Mechanical Properties and Shear Strengthening Capacity of High Volume Fly Ash-Cementitious Composite

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Abstract: This paper discusses development of Poly Vinyl Alcohol (PVA) fibre reinforced cementitious composites taking into account environmental sustainability. Composites with fly ash to cement ratios from 0 to 3 are investigated in this study. The mechanical properties of HVFA –cement composite are discussed in this paper at PVA fiber volume fraction maintained at 1% of total volume of composite. The optimum replacement of cement with fly ash was found to be 75\%, i.e. fly ash to cement ratio (FA/C) of 3. The increase in fiber content from 1\% to 2\% showed better mechanical performance. A strain capacity of 2.38\% was obtained for FA/C ratio of 3 with 2\% volume fraction of fiber. 

With the objective of evaluating the performance of cementitious composites as a strengthening material in reinforced concrete beams, the beams deficient in shear capacity were strengthened with optimal mix having 2\% volume fraction of fiber as the strengthening material and tested under four-point load. The reinforced concrete beams designed as shear deficient were loaded to failure and retrofitted with the composite in order to assess the efficiency as a repair material under shear.

1. Introduction

Concrete being the most popular construction material in the world, the requirement of cement has increased tremendously. It was estimated that 5\% of global greenhouse gas emission is due to cement production. Concrete structures designed to carry compressive loads are subjected to tensile stresses in real field conditions. The tensile strength of concrete is 10\% of its compressive strength and when subjected to tensile stresses concrete cracks and shows brittle failure. Along with the mechanical properties, durability of concrete structures is equally important, and can be due to the brittle nature of concrete.

The service life of civil infrastructure can be enhanced by high performance fiber reinforced cementitious composites (HPFRCC). Engineered cementitious composites (ECC) are special types of HPFRCC having high ductility and low fiber content. The tensile ductility of ECC is several hundred times of conventional concrete and tensile strain in the range of 3 to 5\% using polyethylene and polyvinyl alcohol fiber with fiber volume fraction less than 2\%.

ECC uses more cement when compared with normal concrete as no coarse aggregate is used in the mix design. Higher use of cement increases the heat of hydration, autogenous shrinkage and cost. Moreover, the related increase in the primary energy and emission of CO\textsubscript{2} can make a negative impact on environment. The replacement of a large part of cement in cementitious composites by industrial by-product or waste is one of the solution approaches.
Fly ash, a by-product of coal burning power plants, was initially considered as a waste material. Currently it has been used as a substitute for cement in concrete because of its pozzolanic and cementitious properties. The use of fly ash as a replacement of cement was limited to 10% to 25%, but the developments in water reducing admixtures helped in developing high volume fly ash (HVFA) concrete with reasonable compressive strength. Concrete that has more fly ash than cement is termed as HVFA concrete.

2. Literature review

2.1. HVFA ECC
En-Hua Yang et al. [1] studied about the improvement of mechanical properties of ECC using high volume fly ash. It was observed that as fly ash content increased compressive strength reduced. However high fly ash content reduced the crack width in ECC. Tight crack width promoted the durability of ECC. The study on ECC with high volume fly ash, done by Shuxin Wang et al. [2] observed that the interface frictional stress and chemical bond had a descending trend with increase of fly ash content. This helped in modifying the PVA fiber bridging behaviour. It was observed that at high ash content fibers are pulled out instead of rupture thereby minimising the bridging stress in the fiber.

Jiangtao Yu [3] investigated the residual mechanical performance after temperature exposures of 20°C, 50°C, 100°C and 200°C of ECC containing HVFA (FA/C = 4.4) and polyvinyl alcohol fibers (HVFA-ECC). The test results indicated that HVFA-ECC maintained good residual tensile ductility after sub-elevated temperature (<200 °C) exposure, and a moderate temperature treatment (<100 °C) actually enhanced ECC’s tensile ductility. It was inferred that the high fly ash content have aided HVFA-ECC in maintaining good residual tensile ductility after the sub-elevated temperature exposures. Mustafa Sahmaran et al [4] discussed the fire resistance and microstructure of engineered cementitious composites under the influence of high volume fly ash and micro polyvinyl alcohol (PVA) fibers. When fly ash content was increased from 55% to approximately 70%, ECC with better residual mechanical properties were obtained even after exposure to temperatures from 200 to 600°C.

