand**

2.5 Synthetic Fibres

Only the polymers contained in natural gas and petroleum by-products are used to make synthetic fibres. Synthetic fibres are man-made fibres, and the majority of them are created from petrochemicals, a by-product of the processing of petroleum. Fibres are the basis for all fabrics, and they come from artificial or man-made sources. Polyvinyl alcohol and polypropylene fibres were used in this investigation out of these fibres.

2.6 Polyvinyl Alcohol (PVA) Fibre

To make PVA fibre, polyvinyl alcohol is the primary raw material. It goes through a dissolving, spinning, heat-setting, cutting, and baling process to create a fibre with a high strength and high modulus. Table 3 displays the PVA fiber's physical attributes. The PVA fibre and SEM image of the same is shown in Figure 5.

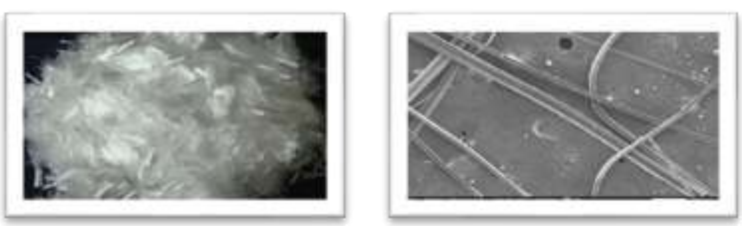

Fig 5. Polyvinyl Alcohol Fibre and SEM image of PVA Fibre

Type	Fiber Diameter (μm)	Length (mm)	Specific Gravity	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
PVA	30	12	1.3	1700	6	40

Table 3. The Physical Properties of PVA fiber

2.7 Polypropylene (PP) Fiber

Propylene polymerization produces a specific type of synthetic fibre known as polypropylene fibre. It has some benefits, including low weight, high strength, high toughness, and resistance to corrosion. Table 4 displays the PP fiber's physical attributes. The PP fibre and SEM image of the same is shown in Figure 6.

Fig.6 Polypropylene Fibre and SEM image of Polypropylene Fibre

Type	Fiber Diameter (μm)	Length (mm)	Specific Gravity	Tensile Strength (MPa)	Elongation (%)	Young’s Modulus (GPa)
PP	30	12	0.91	550	25	5

Table 4. The Physical Properties of PP fiber

2.8 Sika Viscocrete

Sika viscocrete is a high performance super plasticizing admixture based on polycarboxylates that provides great workability, sustained workability retention, and permits a significant decrease in water content. It results in higher-quality, more consistently cohesive, free-flowing concrete. Viscocrete has a specific gravity of 1.08. Sika Viscocrete is shown in the figure 7.

Fig 7. Sika ViscoCrete

3. Methodology

3.1 Mix Proportions

Since the material is evolving, no suitable mix designs were available. Using the literature as a guide, a trial-and-error approach to mix design was used. Totally six mortar mixes were prepared to find the optimum content of Alccofine. Those mixes were named as M_0, M_{20}, M_{40}, M_{60}, M_{80} and M_{100}. In that 0, 20, 40, 60, 80, 100 denotes percentage of alccofine added to the mortar. Four ECC mixes were prepared using optimum mix with two fibers and two types of sand. ECC with RS and PVA fiber named as (M_1), ECC with RS and PP fiber named as (M_2), ECC with QS and PVA fiber named as (M_3), ECC with QS and PP fiber named as (M_4). The Mix proportions of mortar and ECC were designed and listed in table 5 and table 6.

