Strength and flexural toughness of hybrid fibre reinforced fly ash based concrete

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Abstract. To overcome concrete brittleness and to provide toughness, fibre reinforcement is commonly utilized. Fibre reinforcement to concrete in the form of hybrid fibre is a new concept to achieve individual fibre benefits. In this paper, the effect of polypropylene fibre (PF) and steel fibre (SF) either individually or with different combinations at 1% fibre volume fraction on the strength, flexural toughness, and Ultrasonic pulse velocity (UPV) value of FIBRE-reinforced fly ash (FA) based concrete has been presented. For this purpose, one control mix having 25% FA and 0% fibre and five mixes with different hybrid fibre combinations of 1%PF-0%SF, 0.75%PF-0.25%SF%, 0.50%PF-0.50%SF, 0.25%PF-0.75%SF, and 0%PF-1%SF were cast. ASTM C 1609 method was utilized to evaluate the flexural toughness. Experimental results have shown an improvement in all the above-said properties (expect UPV) by the addition of fibre, but improvement is more significant in mixes with a higher percentage of SF when compared with mixes at a higher percentage of PF. Mix with a hybrid fibre combination of 0.25% PF and 0.75% SF gave the best result among all the fibre-reinforced fly ash-based mixes.

1. Introduction
In India, after agriculture the construction industry is the second largest industry. Concrete is the most extensively used construction material due to its widespread availability, superior performance, durability, and ability to be moulded into any desired shape. Currently, the most common binder is ordinary Portland cement (OPC), responsible for the greenhouse gasses emission. The cement industry accounts for 5-8% of global CO₂ emission. Therefore, there is an urgent need for partial and full replacement of the existing cementing material. Additionally, a huge amount of agricultural and industrial wastes are being produced annually which are rich in aluminosilicates such as FA, rice husk ash, etc. Usually, these wastes were dumped into vacant land cause severe health-related problems. In India, around 106.37 million tons of FA were produced in the year 2020-2021 [1–3]. The utilization of FA for cement replacement not only reduce its disposal problem but also reduce the concrete unit cost. Generally, concrete made with fly ash is brittle due to low tensile and flexural properties. Microcracks develop in concrete during the initial phases of hardening due to stress and environmental changes. To compensate for the strength losses due to the crack formation, fibres are incorporated. Fibres prevents the development of cracks in the microstructure of concrete and disappear concrete fracture energy, thus improve the flexural toughness and minimize the brittle failure of concrete. Fibres from both metallic and non-metallic families are used in concrete either individual or hybridized form [4–6]. PF from the non-metallic family and SF from the metallic family are among the most commonly used hybrid combination due[7,8] to easy availability and low cost. Hybrid fibre composites consist of...
two or more fibre combinations simultaneously to explore their unique properties. Therefore, lower moduli and smaller size PF and higher moduli and larger size SF are hybridized to achieve benefits of individual fibre simultaneously and are expected to enhance the overall performance of concrete at every phase of crack opening [9–11]. Several studies have shown that hybrid fibre-reinforced concrete (HFRC) behave good than the single fibre reinforced concrete and ordinary concrete in terms of compressive strength, flexural strength, and flexural toughness, tensile strength, and impact strength. The size, type, aspect ratio, and volume percentage of fibres all have a role in optimising mechanical properties investigated the effect of a large volume of FA on the compressive strength, the heat of hydration chloride diffusivity, hydration level, and pore structure of high strength concrete. observed an enhancement in compressive and flexural strength by SF addition, because before cracking SF provides resistance to the growth of cracks and hence enhances strength properties [12–15].

Various researches have been carried out globally to examine the compressive strength, flexural strength, and flexural toughness of plain and HFRC under different testing methods but still, there is a lack of information regarding the effect of fibre on the strength and flexural toughness of FA based concrete. In this study, the author has examined the influence of SF, PF, and steel-polypropylene hybrid fibre on the strength and flexural performance of fly ash-based concrete and compared the result obtained with a reference mix.

2. Materials and Methodology

2.1. Materials

Locally available Pozzolana Portland cement (PPC), FA, F.A., C.A., potable tap water, and hybridized SF and PF were used in this experimental study. All the materials used are conformed to the provision laid down by respective IS codes before the casting of specimens [16–18].

2.1.1. Cement

Pozzolana Portland cement (PPC) as per containing an already mixed content of 34% FA by total weight of cement was used to produce concrete mixes. The specific gravity and compressive strength after 28 days were found to be 2.93 and 33 MPa respectively [19–21].

