Influence of Metakaolin and Manufactured Sand on Fresh and Hardened Properties of Fiber Reinforced Concrete

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***Abstract*: This study examines the influence of metakaolin and manufactured sand on the fresh and hardened properties of fiber reinforced concrete. Metakaolin was used as a partial replacement of cement at different replacement levels, while manufactured sand replaced natural river sand. Steel fibers were incorporated at a constant volume fraction. Workability was evaluated using the slump test, and hardened properties were assessed through compressive, split tensile, flexural, bond, and shear strength tests. The results showed a reduction in workability with increasing metakaolin content; however, adequate workability was achieved using a superplasticizer. Significant improvements in mechanical properties were observed compared to control concrete. The optimum performance was obtained at approximately 30% metakaolin replacement. The enhancement is attributed to the pozzolanic and filler effects of metakaolin, improved particle packing of manufactured sand, and crack-bridging action of steel fibers.**

Keywords: Metakaolin; Manufactured sand; Fiber reinforced concrete; Mechanical properties; Sustainable concrete; Steel fibers

I. Introduction

Over the years, concrete is the most common construction material in the world, as it is versatile and its raw materials are also available, besides the fact that it is relatively cheap. Nevertheless, traditional concrete has some natural constraints in terms of sustainability and performance, which include high cement, extensive emission of carbon dioxide in the manufacturing of cement, low tensile strength, and softness to tensile cracking [1]. As the construction of infrastructures has increased tremendously, the concerns have escalated such that the creation of sustainable and high-performance concrete materials to satisfy the structural requirements at the lowest possible environmental impact is necessary [2].

Supplementary Cementitious Materials (SCMs) is one of the viable methods of enhancing sustainability and performance of concrete. SCMs partly substitute Ordinary Portland Cement (OPC), thus lowering cement content and CO_2 emissions emitted by it and increasing the concrete qualities due to the presence of pozzolanic and filler effects [3]. Ordinary SCMs like fly ash, silica fume, and ground granulated blast furnace slag have been well-researched but metakaolin has received more and more attention because it is very reactive and has a consistent quality.

Metakaolin is a very reactive pozzolanic substance which is derived by calcification of pure kaolinite clay in regulated temperatures. Metakaolin used as a partial replacement of cement reacts with calcium hydroxide that is generated by cement hydration to produce more calcium silicate hydrate (C-S-H) gel. This response causes an increase in the density of the microstructure in order to increase the mechanical strength, the permeability, and the durability [4]. The metakaolin is especially effective in imparting early-age strength when compared to other SCMs because it has high pozzolanicity and fine particle size.

Along with the substitutes of cement, shortage of natural river sand has become one of the significant issues in the concrete production. The over exploitation of the river sand has resulted in environmental degradation, riverbank erosion and regulation restrictions [5]. This has led to manufactured sand (M-sand), which is a hard rock crushed sand, and has become a possible substitute, sustainable. Controlled gradation, enhanced shape of particles and enhanced packing properties are provided by M-sand which can enhance strength and durability of concrete given that it is appropriately proportioned [6].

Although the tensile strength of conventional concrete has been improved with the use of SCMs and other types of fine aggregates, it has a low tensile strength and it fails brittlely. To overcome such inadequacies, Fiber Reinforced Concrete (FRC) has been highly embraced [7]. This is because the addition of steel fibers to concrete enhances post-cracking, tensile, flexural, shear resistance, and energy absorption capacity since the fibers bridge cracks and slow down crack development. The fiber of steel also plays a role in enhancing the nature of the bond and ductility and therefore FRC is used in structural work where toughness and crack containment is of essence [8].

A combination of metakaolin, manufactured sand, and steel fibers is a promising approach that can be used to create sustainable high-strength and high-performance concrete. Metakaolin strengthens the cement matrix with the help of the pozzolanic reactions, M-sand optimizes the particle packing process and decreases the reliance on the natural resources, and steel fibers maximize the mechanical performance of the cement and crack resistance. The synergistic effect of these components can be used to enhance fresh and hardened properties of concrete greatly [9].