Mix ID	Cement (kg/m^3)	Alccofine (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	HRWR* (kg/m^3)	W/C*	W/B*
M_0	1233	0	617	333	7	0.27	0.27
M_{20}	1027	205	616	333	7	0.32	0.27
M_{40}	880	352	616	332	7	0.38	0.27
M_{60}	769	461	615	332	7	0.43	0.27
M_{80}	683	546	615	332	7	0.49	0.27
M_{100}	614	614	614	332	7	0.54	0.27

*** W/C – Water –Cement Ratio, W/B – Water – Binder Ratio, HRWR – High Range Water Reducer**

Table 5. Mix Proportions of Mortar with Alccofine

Mix ID	Cement (kg/m^3)	Alccofine (kg/m^3)	Fine Aggregate (kg/m^3)		Water (kg/m^3)	Fibres (kg/m^3)		HRWR (kg/m^3)
			River Sand	Quartz Sand		PVA	PP	
M_1	683	546	615	-	332	24.5	-	7
M_2	683	546	615	-	332	-	24.5	7
M_3	683	546	-	612	332	24.5	-	7
M_4	683	546	-	612	332	-	24.5	7

Table 6. Mix Proportions of ECC

3.2 Mixing and Specimen Preparation

Heavy duty driller with mixing bit was used to mix the ingredients to cast both mortar and ECC specimens. For each mortar mixes 12 numbers of 70.7mm cubes for compressive strength, 3 numbers of dog bone specimens specified in the Japan Society of Civil Engineers [14] for direct tension test, 3 numbers of notched prisms of size 300 x 100 x 30 mm for matrix toughness. For Each ECC mixes 6 numbers of 70.7 mm cubes for compressive strength, 3 numbers of dog bone specimens for direct tension strength, 3 numbers of notched dog bone specimens for finding complementary energy, 3 numbers of prisms of 150 x 40 x 30 mm for finding flexural strength. Number of specimen's casted shown in table 7.

Sl No	Specimen	No. of Specimens		Type of Test
		Mortar	ECC	
1	Cube (70.7mm)	72	24	Compressive Strength
2	Dog Bone (330 x 60 x 30mm)	18	12	Direct Tension Test and J_b'
3	Notched Dog Bone (330 x 60 x 30mm)	-	12	PSH Strength Criterion
4	Notched Prisms (150 x 50 x 30)	18	-	To find J_{tip}
5	Prisms (150 x 40 x 30)	-	12	Flexural Strength

Table 7. Number of Specimens

4. Experimental Works

4.1 Compressive Strength of Mortar and ECC Cubes

Mortar cubes were casted as per mix designs mentioned above. 12 cubes were casted for each mix to test the compressive strength of mortar cubes at different curing ages. The curing days of 7, 14, 21, and 28 days and tested 3 cubes on each curing period. After the end of respective curing ages all the cubes were tested in the compression testing machine, at a uniform rate of speed. Figure 8 shows compression testing setup.

Fig 8. Compression testing setup

4.2 Direct tension test on ECC Dog bone Specimens

Mortar dog bones of dimension mentioned in Japan Society of Civil Engineers were casted as per proposed mix design. 3 Dog bones were casted for each mix to test direct tensile strength after 28 days of curing. 100kN capacity servo controlled universal testing machine at a uniform rate of 0.05mm/sec was used to test the specimens. Figure 9 shows the direct tension test setup.

Fig 9. Direct tension Testing Setup

4.3 Three point bending test on matrix prisms

The pseudo-strain hardening energy criteria, also known as the "Pseudo Strain Hardening (PSH) Criterion," is a fracture criterion used in materials science and engineering to assess the ductile fracture behaviour of materials under various loading conditions. It is often used to predict whether a material will undergo ductile fracture based on the accumulated strain energy. The PSH criterion does not have a specific universal limit because its applicability and threshold values depend on the material, its properties, and the specific loading conditions. ASTM E399 [15] is a standard test method for measuring the fracture toughness of materials using the third-point bending test. To use the PSH criterion, need to characterize the material's behaviour through tests such as tensile tests, and then apply the criterion to assess whether the accumulated strain energy exceeds a certain threshold value under the given loading conditions. The fracture energy value (J_{tip}) is less than complementary energy value (J_b'), satisfying the pseudo strain hardening energy criteria. Based on the values of (J_b'/ J_{tip}), Strain hardening behaviour varied. During the test, the load is continuously increased until the specimen fractures. The critical load and corresponding crack length are recorded. Using the critical load and crack length data, fracture toughness values, such as the stress intensity factor (K), can be calculated. These values are important for assessing the material's resistance to crack propagation and fracture. To assess these parameters 150 x 50 x 30 mm specimens were cast and kept in water curing for 28 days. The test setup is shown in fig 10.

