Experimental study on the effect of aspect ratio and volume fraction of steel fibre on the mechanical properties of metakaolin SFR concrete with mathematical model

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Abstract: The study is undertaken to find the combined effect of 16% metakaolin (MK) along with steel fiber reinforcement (SFR) on M40 grade of concrete with Portland pozzolana cement (PPC). For this purpose steel fiber of aspect ratio (l/d) as 41.67 and 81.33 were used. Cubes, cylinders and prisms were casted by using different eight concrete mixtures using 0.5% 1% and 1.5% steel fibers by volume of concrete. At 28 days of water curing these casted specimens were subjected to tests like compressive strength, split tensile strength, flexural strength and ultrasonic pulse speed test. It was located that metallic fiber along with metakaolin mixture has significantly stepped forward these properties. Regression analysis on experimental results generated some statistical model predicting the results in good agreement.

Key words: Compressive strength; Flexural strength; Split tensile strength; Metakaolin; Volume fraction; Aspect ratio

1. Introduction
The escalating demand for low cost high strength concrete is the immediate need of construction industry. Addition of pozzolonic raw material like blast furnace slag, fly ash, silica fume etc has been proved to be the better additives to the existing Portland cement in improving the strength properties of cement [1]. Addition of pozzolonic minerals to cement has increased its workability strength resistance to the chemical attack and possibility of generating high strength concrete [2]. Metakaolin additive is used as a cementitious material to reduce the porosity permeability and to increase the uniformity of the concrete to give the concrete better mechanical properties [3]. Naturally occurring kaolinite rock is calcined at a temperature of 700oC to 900oC to reduce its bound moisture and destroy its crystalline structure to produce ultrafine pozzolonic metakaolin [4–6]. Inline to generate high performance concrete subjected to overload limit in bending and shear, under seismic and cyclic action addition of steel fiber reinforcement is gaining importance [7-9]. Extensive research indicates the importance of fibers in concrete to improve the mechanical properties of concrete such as compression, tensile, flexibility, impact, wear strength, fatigue, deformation, crack load carrying capacity and toughness. [10-17]. Steel fiber reinforcement advances the uniformity of concrete. The volume percentage of SFR and the l/d ratio of fiber affect...
the properties of concrete considerably [9]. Generally, l/d ratios of SFR are in the range of 50 to 100, whereas the volume fraction Vf are between 0.5% and 2.5% by volume of concrete [7, 9, 18, 19]. SFR prevents the extension and prorogation of micro cracks because of their stress transfer capabilities [7, 20, 21]. This present work deals with the combination of metakaolin ,aspect ratio (l/d) and volume fraction (Vf) of steel fibers with mechanical properties like compressive, flexural, tensile strength and ultrasonic pulse speed . Here Hook-end steel fibers having aspect ratios of 41.67 and 83.33 were used. Concrete specimens were casted with and without metakaolin and steel fibers were placed in 0.5%, 1.0% and 1.5% concrete sizes for M40 grade of concrete. At 28 days of standard period of curing, laboratory tests were performed to determine strengths such as compressive, split and flexural along with ultrasonic pulse velocity.

2. Experimental study
The M40 grade of concrete was used as per standards given by standards [22, 23] and ACI Committee 544 [23]. The desired properties 1:1.73:3.22fractions with W/C Ratio of 0.38 were adjusted. The total binder was 400 Kg/ m3. Two different types of aggregate 20mm and 10mm with ratio 60:40 were used as a coarse aggregate. Addition of metakaolin as 16% substitute of cement, selected steel fibers of 25 mm and 50 mm length and 0.6 mm diameter were tried. The volume fraction of these fibers varied as 0%, 0.5 %, 1.0 % and 1.5 %. Experimental test sample of cubes of size 150X150X150 mm for compressive strength, cylinders of 150x300mm size for split tensile strength and prisms of size 100x100x500 mm for flexural strength were molded; demolded after one day of setting and cured for 28 days in water. All samples were tested as per the standards [24, 25].

3. Materials Used & its Properties
3.1. Portland Pozzolona Cement
PPC confirming by (IS 1489:1991) [26]was in use. 28 days compressive strength is 55.60 N/mm².