Nevertheless, an overview of the available literature shows that there is a gap in research. Though various studies have been done on the metakaolin based concrete and fiber reinforced concrete on a case by case basis, few studies have been done on the fiber reinforced concrete with metakaolin and manufactured sand combined together [10]. Moreover, the majority of the available literature concentrate on low and moderate metakaolin replacement levels, and little research has been conducted on a greater percentage of metakaolin replacement in fiber reinforced concrete structures. This is due to absence of comprehensive experimental data that can lead to the individual and combined effects of such materials on the fresh and hardened concrete properties. In light of the above considerations, the present study aims to:

- Investigate the influence of metakaolin as a partial replacement of cement on the fresh and hardened properties of fiber reinforced concrete.
- Evaluate the effect of replacing natural river sand with manufactured sand in fiber reinforced concrete.
- Examine the combined effects of metakaolin, manufactured sand, and steel fibers on workability, compressive strength, split tensile strength, flexural strength, bond strength, and shear strength.
- Identify suitable replacement levels that result in improved mechanical performance while promoting sustainability in concrete construction.

II. MATERIALS AND METHODS

Figure 1 illustrates the test specimens employed for evaluating the mechanical properties of fiber reinforced concrete.

A. Cement

In all the concrete mixes, use was made of ordinary Portland Cement (OPC) of 53 grade as the main binder. The cement was compliant with the above specifications of IS 12269. To ensure that it was suitable to be used in the high-strength concrete applications, physical characteristics like specific gravity, standard consistency, initial and final setting time, and compressive strength were established beforehand [11].

B. Metakaolin

Supplementary cementitious material was metakaolin which was a partial substitute of cement. It is a very reactive pozzolanic substance and a product of controlled calcination of refined kaolinite clay between temperatures of 600 0 C to 750 0 C. The metakaolin was a commercial source of the product used in this research and was described as having a fine particle size, with a high content of alumina and silica [12]. This was done by evaluating the physical characteristics including specific gravity and fineness, as well as, the chemical composition in order to determine its reactivity as a pozzolan. Metakaolin is used to enhance the strength as well as the microstructural densification since more calcium silicate hydrate (C-S-H) gel forms as a result of pozzolanic reaction.

C. Fine Aggregate

Fine aggregate was applied in two forms in the assessment of the impact on concrete performance:

- Natural Sand: River sand that satisfied Zone II grading according to IS 383 was applied in the control concrete mixes. The sand was clean and did not contain any organic impurities and was analyzed on the characteristics of specific gravity, water absorption, and particle size distribution.
- Manufactured Sand (M-sand): manufactured sand was a sand made out of the natural sand, which was crushed in a hard rock and utilized in its place. M-sand was graded, specific gravity of the sand, water absorption, and fineness modulus were described. Because of its angular shape of particles and gradation, M-sand enhances the process of packing of the particles and it also leads to increased strength when utilized correctly in concrete.

D. Coarse Aggregate

All concrete mixes were made using crushed angular coarse aggregates having nominal maximum size of 20 mm. Specific gravity, water absorption, impact value and grading of the aggregates were done in compliance with IS 383 to provide sufficient strength and durability of the concrete [13].

E. Steel Fibers

Steel fiber was crimped to create fiber reinforced concrete. The fibers were made in accordance with the specifications of ASTM A820 Type I, and were produced using high tensile cold-drawn steel wire. The key parameters of steel fibers considered in this study include:

- **Type:** Crimped steel fibers
- **Geometry:** Uniformly crimped profile to enhance mechanical anchorage
- **Aspect ratio (l/d):** Ratio of fiber length to diameter, selected to ensure effective crack bridging
- **Volume fraction (Vf):** Maintained constant for all fiber reinforced concrete mixes

The inclusion of steel fibers enhances tensile strength, flexural strength, shear resistance, and post-cracking behavior of concrete.