Fig 10. Three Point Bending Test setup

4.4 Direct tension test on Notched dog bone ECC Specimens

The ratio of ultimate stress to first crack stress, often referred to as the "crack-to-ultimate stress ratio," varies depending on the material and its properties. This ratio signifies how much stress a material can withstand after it has developed its first crack or defect compared to its ultimate strength, which is the maximum stress the material can endure before failure. Direct tension tests on Notched Dog bone specimens are used to assess the ductile or brittle behavior of materials, evaluate their fracture resistance, and provide critical data for structural integrity assessments and material selection in engineering applications. To assess these parameters dog bone specimens as prescribed in JSCE [14]. The test setup for the notched dog bone specimens shown in the fig 11.

Fig 11. Direct Tension test on Notched Dog bone Specimens

4.5 Flexural strength on ECC Specimens

Based on the procedure given in IS 516 (Part1/Sec1):2021 [16], to find the modulus of rupture for the ECC specimens of size 150 x 50 x 30 mm were cast. The curing period for the specimen is

28 days. After the curing period, specimens were taken out from the water and surface was cleaned thoroughly. The two point load was applied and the test was carried out till the specimens were failed. The test setup for the flexural strength specimens were shown in the fig 12.

Fig 12. Flexure test on ECC specimens

5. Results and Discussions

5.1 Compressive Strength of Mortar Cubes

From the result, it is obvious that addition of alccofine increases its compressive strength up to 80% but the trend started decreasing at 100% addition. This is because, after 80% addition the alccofine particles behaves as a filter material. Up to 80% addition it acts as a pozzolonic material and contributes to the formation of C-S-H. Compared to the control mix, the compressive strength increased about 1.82%, 9.04%, 11.29%, 22.22%, and 5.06% in M_{20}, M_{40}, M_{60}, M_{80}, and M_{100} respectively. The compressive strength values for the respective days were tabulated in table 8. Failure pattern of mortar cubes were shown in figure 13.

Mix ID	Days			
	7	14	21	28
M_0	36.55	44.94	51.29	53.41
M_{20}	33.94	44.69	50.86	54.38
M_{40}	39.41	42.65	53.28	58.24
M_{60}	41.88	4.12	54.78	59.44
M_{80}	42.31	49.29	59.21	65.28
M_{100}	39.08	42.24	51.35	56.11

Table 8. Compressive Strength of Mortar Cubes

Fig 13. Failure modes of the mortar cubes

5.2 Pseudo Strain hardening

5.2.1 Energy Criteria

Mix containing Quartz sand and PVA fibre showed lesser ratio value and also lesser strain hardening behaviour, whereas quartz sand and PP fibre showed higher PSH value and also higher strain hardening behaviour. From PSH value it is concluded that addition of PVA fibre showed lesser strain hardening than PP fibre. This is because of usage of uncoated PVA fibre and lesser matrix Toughness. Pseudo strain hardening Energy criteria values showed in table 9.