2.1.2. Fly ash

FA of class F as per supplied by the Ropar Thermal Power plant was used. In this study additional 25 % FA was added to PPC to produce fibre-reinforced FA based concrete mixes. The chemical characteristics of FA are presented in Table 1.

| S. No. | Constituents | Abbreviations | Fly Ash |
|-------|--------------|---------------|---------|
| 1     | Lime         | CaO           | 1.10    |
| 2     | Silica       | SiO<sub>2</sub> | 57.6    |
| 3     | Alumina      | Al<sub>2</sub>O<sub>3</sub> | 30.5    |
| 4     | Iron oxide   | Fe<sub>2</sub>O<sub>3</sub> | 3.72    |
| 5     | Sulphate     | SO<sub>3</sub> | 0.22    |

2.1.3. Fine Aggregates

In our study locally available coarse sand having fineness modulus of 2.66 and specific gravity of 2.63 conforming to as fine aggregate in saturated surface dry condition was used.

2.1.4. Coarse Aggregates
Coarse aggregate as per having a nominal size not more than 12.5mm/10mm and most of them retained over IS 4.75mm size sieve used as coarse aggregate. The Fineness modulus and specific gravity were found to be 6.6 and 2.65 respectively.

2.1.5. Water
Potable tap water having a pH between 6.5-8.0, which is suitable for drinking purposes and is free from impurities was used throughout the entire curing and casting work.

2.1.6. Fibres
Steel and Polypropylene fibres from metallic and non-metallic families having different sizes, aspect ratios, modulus of elasticity, density were utilised for the reinforcement of FA based concrete mixes. Table 2 presents the fibres properties.

| S. No. | Characteristics                   | Steel fibre (SF) | Polypropylene fibre (PF) |
|--------|-----------------------------------|------------------|--------------------------|
| 1      | Density (kg/m³)                   | 7850             | 910                      |
| 2      | Length (l)                        | 30 mm            | 15 mm                    |
| 3      | Modulus of Elasticity (GPa)       | 200              | 35                       |
| 4      | Aspect Ratio (l/d)                | 30               | 15                       |
| 5      | Diameter (d)                      | 1 mm             | 1 mm                     |

2.2 Mix Details and Proportions
For fibre-reinforced FA based concrete, a total of 18 beams and 36 cubes were cast. For each mix, Six (100 mm x 100 mm x 100 mm) size cubes for compressive strength and for the flexural strength and toughness three (100 mm x 100 mm x 500 mm) size beams were cast. The fibres volume proportion was held constant at 1%. A power-operated tilting type rotary concrete mixer having a capacity of 90 litres was used to mix the various ingredients. All the specimens were cast in a typical laboratory environment and for appropriate compaction vibrating table was utilized. After 3 hours of casting, all the specimens were marked with their respective mix designation and allowed to set for 24 hours. After 1 day of casting, Specimens were demoulded and put into the curing tank till the age of test. Table 3 presents the various mix details. The quantity of different materials per cubic meter is presented in Table 4.

| S. No. | Mix ID       | Mix Details                                                                 |
|--------|--------------|------------------------------------------------------------------------------|
| 1      | HV0PF0SF     | Control mix, 75% PPC+ 25% FA, 0% fibre (0%PF & 0%SF)                         |
| 2      | HV1PF0SF     | 75% PPC+ 25% FA, 1% fibre (1%PF & 0%SF)                                      |
| 3      | HV0.75PF0.25SF | 75% PPC+ 25% FA, 1% Hybrid fibre (0.75%PF & 0.25%SF)                         |
| 4      | HV0.5PF0.5SF  | 75% PPC+ 25% FA, 1% Hybrid fibre (0.50%PF & 0.50%SF)                         |
| 5      | HV0.25PF0.75SF | 75% PPC+ 25% FA, 1% Hybrid fibre (0.25%PF & 0.75%SF)                         |
| 6      | HV0PF1SF     | 75% PPC+ 25% FA, 1% fibre (0%PF & 1%SF)                                      |

| Binder (kg/m³) | Water (kg/m³) | Aggregates(kg/m³) | Fibres (m³) |
|----------------|---------------|-------------------|-------------|
|                |               |                   |             |
2.3 Test Method on Hardened Concrete

2.3.1. UPV Test
All cube specimens of 100mm×100mm×100mm size were UPV tested on 7 and 28 days of curing age according to UPV test method recommended by shown in Figure 1. To know the concrete mix homogeneity, internal crack, and flaws, an ultrasonic pulse was induced into the cube specimen and time taken by pulse wave to travel through the concrete specimens in terms of pulse velocity was measured accurately to further define concrete quality i.e., excellent, good, medium, or doubtful.