F. Superplasticizer

Sulphonated naphthalene formaldehyde type of super plasticizer was employed to enhance the workability of concrete mixes made of metakaolin and steel fiber. The mix was IS 9103 conforming and it contained a specific gravity of about 1.20. Dosage was adjusted to bring the desired workability and not to increase the water content [14].

G. Water

Concrete was mixed and cured using potable water that was present in the laboratory. The water contained no salts, oils, acids, and organic matter that would make it harmful to the environment and met the requirements required in concrete production [15]. Figure 1 shows some of the test specimens that are used to measure the mechanical properties of fiber reinforced concrete.

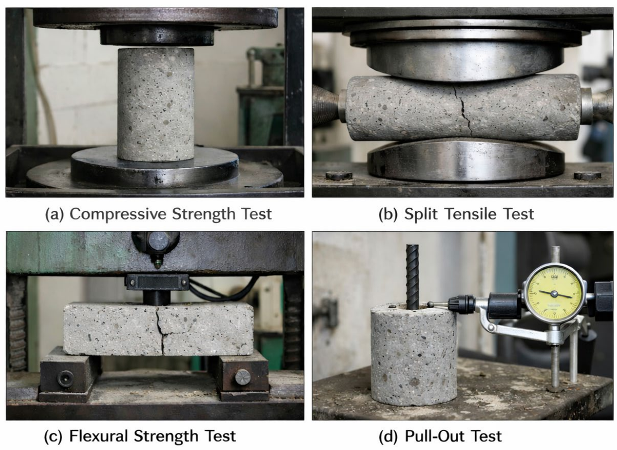

Fig. 1. Test specimens used in this work.

H. Mix Proportions

The concrete mix ratios were developed to create high strength FRC with different contents of metakaolin as the partial replacement of cement and the manufactured sand (M-sand) as the alternative to natural fine aggregate [16]. A control mix using Ordinary Portland Cement and natural river sand was prepared for comparison.

Metakaolin was used as a partial replacement of cement at different replacement levels, while manufactured sand was used to replace natural sand. A constant water–binder ratio was maintained for all mixes to ensure consistency and to isolate the effects of metakaolin and M-sand on concrete properties. Steel fibers were added at a fixed volume fraction to all FRC mixes. A superplasticizer dosage was adjusted to achieve workable concrete without segregation.

All mix proportions were calculated by weight, and the designation of each mix reflects the percentage of metakaolin replacement and the type of fine aggregate used. Assumptions:

- Total binder = **450 kg/m³**
- Water–binder ratio = **0.35**
- Fine aggregate = **650 kg/m³**
- Coarse aggregate = **1200 kg/m³**
- Steel fiber volume fraction V_f = **1.0%**

The details of the mix proportions adopted in the experimental program are presented in Table 1.

TABLE I. DETAILS OF MIX PROPORTIONS FOR CONTROL AND METAKAOLIN-BASED FIBER REINFORCED CONCRETE MIXES

Mix ID	Cement (kg/m³)	Metakaolin (kg/m³)	Fine Aggregate (NS / M-sand)	Coarse Aggregate (kg/m³)	Steel Fibers (% by vol.)	W/B ratio
CC	450	0	NS	1200	0.0	0.35
FRC	450	0	NS	1200	1.0	0.35
MK10-M	405	45	M-sand	1200	1.0	0.35
MK20-M	360	90	M-sand	1200	1.0	0.35
MK30-M	315	135	M-sand	1200	1.0	0.35
MK40-M	270	180	M-sand	1200	1.0	0.35
MK50-M	225	225	M-sand	1200	1.0	0.35

I. Specimen Preparation and Curing

Concrete mixing was carried out using a mechanical mixer to ensure uniform distribution of all constituent materials. Initially, cement, metakaolin, fine aggregate, and coarse aggregate were dry-mixed for approximately two minutes, after which steel fibers were gradually added to the dry mix to prevent fiber balling and to achieve uniform dispersion [17]. This was followed by addition of water with the necessary amount of superplasticizer then the mixing until a uniform concrete mixture was achieved. The fresh concrete was then poured into moulds that were pre-oiled in layers and compacted with the aid of an electrically powered table vibrator to remove air voids and provide proper compaction without segregating and over-vibrating it. The specimens were then compacted before they were finished with a steel trowel on the top surfaces giving a smooth and uniform surface [18].