3.2. Metakaolin
Metakaolin, quality enhancing pozzolana in amorphous powder form was marketed by the 20 Micron Ltd. at Vadodara, Gujarat. The chemical and physical Properties of metakaolin and PPC are as per Table 1.

Table 1. Chemical and Physical properties of Cement and Metakaolin.

| Properties   | Oxides       | Cement (% by mass) | Metakaolin (% by mass) |
|--------------|--------------|--------------------|------------------------|
| Chemical properties | SiO₂ | 21.74 | 53 |
|              | Al₂O₃ | 5.16 | 43 |
|              | Fe₂O₃ | 3.24 | 1.2 |
|              | CaO   | 63.76 | 0.5 |
|              | Na₂O  | 0.33 | 0.12 |
|              | MgO   | 1.15 | 0.4 |
|              | K₂O   | 0.56 | 0.53 |
|              | L₂O₁. | 2.08 | 0.4 |
|              | TiO₂  | - | 2.27 |
| Physical properties | Surface area (m²/kg) | 310 | 16800 |
|              | Specific gravity | 3.12 | 2.6 |
3.3. Fine aggregate
Fine river sand of standard IS 383(2016) [27] was in use.

3.4. Coarse aggregate
The crushed natural rock from local quarry of size 20mm and 10 mm as per IS: 2386-1963 (I, II and III) [28].

3.5. Steel Fibre
Hooked-end steel fibres with l/d ratios of 41.67 and 83.33 conforming to ASTM A820-2001 were used. SF1 (l = 25 mm, d = 0.60 mm) and SF2 (l = 50 mm, d = 0.60 mm) ultimate tensile strength range was 910 Mpa to 1250 Mpa.

3.6. Superplasticizer
To give the additional desired properties, a superplasticizer, water reducing admixture ViscoFlux-2230+ of standard IS: 9103-1999 with specific gravity of 1.1 was used for casting specimens of all the mixes.

3.7. Water: Fresh tap water of standard IS: 456-2000 (29) which is free from acid concentration and organic substance is used for concrete mixing and for curing.

4. Test results and discussions
4.1 Fresh concrete test / Workability
Samples were prepared by adjusting the dosages of super plasticizer to maintain the slump between 50 to 70 mm. Table 2 summarizes the slump and wet density of experimental specimens.

Table 2. Slump value and wet density of concrete mixtures

| Sample Id | Slump value (mm) | Wet density (kg/m³) |
|-----------|------------------|---------------------|
| CC        | 54               | 2528                |
| MK        | 60               | 2563                |
| MKSF₁0.5  | 62               | 2590                |
| MKSF₁1    | 64               | 2610                |
| MKSF₁1.5  | 66               | 2643                |
| MKSF₂0.5  | 63               | 2580                |
| MKSF₂1    | 64               | 2585                |
| MKSF₂1.5  | 68               | 2630                |

4.2. Compressive strength
Table 3 summarizes the strength study on control mix and concrete with SFR having different aspect ratios and volume fraction with metakaolin. The compressive strength of control concrete and metakaolin concrete were 48.2 MPa and 52.4 MPa respectively. For l/d ratio of 41.67 and 83.33 the compressive strength ranges between 53.64MPa to 55.42 MPa and 53.16 MPa to 54.28 MPa respectively. Table 3 reports
these values for different mixtures also it is observed that concrete with SFR and metakaolin improved the compressive strength by 9 to 15%.