2.2. Advantages of fly ash in ECC
Hui Ma et al. [5] observed that the metal cation concentration at the interface governs the chemical bonding of PVA fiber to matrix, in particular Al³⁺ and Ca²⁺. The reduction in the concentrations of Al³⁺ and Ca²⁺ on PVA fiber surface were observed when the fly ash is with lower combinations of Al₂O₃ and CaO contents. This reduction in the concentration of cations on the PVA surface reduced the chemical bonding with the matrix, thus preventing the fiber rupture and enhancing the ductility of ECC. The higher calcium or smaller particle size and lower combined Al₂O₃ and CaO content in fly ash were found beneficial for higher first cracking strength and tensile ductility. With the increase in fly ash content the tensile ductility of ECC increased, however, excess fly ash is responsible for the decrease in compressive strength of the composite.

Shuxin Wang et al. [2] noticed that the aggregation of inert particles on PVA fiber surface contributed to the variation in interface properties. They observed residual carbon from the insufficient combustion in fly ash concentrated on PVA fiber surface during mixing providing extra lubricant for fiber pull out in addition to oil coating. Mechanically this reduced the frictional stress and weakened the chemical bond. At high ash content, less fiber rupture was observed due to the reduction of interface bond. An earlier study [6] on the mechanical behaviour of fly ash cementitious composite has shown tensile strain capacity of about 2% for different mixes incorporating PVA fibres.

2.3. ECC for strengthening
Chung-Chan Hung et al. [7] studied the efficiency of ECC jacketing for retrofitting shear deficit reinforced concrete (RC) members. The cyclic behaviour of shear deficit beams considerably enhanced due to ECC jacket. Rui Zhang et al. [8] observed in a study that the shear capacity of beams with and without stirrups increased by 20.6% and 107.6% respectively by replacing concrete with PP-ECC at beam column joints. The failure of specimens even after eliminating the transverse reinforcements was
still found to be flexural indicating that PP-ECC can be used as an effective replacement for transverse reinforcements. Emily N. Herbert et al. [9] studied on the self-healing ability of ECC in outdoor environmental conditions. It was observed that the extent of self-healing in cracked concrete was mainly dependent on the crack width. ECCs with small micro cracks completely healed at a faster rate than conventional concrete with large cracks under natural environment. The first crack strength recovery directly depends on the duration of environmental exposure after damage and often exceeds 100% recovery values after 6 months exposure. S. Qudah et al. [10] observed that beam column connections incorporating ECC maintained structural integrity under high elastic deformations without developing large cracks or spalling of concrete cover. Moreover, ECC specimens demonstrated enhanced shear strengths indicating that ECC materials are effective in replacing transverse reinforcements. Finally, the failure mode of all specimens incorporating ECC was ductile whereas for control specimens it was brittle.

3. Significance and objectives of study
The high cement content is seen in the mix design of HPFRCC and thus material sustainability is a concern. This study aims at feasibility assessment of making greener composite through utilisation of high volume of fly ash and simultaneously maintaining ductility properties. The objectives of this work are:
1. To study the mechanical properties of HVFA-Cement composites, through compressive strength, flexural strength and direct tensile strength test and find the optimum percentage replacement of cement with fly ash (with 1% volume fraction of PVA fiber).
2. To study the influence of higher volume fraction of fibers on the mechanical properties at the optimum fly ash to cement ratio.
3. To study the efficiency of HVFA-Cement composite as a shear capacity enhancing material in shear deficit beams.

4. Experimental program

4.1. Materials
a) Ordinary Portland Cement: OPC-53 grade of specific gravity 3.15 confirming to IS 12269:1987.
b) Fine aggregate: Silica sand of size less than 250 μm with specific gravity 2.65. The physical properties are conforming to IS 2386:1963 (Part IV).
c) Fly ash: Class F fly ash of specific gravity 2.11 conforming to IS 3812 :2013 (Part II). Table 1 gives the chemical composition.
d) PVA fiber: The properties of PVA fiber used in the mix are given in Table 2.

| Oxide     | CaO | SiO2 | Al2O3 | Fe2O3 | MgO | TiO2 | P2O5 | Na2O | Loss of Ignition |
|-----------|-----|------|-------|-------|-----|------|------|------|-----------------|
| % wt      | 10.19 | 56.52 | 22.52 | 5.78  | 3.16 | 1.2  | 0.06 | 0.49 | 0.08            |