Energy Criterion								
Mix ID	3rd Point Bending			Dogbone uniaxial test				PSHs (Jb'/Jtip)
	Km	E (MPa)	Jtip	Ult Stress	Ult Def	$\int_0^{\delta_0} \sigma(\delta) d\delta$	Jb'	
M_1	1.097	25.24	0.048	4.28	3.59	8.155	7.21	151.2249
M_2	1.097	25.24	0.048	4.32	5.52	6.912	16.93	355.1779
M_3	1.097	25.24	0.048	2.3	2.94	3.21	3.55	74.49876
M_4	1.097	25.24	0.048	3.99	4.98	1.83	18.04	378.3707

Table 9. Pseudo Strain Hardening - Energy Criterion

5.2.2 Strength Criteria

All 4 mixes showed crack to ultimate stress ratio greater than 1. Mix 4 showed higher ratio and have the ability to deform and redistribute the stress. Remaining all the mixes showed reasonable increase in the ratio values. Pseudo strain hardening Strength criteria values showed in table 10.

Strength Criterion					
Mix ID	First crack load (N)	σ_{fc} (N/mm^2)	Ultimate Load (N)	σ_0 (N/mm^2)	PSHs (σ_0/σ_{fc})
M_1	175	0.224359	800	1.025641	4.57
M_2	450	0.5769231	1000	1.2820513	2.22
M_3	200	0.2564103	600	0.7692308	3.00
M_4	150	0.1923077	950	1.2179487	6.33

Table 10. Pseudo Strain Hardening - Strength Criterion

5.3 Compressive Strength of ECC specimens

Compared to Quartz sand, river sand mixes showed higher compressive strength. This is because of the coarse nature of the quartz sand which ultimately leads to the formation of weak links called interfacial zone. The mix containing Fine River sand, showed higher strength than the mix containing coarse quartz sand. PVA fibre-containing mixes showed a 21.22% increase in compressive strength while PP fibre-containing mixes showed a 17.57% increase when compared to the control mix, which contained river sand. PVA fibre-containing mixes showed a 19.47% increase in compressive strength while PP fibre-containing mixes showed a 16.34% increase when compared to the control mix, which contained quartz sand. The compressive strength values of all the 6 mixes were shown in the figure 14.