Table 3. Mechanical properties of concrete mixtures

| S. N | Steel Fiber Aspect Ratio (l/d) | Vf (%) | Compressive Strength of cube (MPa) | % increase in compressive strength | Split tensile strength of cylinder (MPa) | % increase in Split strength (MPa) | Flexural Strength (MPa) | % increase in Flexural strength | UPV m/sec | % increase in UPV |
|------|------------------------------|--------|-----------------------------------|-----------------------------------|----------------------------------------|----------------------------------|-----------------------|----------------------------------|-----------|------------------|
| 1    | -                            | -      | 48.2                              | 0                                 | 3.1                                    | 0                                | 5.6                   | 0                                | 4700.00   | 0                |
| 2    | -                            | -      | 52.4                              | 9                                 | 3.6                                    | 16                               | 6.6                   | 18                               | 4869.00   | 3.6              |
| 3    | 41.67                        | 0.5    | 53.64                             | 11                                | 3.68                                   | 19                               | 6.71                  | 20                               | 4875.25   | 3.73             |
| 4    | 41.67                        | 1.0    | 54.81                             | 14                                | 3.89                                   | 25                               | 7.42                  | 33                               | 4894.34   | 4.13             |
| 5    | 41.67                        | 1.5    | 55.42                             | 15                                | 4.55                                   | 47                               | 8.02                  | 43                               | 4953.61   | 5.4              |
| 6    | 83.33                        | 0.5    | 53.16                             | 10                                | 3.79                                   | 22                               | 6.81                  | 22                               | 4872.95   | 3.68             |
| 7    | 83.33                        | 1.0    | 53.72                             | 11                                | 4.41                                   | 42                               | 7.48                  | 34                               | 4889.02   | 4.02             |
| 8    | 83.33                        | 1.5    | 54.28                             | 13                                | 4.79                                   | 55                               | 8.9                   | 59                               | 4911.00   | 4.49             |

4.3. Split tensile strength
Table 3 also represents the split tensile strength of all concrete mixes studied. The control concrete split tensile strength is 3.10 MPa. For aspect ratio of 40.67 and 83.33 the split tensile strength ranges between 3.68 MPa to 4.55 MPa and 3.79 MPa to 4.79 MPa respectively. Table 3 also gives the percentage increase in split tensile strength values of SFR concrete with metakaolin of various aspect ratios and there volume fractions. It is observed that split tensile strength enhancement of 16 to 55% could be obtained with SFR and metakaolin concrete. Utilization of 1.5% SFR concrete seems to be promising.

4.4. Flexural strength
Table 3 summarizes also the results of flexural strength study. The control concrete flexural strength is 5.6 MPa. Flexural strength for aspect ratio of 41.67 and 83.33 ranges between 6.71 MPa to 8.9 MPa and 6.81 MPa to 8.02 MPa respectively. Metakaolin addition has increased this strength by 18%; whereas SRF improved this strength in the range of 20 to 59%.

4.5. Ultrasonic pulse velocity
Table 3 also reports an average Ultrasonic pulse velocity values for the same cube specimens at 28 days. For control concrete the average ultrasonic pulse velocity was 4700 m/s. For steel fiber reinforced concrete with metakaolin with l/d ratios of 41.67 and 83.33 the average pulse velocity was 4907.7m/s, and 4911 m/s, respectively. Addition of metakaolin and steel fiber has improved UPV by 3.6 –5.4%.
5. Mathematical models

The experimental results were modelled in the form of equations using linear regression analysis in the form Eq. (1-3).

\[ f_c = 48.193 + (191.111 \times Vf) - \left(0.011 \times \left(\frac{1}{d}\right)\right) + (29.167 \times MK), \quad R^2 = 0.971 \quad (1) \]

\[ f_t = 3.10 + (72.092 \times Vf) + \left(0.002 \times \left(\frac{1}{d}\right)\right) + (1.787 \times MK), \quad R^2 = 0.947 \quad (2) \]

\[ f_f = 5.60 + (135.73 \times Vf) - \left(9.292E-05 \times \left(\frac{1}{d}\right)\right) + (4.15 \times MK), \quad R^2 = 0.944 \quad (3) \]

Where \((f_c) = \) Predicted Compressive strength,  
\((f_t) = \) Predicted Split tensile strength,  
\((f_f) = \) Predicted Flexural strength

Figure 1–3 shows good associations between calculated/ experimental and predicted strength parameters.
6. Conclusions

1. The workability of metakaolin concrete with SFR of all aspect ratios and percent volume was found to decrease. So use of superplasticizer is recommended.
2. Wet densities of all concrete mixes increased with addition of metakaolin and steel fibers.
3. Favourable increase of 9 to 15% in compressive strength is observed with metakaolin and steel fiber combination.
4. Considerable increase in the split tensile strength and flexural strength of the order of 16-55% and 18-59% respectively are seen with these additives.
5. Ultrasonic pulse velocity of steel fibers and metakaolin combination increased with their percentages.
6. The proposed statistical model to correlate the data has good accuracy of estimation.
7. As expected the fiber aspect ratio and volume fraction has marginal effect on concrete compressive strength.

7. References

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