Table 2. Properties of PVA fiber

| Specific Gravity | Length of Fiber (mm) | Dia of fiber (μm) | Aspect ratio (l/d) | Elongation | Tensile Strength (MPa) | Young's Modulus (GPa) |
|------------------|---------------------|-------------------|-------------------|-------------|------------------------|-----------------------|
| 1.3              | 6                   | 38                | 158               | 7           | 1317                   | 39                    |

1 Manufacture’s data. It is surface coated with a proprietary oil agent (1.2% by weight)

e) Superplasticizers / High range water reducing admixtures (HRWA): Auramix 400 which belongs to Polycarboxylate Ether family was used. It complies with IS 9103-1999.
4.2. Mixing and curing
The control mix proportion for this study is adopted from the study done by Shwan H Said et al [13]. The 1% fiber volume was incorporated in the mixes after converting into gravimetric measure (13 kg/m3) using fiber specific gravity. The mix design of ECC is to be done by adopting micromechanics which is based on fiber pull out test. Important parameters for the design of ECC like interfacial chemical bond $G_d$, interface frictional bond $\tau_o$ and slip hardening coefficient $\beta$ have to be derived from the pull-out test and if required the fiber surface characteristics are modified. However due to time and experimental set up constraints the pull-out test was not attempted in this study and fiber available from market was utilised as such. the optimum superplasticizer to binder ratio had to determine as the fly ash content in each mix were different. Flow table test was conducted to find the optimum dosage of superplasticizer and the flow percentage was maintained between 210 to 220 for proper blending of fiber in the mix. The mix proportions used for the study are shown in table 3. Materials were dry mixed in the mortar mixer for about 2 minutes. Water was then added gradually and mixed with the materials. This was followed by the addition of super plasticizer and the entire matrix was mixed for another 5 minutes to attain suitable workability. Finally, the PVA fibers were carefully added such that it does not stick to the surface of the mortar mixer and mixed with the matrix for 3 minutes. Finally, the mortar was placed in the moulds. All the specimens were covered with moist jute bags and cured for 28 days.

| Mixture | FA/C | Cement (kg/m$^3$) | Fly Ash (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) | SP/B (%) | SP (kg/m$^3$) | Fiber (kg/m$^3$) |
|---------|------|-------------------|--------------------|----------------|-----------------|----------|--------------|-----------------|
| CS      | 0    | 1025              | 0                  | 656            | 379.25          | 0.2      | 2.05         | 0               |
| MIX 1   | 0.5  | 683.33            | 341.67             | 656            | 379.25          | 0.28     | 2.87         | 13              |
| MIX 2   | 1    | 512.50            | 512.50             | 656            | 379.25          | 0.4      | 4.10         | 13              |
| MIX 3   | 1.5  | 410.00            | 615.00             | 656            | 379.25          | 0.49     | 5.02         | 13              |
| MIX 4   | 2    | 341.67            | 683.33             | 656            | 379.25          | 0.58     | 5.95         | 13              |
| MIX 5   | 3    | 256.25            | 768.75             | 656            | 379.25          | 0.71     | 7.28         | 13              |

4.3. Test details
4.3.1. Compressive strength test. Compressive strength was evaluated by casting three cubes of dimensions 50 mm × 50 mm × 50 mm. Cement composite cubes were tested to evaluate the compression strength at the age of 28 days. A dial gauge was fixed at the lower arm of the universal testing machine to measure the axial deformation. The test procedure was followed in accordance with IS 516-1959 [15]

4.3.2. Flexural test Steel moulds with dimensions of 500 mm × 100 mm × 25 mm were used to cast and prepare beams. The HVFA-Cement composite beams were tested with Universal testing machine of 400 KN capacity under four-point flexural loading. The span of 450 mm was equally divided into three parts. For each beam the deflection was measured using a dial gauge which was fixed at the center as shown in figure 1. The test was followed as per IS 516-1959. [15]

4.3.3. Direct tensile strength test Figure 2 shows the dimensions of the specimen used for direct tensile test in accordance with ASTM E646-07 [16] I-shaped specimens as shown in figure 3 after 28 days of curing were used to conduct uniaxial tensile test using UTM of 200 KN capacity. The rate of loading was maintained at 0.1 mm/min.
5. Results and discussions