The specimens cast were left to dry at room temperature and after 24 hrs, they were demoulded and allowed to cure in clean water at the laboratory under the given conditions till the testing ages. Evaluation of fresh and hardened concrete properties was done by using standard curing periods of 7 and 28 days. Concrete samples of the right size were set to undergo compressive strength, split tensile strength, flexural strength, bond strength and shear strength. To achieve accuracy and reliability in the experimental results, three same specimens were cast and tested in every mix and test category and the mean value was reported [19].

III. EXPERIMENTAL PROGRAM AND RESULTS

A. Fresh Properties of Concrete

Slump test was used to determine the workability of fresh concrete. Table 2 below presents the obtained results of various mixes. It was noted that slump value reduced along with the rise in metakaolin replacement as well as steel fibers. The decrease in workability is explained by smaller particle size and a larger surface area of metakaolin, angularity of manufactured sand, and the presence of steel fibers, which increases the internal friction. All mixes with superplasticizer were made to have workable concrete even after the reduction.

TABLE II. SLUMP VALUES OF FIBER REINFORCED CONCRETE MIXES

Mix ID	Slump (mm)
CC	95
FRC	80
MK10-M	75
MK20-M	68
MK30-M	60
MK40-M	52
MK50-M	45

B. Hardened Properties of Concrete

The compressive strength tests were carried out at 7 and 28 days. Table 3 summarizes the results. Metakaolin replacement increased the compressive strength till 30-40, after which a slight decrease was recorded. This enhancement has mostly been brought about by pozzolanic reaction and filler effect of metakaolin that result in a denser cement matrix [20].

TABLE III. COMPRESSIVE STRENGTH OF CONCRETE MIXES

Mix ID	7 Days (MPa)	28 Days (MPa)
CC	38.5	52.0
FRC	40.2	55.6
MK10-M	43.8	60.4
MK20-M	46.9	64.8
MK30-M	49.5	68.2
MK40-M	48.1	66.5
MK50-M	45.0	62.3

Table 4 shows the split tensile strength at 28 days. Concrete mixtures that contained fiber reinforced concrete showed a high tensile strength as compared to plain concrete.

This is due to the effective crack bridging and stress transfer as a result of the steel fibers.

TABLE IV. SPLIT TENSILE STRENGTH OF CONCRETE MIXES

Mix ID	Split Tensile Strength (MPa)
CC	3.8
FRC	4.5
MK10-M	4.9
MK20-M	5.3
MK30-M	5.7
MK40-M	5.5
MK50-M	5.1

Table 5 displays flexural strength results obtained using beam tests. The addition of steel fibers led to the increase in flexural capacity and the post-cracking behavior. The best performance was noted in mixes of 3040% metakaolin replacement.

TABLE V. FLEXURAL STRENGTH OF CONCRETE MIXES

Mix ID	Flexural Strength (MPa)
CC	5.6
FRC	6.8
MK10-M	7.4
MK20-M	8.1
MK30-M	8.7
MK40-M	8.4
MK50-M	7.9

The obtained bond strength results of pull-out tests are discussed in Table 6. The confinement by fibers and the increase of the densification of the matrix caused by the metakaolin led to the better bond strength of fiber reinforced concrete mixes [21].

Table 7 summarizes the results of the shear strength determined with the use of push-off specimens. According to the results, the shear resistance of fiber reinforced mixes has significantly improved as well as the mixes using metakaolin and manufactured sand.