2.3.2. Compression Test
Following the provisions of, a compression test was performed shown in Figure 2. The rate of load without any shock or jerk was 140 kg/cm²/min, till the failure. The final compressive strength of any particular mix was calculated using the average compressive strength of three test specimens.

2.3.3. Flexural Test
The beam flexural strength is determined by following the recommendation provided. Figure 3 shows the flexural test arrangement. A constant load of 0.05 cm/min was applied to obtain the peak load. Expression (1) was used to calculate the flexural strength

\[ F_b = \frac{(P L_{\text{eff}})}{(bd^2)} \]  

Where, \( F_b \) = Flexural Strength; \( P \) = Peal Load; \( L_{\text{eff}} \) = effective span length i.e., 450 mm; \( b \) = beam width i.e., 100mm and \( d \) = beam depth i.e., 100 mm.

| 495 | 225 | Fine | 752 | 930 | Coarse | 0.01 |

Figure 1. UPV test arrangement

Figure 2. Compressive test arrangement
2.3.4. Flexural Toughness
Flexural toughness was calculated by using the method which involves the calculation of various parameters such as residual load, residual strength, and flexural toughness. Toughness $T_{150}$ and $T_{600}$ is the area under load displacement curve up to the $1/150$ and $1/600$ mm of span deflection respectively. $P_{150}$ and $P_{600}$ are the loads corresponding to these deflection values. Following expressions (2) were used to calculate the residual strength factor.

$$F_{150} = \frac{(P_{150} L_{\text{eff}})}{bd^2}; F_{600} = \frac{(P_{600} L_{\text{eff}})}{bd^2}$$  \hspace{1cm} (2)

3. Results

3.1. UPV Test
Figure 4 presents the obtained UPV values for FA based concrete. Insignificant change in UPV values was detected in all fibre-reinforced FA based concrete mixes when compared with the control mix. A slight decrease in UPV value was noted in mixes with a higher percentage of PF. However, an increase in UPV value was observed on successive replacement of PF with SF and for mix HV0PF1SF highest value of UPV was obtained. Furthermore, improvement in UPV value was noticed with increase in curing age of 7 to 28 days. According to, as concrete ages elimination of capillary pores and crack occurs in concrete due to increased hydration which results in less resistance against pulse transmission.
3.2. Compressive strength

Figure 5 presents the obtained compressive strength for FA based concrete after 7 and 28 days of curing period. Irrespective of fibre type, an increase in compressive strength was noticed when compared with the control mix, but the increase was more concerned with steel fibre percentage. The lower stiffness of PF makes them less effective for the compressive strength enhancement when compared to SF being stronger, having high stiffness, and have high efficiency in bridging cracks. From Figure 5, it can also be seen that due to the positive synergetic effect of hybrid fibres the compressive strength of hybrid mix HV0.25PF0.75SF was found to be higher than those with steel and polypropylene fibre alone. Explained that the fibres constrain the expansion of cracks, minimize the level of stress concentration at the tip of the crack by bridging the micro cracks, divert the direction of cracks, and slower the crack growth rate, and hence improve the compressive strength of the concrete.

![Figure 5. Average compressive strength of fibre-reinforced FA based concrete](image)

3.3. Flexural Strength

Figure 6 shows the average flexural strength obtained for FA based concrete after the curing of 28 days. Enhancement in flexural strength was observed with both steel and polypropylene fibre when compared with the reference mix. The addition of fibre to concrete improved the flexural strength as fibre tends to slow down the crack growth rate by their crack bridging effect. More improvement in flexural strength was observed in mixes with a higher percentage of SF because of the high modulus of elasticity and tensile strength of SF than PF. Mix with 0.25% PF and 0.75% SF has shown the highest flexural strength due to the positive synergetic effect of hybrid fibre. PF mainly bridges the young micro-crack formed in concrete in early ages while steel SF restricts the growth of macro cracks, enhances the flexural strength of concrete.
3.4. Load-deflection curves
The load versus deflection curve obtained for each fibre-reinforced FA based concrete mix under flexural loading is shown in Figure 7. Each curve represents the average of three-beam specimens. No post cracking behavior was obtained for the control mix and fails immediately after having the first crack in it due to its high brittleness, as shown in Figure 7. The detailed summary of average peak load and corresponding deflection obtained for each mix is presented in Table 5. Considering Table 5, an increase in both load-carrying capacity and corresponding deflection values was observed due to the introduction of fibre PF, SF, and steel-polypropylene hybrid fibres when compared with the control mix. In a single type of fibre mixes, the highest deflection capacity and lowest peak load were obtained for mix with 1% PF, highest peak load and lowest deflection was obtained for mix with 1% SF. Enhancement in both peak load and corresponding deflection can be seen in all hybrid fibre reinforced FA based concrete mixes when compared with mixes having a single type of reinforcement. According to [20] higher stiffness of SF increases the load taking capability and PF enhances the deflection capacity due to its lower stiffness.
3.5. Flexural toughness