The results of compressive test, flexural test and direct tensile strength test are tabulated in table 4.

| Mix     | Compressive Strength (MPa) | Modulus of Rupture (MPa) | Deflection at Ultimate Load (mm) | Max. Deflection (mm) | Direct Tensile Strength (MPa) |
|---------|-----------------------------|--------------------------|----------------------------------|---------------------|-------------------------------|
| CS      | 45.20                       | 3.02                     | 0.32                             | 0.55                | 1.70                          |
| MIX 1   | 36.92                       | 3.6                      | 1.22                             | 3.1                 | 2.15                          |
| MIX 2   | 29.68                       | 3.17                     | 1.05                             | 2.8                 | 2.10                          |
| MIX 3   | 25.76                       | 3.17                     | 1.5                              | 2.69                | 1.92                          |
| MIX 4   | 23.12                       | 3.31                     | 0.8                              | 2.56                | 1.76                          |
| MIX 5   | 20.92                       | 3.74                     | 1.21                             | 2.99                | 1.85                          |

5.1. Compressive strength

The compressive strength of different mixes are given in table 4. It can be observed that the compressive strength decreases and compressive strain increases as the fly ash content in the mix increases. Earlier study [1] showed a similar decreasing trend in compressive strength as the fly ash content increases. Fibers in the specimen aided in retaining the shape even after failure. Stress strain relationship of different mixes are shown in figure 3. The maximum compressive strain of control specimen was 1.96% whereas for specimens with fibers it was in the range of 3.5% to 6%. The maximum compressive strain of 5.7% was observed for mix 5 (FA/C = 3).
5.2. Flexural strength

Modulus of rupture given in Table 4 was calculated for all the HVFA-Cement composites from the maximum axial load obtained from the test. Results showed that all the mix proportions in which fly ash was incorporated, showed better flexural strength than the control specimen. Load Vs deflection graph for different mixes is shown in figure 5. It can be observed from figure 7 that after failure a load regaining behaviour was shown by MIX 4 (FA/C= 2) and MIX 5 (FA/C= 3). MIX 5 showed better performance with modulus of rupture 3.74MPa and maximum deflection of 2.99 mm.

5.3. Direct tensile strength

Stress strain relationship in direct tension is shown in figure 6. The mixes with fly ash showed better tensile properties than control specimen. It was observed that strain hardening behaviour was shown by MIX 4 and MIX 5 even with 1% volume of fiber fraction. At higher fly ash content (FA/C= 2 and FA/C= 3) strain hardening behaviour were observed. MIX 5 showed higher strain when compared with other mixes. An increase in tensile ductility was observed in [5] as the fly ash content increased in the mix.
6. Influence of higher fiber content
From the above mechanical tests, it was observed that Mix 5 (with 1% fiber and FA/C= 3) showed better flexural performance when compared with the rest of the mixes. The same mix showed strain hardening behaviour and maximum tensile strain in direct tensile test. The tensile and compressive strength of mix 5 can be improved with increase in fiber content. Hence for Mix 5, an increase in volume fraction of fiber of 2% (26 kg/m$^3$) was tried. The compressive test, flexural test and direct tensile test with higher volume fraction of fiber were done. The results of these tests are discussed in the following section.

6.1. Results and discussions
The results of compressive test, flexural test and direct tensile test with higher volume fraction of fiber of 2% (Mix 6) are tabulated in table 5. On comparing the results of MIX 6 with MIX 5, all the properties have been enhanced due to the increase in the volume fraction of fibers from 1% to 2%.

**Table 5. Compressive, flexural and tensile strength at higher volume of fiber**

| Mixture | Volume fraction | Avg. Compressive strength (MPa) | Modulus of rupture (MPa) | Deflection at the ultimate load (mm) | Deflection at failure (mm) | Direct tensile stress (MPa) |
|---------|----------------|---------------------------------|-------------------------|-----------------------------------|---------------------------|--------------------------|
| MIX 5   | 1              | 20.92                           | 3.74                    | 1.21                              | 2.99                      | 1.85                     |
| MIX 6   | 2              | 31.12                           | 5.47                    | 2.22                              | 6.44                      | 2.05                     |