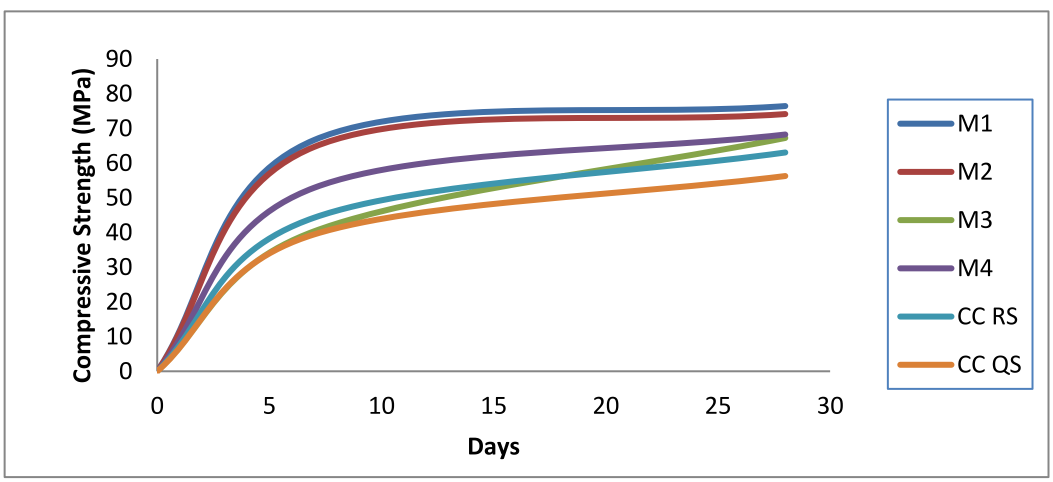

Fig 14. Compressive Strength of ECC Cubes

5.4 Direct tension test on ECC Specimens

Below figure shows the uniaxial stress strain curve for all the 4 ECC mixes. Out of 4 ECC mixes, mix containing Polypropylene fibre showed higher strain capacity than uncoated polyvinyl alcohol fibre. From the figure it is obvious that all the 4 mixes showed almost same stress values but strain hardening stage differs and it is because of the nature of fibre and sand used. Polypropylene fibre with coarse quartz sand and river sand showed more strain hardening effect than Polyvinyl Alcohol fibre. Increase of ultimate tensile strength of ECC mixes showed 60% in M_1, 60% in M_2, 77% in M_3, and 65% in M_4 compared to the control mortar respectively. Tensile strain capacities of the mixes were 5.04% in $M_{1,}$ 7.08% in M_2, 4.29% in M_3, and 7.46% in M_4. Direct tensile stress Vs strain relationship of ECC mixes shown in fig 15.

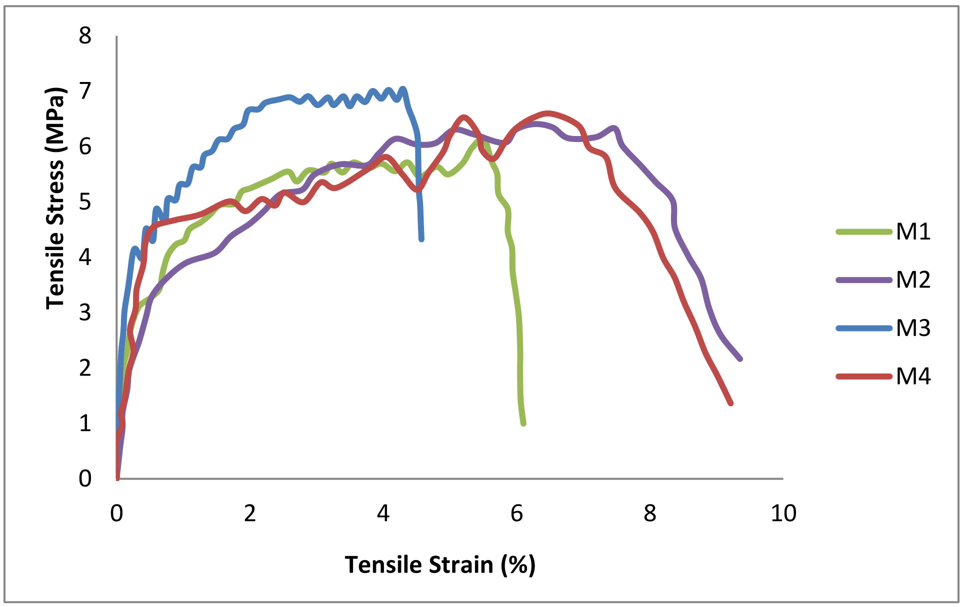

Fig 15. Tensile Stress Vs Strain Curves of ECC Mixtures

5.5 Flexural strength on ECC Specimens

Flexural strength results also resembles similar trend as in tensile strength. Mixes containing polypropylene fibre showed higher curvature than Polyvinyl Alcohol fibre. Regarding sand, Mix containing coarse quartz sand showed higher curvature than mixes containing fine river sand. From the below figure, it is found that the percentage increase in the moment is 68%, 45%, 78% and 86% compared to the control mixes in M_1, M_2, M_3 and M_4 respectively. Similarly the curvature also increased to 9%, 30%, 15%, and 42% compared to the control mixes in M_1, M_2, M_3 and M_4 respectively. Moment Vs Curvature relationship for the prisms of size 150 x 50 x 30 mm of all the mixes were shown in fig 16.