To study the effect of fibre reinforcement on the fracture toughness of fibre-reinforced FA concrete, various toughening parameters as per ASTM C 1609, such as flexural toughness ($T_{150}$, $T_{600}$) residual load ($P_{150}$, $P_{600}$), and residual strength ($F_{150}$, $F_{600}$) were also calculated and summarised in Table 5. Figure 8 presents the effect of fibre incorporation on the flexural toughness, residual load and residual strength of fibre-reinforced FA based concrete.

Table 5. Average peak load, deflection and flexural toughness parameters

| Mix ID's            | Average Peak Load (kN) | Average Peak Load Deflection (mm) | $T_{150}$ (Joules) | $T_{600}$ (Joules) | $P_{150}$ (kN) | $P_{600}$ (kN) | $F_{150}$ (MPa) | $F_{600}$ (MPa) |
|---------------------|------------------------|----------------------------------|--------------------|--------------------|----------------|----------------|----------------|----------------|
| HV0PF0SF            | 6.06                   | 0.389                            | -                  | -                  | -              | -              | -              | -              |
| HV1PF0SF            | 6.87                   | 0.495                            | 12.50              | 3.61               | 2.57           | 4.73           | 1.16           | 2.13           |
| HV0.75PF0.25SF      | 10.09                  | 0.587                            | 17.71              | 4.61               | 4.48           | 6.75           | 2.01           | 3.04           |
| HV0.5PF0.5SF        | 11.74                  | 0.682                            | 23.05              | 5.04               | 6.34           | 9.40           | 2.86           | 4.23           |
| HV0.25PF0.75SF      | 14.16                  | 0.658                            | 28.46              | 6.52               | 7.63           | 10.85          | 3.43           | 4.88           |
| HV0PF1SF            | 12.34                  | 0.433                            | 20.55              | 5.76               | 4.83           | 6.43           | 2.17           | 2.89           |
Figure 8. Effect of fibre on flexural toughness and residual strength

Control mix has shown almost no post cracking toughness under flexural loading, hence not analysed here. As expected, flexural toughness of mix reinforced with 1% SF was found to be more when compared with mix reinforced with 1% PF. For hybrid fibre reinforced mixes, increasing the content of SF increased the flexural toughness, residual strength, and residual load as shown in figure 8. Furthermore, the mixture reinforced with 0.25% PF and 0.75% SF showed the highest efficiency of the hybrid fibres in enhancing flexural toughness.

4. Conclusions
1. Fibres addition slightly reduced the UPV value of FA based concrete mixes, but all the values have been recorded between 3500-4500 m/sec, indicating a good quality concrete.
2. Improvement in compressive strength with SF was found to be higher than that of PF. On comparing with reference mix, maximum improvement in compressive strength was found for mix with 0.25% PF and 0.75% SF after the curing age of 7 and 28 days.
3. The flexural strength of all fibre-reinforced FA based concrete mixes was found to be higher than the control mix. Maximum flexural strength was observed for hybrid mix HV0.25PF0.75SF followed by HV0PF1SF, HV0.5PF0.5SF, HV0.75PF0.25SF, and HV1PF0SF respectively.
4. No post-cracking toughness was observed for the control mix. Moreover, enhancement in flexural toughness and residual strength was observed for all FA based concrete mixes by the addition of fibre, particularly for mix hybridized with 0.25%PF & 0.75%SF. Toughening effect of SF was found to be more dominant than the PF which indicates the better crack-bridging efficiency of SF than PF.
5. For overall enhancement of fibre-reinforced FA based concrete in terms of strength and flexural toughness, hybrid fibre combination (0.25% PF and 0.75% SF) is recommended.

Acknowledgments
The work presented in this paper would not have been possible without the help of Dr B R Ambedkar NIT Jalandhar, concrete laboratory of civil department. The author would also like to thank Er Amandeep Meena and Er Ashish Simalti, PhD Research scholars from Dr B R Ambedkar NIT Jalandhar, for their continued help and support throughout the entire research work.
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