As the fiber content increases, an increase in the compressive strength, modulus of rupture and direct tensile stress were observed. The compressive strength and modulus of rupture increased by 48.75% and 46.25% when the fiber content increased from 1% to 2%. Figure 7 and figure 8 shows the compressive stress strain relationship and load deflection graph for mixes with increase in fiber content. Strain hardening behaviour was observed for both MIX 5 and MIX 6. Figure 9 shows the stress strain relationship under direct tension. A tensile strain capacity of 2.38% was observed for MIX 6. Earlier studies [15] have indicated that at higher volume fraction of fiber there will be reduction in spacing between the microcracks. This, indirectly indicates fiber influence on increasing the ductility of the composite.

![Figure 7. Compressive stress strain relationship](image1)

![Figure 8. Load VS Deflection curve for various mix](image2)
At higher volume fraction of fiber both compressive and tensile properties enhanced. The effectiveness of the mix in a practical application has to be evaluated. The tensile properties of engineered cementitious composites is far better than conventional concrete. Due to this ECC finds wide areas of applications in structural members. The studies in the past indicate that ECCs help in enhancing the shear resisting capacity of structural members. A study was done to check the efficiency of HVFA-Cement composite (Mix 6) as a retrofitting material in simply supported beams.

7. Retrofitting of shear deficit of RCC beams

The objective of the final stage of study was to evaluate the performance of PVA- HVFA-Cement composites as a shear repairing and strengthening system in shear deficit RCC beams. For this purpose, four RCC beams that would present shear failure were designed. M20 grade concrete was used for RCC beams with Fe 250 as reinforcing bars. The detailing of beam is shown in figure 10. Two beams were loaded to failure, and maximum shear load were noted. Simultaneously two beams were strengthened using ECC at zones where shear failure was observed for other set of beams. The mix used for strengthening was MIX 6.

7.1. Test details and observations

Two reinforced concrete beams were tested to failure and observe the shear capacity. Four-point load test was done on the beams to keep the middle section of the beam to be free from shear failure. The central portion of the reinforced beams were free from damage. Failure was observed under the point of application of load at one side of the beam for both the specimens. An average shear load of 70kN was resisted by the reinforced beam.

7.2. Process of strengthening

The reinforced beams were strengthened with cementitious composites by packing it on both lateral and bottom sides with a thickness of 25mm. The beams were cleaned to remove all the loose material and the lateral and bottom sides were chipped to provide bonding between beams concrete and jacketing mix. The MIX 6 was placed at bottom side of jacket to the required thickness of 25mm and beam was placed on the jacket and rest of HVFA-Cement composite was packed in the lateral sides. The beams
were strengthened at both sides under the points of application of load. Figure 11 shows the side profile of the strengthened beam. The strengthening sequence is illustrated in figure 12.

![Side view of strengthened beam](image1)

**Figure 11.** Side view of strengthened beam

![Strengthening sequence](image2)

**Figure 12.** Strengthening sequence

7.3. **Testing of strengthened beams**
The same testing procedure which was done for reference beams were carried out on the strengthened beams after 28 days of curing of the retrofitting material. Four point loading test were done on the retrofitted beams by applying loads on the strengthened sections. The maximum load at which the specimens failed were noted.

7.4. **Result**
When compared with the reference beam the strengthened beams showed better shear resisting capacity. From figure 13 it can be clearly observed that the maximum load resisted by strengthened beams were 107kN, which is greater than that of reference beam.

![Shear capacity of beams](image3)

**Figure 13.** Shear capacity of beams

8. **Conclusion**
The following conclusions could be drawn from the study
1. The increase in fly ash content reduces the compressive strength, but for MIX 5 with FA/C ratio of 3, a compressive strength of 20.92 MPa was obtained.
2. Mix with FA/C of 2 and 3 showed load regaining tendency after first cracking during flexural test.
3. For FA/C of 2 and 3 strain hardening behaviour was observed at 1% volume fraction of fibers under tensile load.
4. With the increase in fiber content for mix with FA/C = 3 from 1% to 2% an increase in the compressive strength, modulus of rupture and direct tensile strength were observed. Tensile strain of 2.38% was obtained for mix with FA/C = 3 and fiber content 2%.

5. A shear enhancement of 52% was obtained by using the composite as a strengthening material when compared with reference beam.

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