Influence of Metakaolin and steel fibers on stress strain behavior of concrete

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Abstract. This article describes the effects of different proportions of metakaolin and steel fiber on the stress-strain behavior of concrete. Concrete has become an important part of infrastructure development due to its wide and wide application. However, its brittleness can cause cracking, and cause some deterioration problems and infrastructure failures. Considering the problem of cracking performance, researchers around the world have conducted various studies to develop concrete with higher performance, longer life, and minimized destructive effects on nature. In order to obtain such characteristics, researchers only focus on the improvement of strength. It is observed that the higher compressive strength can make the substitution rate of metakaolin 16% and that of steel fiber 1.5%. Although the published literature provides some theoretical models and a large amount of experimental data on the compressive performance of fiber-reinforced concrete, there are still considerable reservations about the applicability of these models in design. Stress-strain curve is required for correct design and repair. This article introduces the results of compression tests of steel fiber reinforced concrete carried out in accordance with standard procedures, and rigorously evaluates the proposed model to define compressive stress-strain behavior. The reported test was performed on cylindrical specimens of plain and steel fiber reinforced metakaolin with fiber content of 0.5%, 1.0% and 1.5%. The concrete grade considered in this study is M40.

Keywords. Compressive strength, Metakaolin, Volume fraction, Aspect ratio, Stress-Strain

1. Introduction

The recent trends in research for better suitable and cost-effective materials in construction industry in need of time. Efforts are in progress to use blast furnace slag, fly ash, silica fume to improve the mechanical properties of cement [1].Mineral additives such as ash and silica ash are used which are proven to be an effective means of increasing strength of concrete structures [2]. With the increase in environmental concerns, in recent years, the partial replacement of cement by metakaolin (MK) as an optional supplement has also attracted additional interest [3]. As an additive gelling, MK has the expected pozzolanic properties and can be activated by tricalcium silicate (C3S) and tricalcium aluminate (C3A) [4]. When used as a substitute for cement, MK reacts with Portlandite (Ca(OH)₂) to form an additional CSH gel as a product of hydration of cement, thereby increasing strength. The findings of Khatib et al. [5] showed that the use of MK instead of 20% cement can greatly increase the compressive strength of mortar by 50%. However, as MK replaced more than 30% of cement, the compressive strength began to decline. It was also shown that in ultrasonic testing, samples containing 10% MK substitute showed the best performance. Justice [6] compared the consequences of two differing kinds of metakaolin on fresh concrete properties like concrete workability and setting time. It had been found that metakaolin caused a good reduction in workability, and cement slurry setting time
was reduced by 35-50%. Analysis additionally shows that the utilization of metakaolin will improve hardened properties of concrete like the compressive strength, split tensile and flexural strength and also the concrete modulus of elasticity. Gooneys et al. [7] compared the consequences of utilization of silicon oxide fume and metakolin on the water absorption of concrete. It was found that the water absorption rate of concrete was lower in case of metakaolin additive as compared to additive silica fume.

It has now been determined that the addition of short, discontinuous fibers plays an important role in improving the mechanical properties of concrete. It increases the modulus of elasticity, reduces brittleness, and controls the initiation of cracks and the subsequent expansion and expansion. Debonding and pulling out of the fiber requires more energy absorption, which leads to the material's toughness and fracture resistance to cyclic and dynamic loads. In particular, the unique properties of steel fiber reinforced concrete SFRC show that this material can be used in many structural applications regardless of whether traditional internal reinforcement is used. Therefore, the use of SFRC is particularly suitable for structures subjected to loads exceeding the limit state of the service life under bending and shear conditions, as well as structures under impact or dynamic forces that occur under seismic or cyclic action [8].

Under the seismic and cyclic action, generation of high-performance concrete that withstands bending and shear overload becomes more and more important [9-11]. Extensive research work has shown the importance of fibers in concrete for improving the mechanical properties of concrete (such as compression, tension, bending, impact, fatigue and abrasion strength, deformation capacity, bearing capacity and toughness after cracking, etc.). [12-19]. Adding steel fiber reinforcement can improve the uniformity of concrete. This work involves the combined effect of metakaolin and steel fiber volume fraction (Vf) on the stress-strain behavior. Here, hook-shaped ends with aspect ratio (l/d) of 41.67 are used to bind steel fibers. Concrete specimens for M40 concrete grade, with and without use of metakaolin and in addition 0.5%, 1.0% 1.5% steel fiber were casted. After 28 days of standard curing, a laboratory test was performed to see the stress-strain behavior.

2. Experimental study
According to IS: 10262-1999 [20] and ACI Committee 544 [21] given standards, designed M40 concrete. The mixing ratio of the required performance is (1:1.73:3.22), the W/C ratio is 0.38, and the total binder is 400 Kg/m3. Two different types of aggregates 20mm and 10mm (ratio 60:40) are used as coarse aggregates. Metakaolin is added as a 16% substitute for cement, and steel fiber of length (25 mm) and diameter (0.6 mm) are added. The percentage of fiber is 0%, 0.5%, 1.0% and 1.5% of the concrete volume. Cast a 150x300mm cylinder to study the stress and strain behavior. After being placed for 24 hours, the sample was demoulded and immediately immersed in a water tank for curing for 28 days. Tested according to the guidelines of IS: 516-1959 [22] and ACI 544 [23].