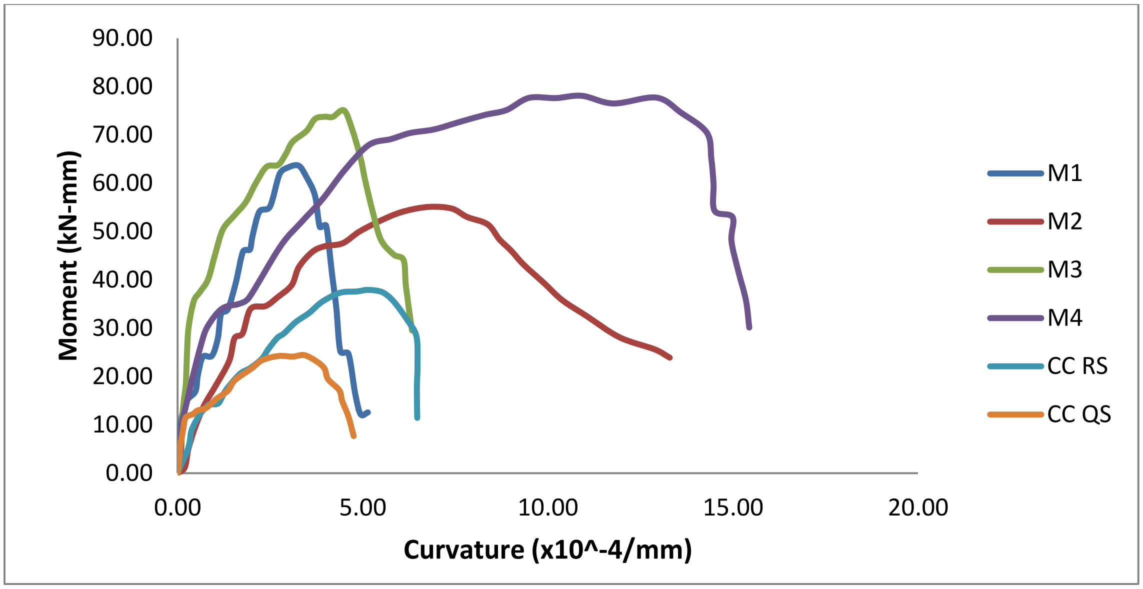

Fig 16. Moment Vs Curvature of control and ECC Mixtures

6. Conclusion

In this paper, to design the matrix various proportions of alccofine used as a replacement of fly ash and found 80% addition is the optimum level and successfully developed to widen its utilization in structural elements. The compressive strength, tensile strength and flexural strength of ECC mixtures were experimentally investigated.

- In terms of micromechanical properties, Polypropylene fibre performs well compared to the uncoated polyvinyl alcohol fibre and the same was found based on the pseudo strain hardening properties.
- Replacement of fine river sand by coarse quartz sand increases the flexural strength of the ECC mixtures whereas no significant improvement in the compressive and tensile strength values.
- According to the aforementioned trials, ECC incorporating PVA fibre and quartz sand (M_2) increased compressive strength by 19.47% and ECC incorporating PVA fibre and river sand (M_1) by 21.22%. ECC incorporating PP fibre and quartz sand (M_4) increased compressive strength by 16.34% and ECC incorporating PP fibre and river sand (M_3) by 17.57%.
- Regarding uniaxial tensile strength prescribed by JSCE, test conducted on all 6 mixes including control mortar. Increase in the ultimate tensile strength in M_1, M_2, M_3, and M_4 are 60%, 60%, 77%, and 65% respectively.
- Strain capacity of mixes M_1, M_2, M_3, and M_4 are 5.04%, 7.08%, 4.29% and 7.46% respectively. From the results, mix containing PP fibre showed better results than PVA fibre. Around 7% strain capacity was found in the mix containing PP in quartz sand.

- Regarding flexural strength, four point bending setup was used. Moment curvature relationship of the specimens of all the mixes has been found. Compared to the control mix, the moment values of M_1, M_2, M_3, and M_4 are increased to 68%, 45%, 78%, and 86% respectively.
- The curvature values of M_1, M_2, M_3, and M_4 are increased up to 9%, 30%, 15%, and 42% respectively. Ductile behaviour for ECC mixes observed due to increment of curvature ductility on ECC mixes.

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