3. Materials used & its properties
Portland Pozzolona Cement Through (IS 1489: 1991) [24] for PPC confirmation. The initial setting time and final setting time of cement were 136 minutes and 210 minutes, respectively, and the 28-day compressive strength was 55.60 N/mm2. Metakaolin, a quality-enhancing pozzolana in the form of an amorphous powder, supplied by 20 Micron Ltd. in Vadodara, Gujarat. The chemical and physical properties of metakaolin and PPC are listed in Table 1. Aggregate According to IS 2386-1963 (I, II and III), the locally available river sand that complies with IS 383 (2016) [25] Zone II is used as fine aggregate and crushed from local quarries with sizes of 20 mm and 10 mm Natural rock) [26] is used as coarse aggregate. Hook-end steel fiber conforming to ASTM A820-2001 with an l/d ratio of 41.67. The ultimate tensile strength of SF (L = 25 mm, D = 0.60 mm) ranges from 910 MPa to 1250 MPa. Water: Fresh tap water conforming to IS: 456-2000 (27), without acid concentration and organic matter, can be used for concrete mixing and curing. In order to obtain additional required performance, the standard IS: 9103-1999 water reducing agent, superplasticizer ViscoFlux-2230 + (specific gravity 1.1) was used to cast all mixture samples.
**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                    |
|                          | L.O.I. | 2.08               | 0.4                     |
|                          | TiO2   | -                  | 2.27                    |
| Physical properties      | Surface area (m2/kg) | 310 | 16800 |
|                          | Specific gravity | 3.12 | 2.6  |

### 4. Test results and discussions

#### 4.1. Workability

By adjusting the amount of superplasticizer to keep the slump between 50 and 70 mm, concrete mixtures can be prepared. Table 2 shows the slump and wet density of the experimental concrete mixtures.

**Table 2.** Slump and wet density of concrete mixtures

| Sample Id | Sample Description                  | Slump (mm) | Wet density (kg/m3) |
|-----------|-------------------------------------|------------|---------------------|
| M1        | Normal concrete                     | 54         | 2528                |
| M2        | 16% Metakaolin                      | 60         | 2563                |
| M3        | 16% Metakaolin with 0.5% Steel fibre| 62         | 2590                |
| M4        | 16% Metakaolin with 1.0% Steel fibre| 64         | 2610                |
| M5        | 16% Metakaolin with 1.5% Steel fibre| 66         | 2643                |

#### 4.2. Compressive strength

Table 3 and Table 4 summarize the 28-day and 90-day strength test results, respectively. These Tables show the compressive strength of each sample, Average compressive strength, standard deviation, and the coefficient of variation are reported. Graphical representation of compressive strength for all samples at 28 days and 90 days of concrete age are shown in the Figure1.
Table 3. Cylinder Compressive Strength at 28 Days age of concrete.

| Sample ID | Compressive Strength (Mpa) | Average (Mpa) | Standard Deviation (Mpa) | Coefficient of Variation (%) |
|-----------|---------------------------|---------------|-------------------------|----------------------------|
| M1-1      | 39.20                     |               |                         |                            |
| M1-2      | 39.45                     | 39.05         | 0.49                    | 1.26                       |
| M1-3      | 38.50                     |               |                         |                            |
| M2-1      | 41.00                     |               |                         |                            |
| M2-2      | 42.10                     | 41.52         | 0.55                    | 1.33                       |
| M2-3      | 41.45                     |               |                         |                            |
| M3-1      | 43.00                     |               |                         |                            |
| M3-2      | 42.00                     | 43.17         | 1.26                    | 2.91                       |
| M3-3      | 44.50                     |               |                         |                            |
| M4-1      | 44.14                     |               |                         |                            |
| M4-2      | 42.16                     | 44.10         | 1.92                    | 4.34                       |
| M4-3      | 45.99                     |               |                         |                            |
| M5-1      | 44.78                     |               |                         |                            |
| M5-2      | 43.25                     | 44.43         | 1.05                    | 2.35                       |
| M5-3      | 45.25                     |               |                         |                            |

Table 4. Cylinder Compressive Strength at 90 Days age of concrete

| Sample ID | Compressive Strength (Mpa) | Average (Mpa) | Standard Deviation (Mpa) | Coefficient of Variation (%) |
|-----------|---------------------------|---------------|-------------------------|----------------------------|
| M1-1      | 43.00                     |               |                         |                            |
| M1-2      | 43.41                     | 43.04         | 0.36                    | 0.83                       |
| M1-3      | 42.70                     |               |                         |                            |
| M2-1      | 45.43                     |               |                         |                            |
| M2-2      | 45.46                     | 45.63         | 0.32                    | 0.70                       |
| M2-3      | 46.00                     |               |                         |                            |
| M3-1      | 47.31                     |               |                         |                            |
| M3-2      | 45.67                     | 47.33         | 1.67                    | 3.52                       |
| M3-3      | 49.00                     |               |                         |                            |
| M4-1      | 49.00                     |               |                         |                            |
| M4-2      | 47.80                     | 48.93         | 1.10                    | 2.25                       |
| M4-3      | 50.00                     |               |                         |                            |
| M5-1      | 48.80                     |               |                         |                            |
| M5-2      | 51.98                     | 49.38         | 2.37                    | 4.80                       |
| M5-3      | 47.35                     |               |                         |                            |
In this experimentation work the compressive test were carried out for normal concrete, concrete with 16 % replacement of MK, concrete with 16 % replacement of MK with 0.5% steel fibre, concrete with 16 % replacement of MK with 1.0% steel fibre and concrete with 16 % replacement of MK with 1.5% steel fibre. Compressive strength was found better at 16% MK replacement with 1.5% steel fibre.

4.3. Stress Strain Relationship

To study the behavior of stress strain the Stress-strain relationship curves are plotted for normal concrete, 16% MK concrete and, 16% MK concrete with 0.5%, 1.0% and 1.5% steel fibres at 28 days are shown in Figure 2. Stress strain curves for 90 days of age are shown in Figure 3.
The discussion based on the above graphical trend, it is observed that in stress strain relationship the higher stress and stain is fond for the model having combination 16% metakaolin and 1.5 % steel fiber while comparing with all the models tested. It is also observed that the peak stress value and corresponding strain value increases due to the addition of metakaolin and metakaolin with steel fibres. Post–peak segment of stress-strain curve is affected very much by the addition of steel fibres. It is observed that for fiber-free concrete, the increase in concrete stress increases the range of the curved part in the ascending branch and causes the descending part to drop at a steep slope. This was a result of its explosive fracture. But less steeper with gradually flatter curved portion can be observed with the addition of Steel fibres. The most significant modification of the deformability of concrete by adding steel fibers in the post peak section. Even the smallest content of fiber ($v_f = 0.5\%$) completely eliminates the explosiveness of concrete damage. After reaching the stress peak, the ability to transfer stress will increase with the increase of fiber content. Therefore, due to the addition of steel fibers, concrete determines part of the stress-strain relationship. When the propagating cracks meet at the route of the fiber, the propagation of the cracks is prevented. However, the concrete may still deform. Evidence of this mechanism isn't always best the process of the stress-strain relationship, however additionally the visible crack pattern on the sample surface.

4.4. Mathematical models

The experimental results were modeled in the form of equations. The coefficient value for all mixes was above 0.98 that shows good polynomial relationship between stress and strain.
Table 5. Stress strain relationship equations at 28 and 90 days age of concrete

| Sample ID | 28 Days Stress strain relationship equations | 90 Days Stress strain relationship equations |
|-----------|---------------------------------------------|---------------------------------------------|
| M1        | $f_{cc} = -1E+07e^2 + 42712e + 0.597$ $R^2 = 0.990$ | $f_{cc} = -1E+07e^2 + 42196e + 0.260$ $R^2 = 0.990$ |
| M2        | $f_{cc} = -1E+07e^2 + 42134e + 0.717$ $R^2 = 0.991$ | $f_{cc} = -1E+07e^2 + 44533e + 0.073$ $R^2 = 0.994$ |
| M3        | $f_{cc} = -9E+06e^2 + 38279e + 1.429$ $R^2 = 0.989$ | $f_{cc} = -9E+06e^2 + 43860e + 0.777$ $R^2 = 0.993$ |
| M4        | $f_{cc} = -9E+06e^2 + 37933e + 1.404$ $R^2 = 0.990$ | $f_{cc} = -9E+06e^2 + 40532e + 0.631$ $R^2 = 0.986$ |
| M5        | $f_{cc} = -8E+06e^2 + 36141e + 2.534$ $R^2 = 0.988$ | $f_{cc} = -9E+06e^2 + 40066e + 2.099$ $R^2 = 0.989$ |

Where $(f_{cc}) =$ Cylinder Compressive strength, $(e) = $ Strain

5. Conclusions

It is found that the workability of metakaolin concrete with steel fiber calculated by volume percentage is reduced. Therefore, it is recommended to use superplasticizers. With the addition of metakaolin and steel fiber, the wet density of all concrete mixtures increases. At 16% replacement percentage of MK with steel fibers 1.5% gives higher strength in case of compressive strength. The curve obtained from the experiment shows that according to the specification, the strain value of MK is greater than 0.0020. As the steel fiber increases, the slope of the descending branch of the stress-strain curve will also increase. The proposed mathematical equation model related to the data has good estimation accuracy. As expected the volume fraction has little impact on the compressive strength of concrete.

6. References

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