TABLE VI. BOND STRENGTH OF CONCRETE MIXES

Mix ID	Bond Strength (MPa)
CC	6.2
FRC	7.1
MK10-M	7.6
MK20-M	8.3
MK30-M	8.9
MK40-M	8.6
MK50-M	8.0

TABLE VII. SHEAR STRENGTH OF CONCRETE MIXES

Mix ID	Shear Strength (MPa)
CC	4.8
FRC	5.9
MK10-M	6.4
MK20-M	6.9
MK30-M	7.4
MK40-M	7.2
MK50-M	6.8

IV. COMPARATIVE ANALYSIS

All of the concrete mixes are compared in terms of the performance with references to the CC and plain FRC. Table 3 above shows that addition of steel fibers alone FRC led to a significant increase in compressive strength in comparison to CC, which emphasizes the positive effect of fibers in apprehending microcracks and improving load transfer [21].

Additional strength improvement was seen as metakaolin and manufactured sand were added. Figure 2 shows that there was a positive correlation between compressive strength 28 days and the amount of metakaolin replaced. Compressive strength was rising gradually until 30 percent metakaolin replacement (MK30-M) where it was slightly decreasing. The trend is in line with the findings reported in Table 3, which authenticate the fact that MK30-M had the highest compressive strength of all mixes.

The same case was seen in split tensile and flexural strengths. Table 4 and Table 5 indicated that fiber reinforced mixes, including the metakaolin and M-sand mixes, had much higher tensile and flexural strengths than the CC and FRC mixes. The increase is stronger to 30-40% replacement of metakaolin, and then the strength increases slightly slower. This can also be attributed to the fact that the Portland cement has less availability to be used to hydration at elevated replacement levels.

The higher results of metakaolin-based FRC mixes are further confirmed by bond and shear strength results (Tables 6 and 7). Figure 3 illustrates the change of shear strength of the individual mixes, which implies that metakaolin and fiber-modified concretes have a stronger shear strength. Among all mixes, MK30-M demonstrated the most balanced performance across all strength parameters and is therefore identified as the optimum mix in the present study [22].

The observed results are in good agreement with previous studies, which reported improved mechanical properties due to the pozzolanic activity of metakaolin and crack-bridging action of steel fibers. Nevertheless, the majority of previous studies were concentrated on the lower levels of metakaolin substitution. The current paper develops previous research by providing proof that greater replacement level can be successfully employed in fiber reinforced concrete supplemented by manufactured sand thus providing more experimental data.

A. Discussion on Mechanism

It is possible to attribute the enhancement of concrete performance in this case to the synergistic effect of metakaolin, manufactured sand, and steel fibers. The leading role is played by the pozzolanic reaction of metakaolin that reacts with the calcium hydroxide that is liberated throughout the hydration of cement to produce more calcium silicate hydrate (C 4 S 4 H) gel. This C-S-H formation is the secondary and causes matrix densification which is manifested in the high compressive and bond strength in Table 3 and Table 6. Metakaolin also has a strong filler effect with its ultrafine particle size besides contributing its chemical effect. These fine particles fill up micro-voids in the cement paste and in the interfacial transition zone leading to refinement of pore and low porosity. This smooth microstructure makes it stronger and stiffer especially in the middle replacement levels as shown in Figure 2.

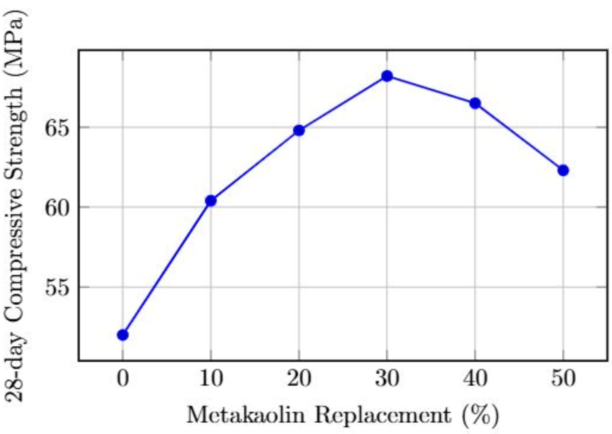

Fig. 2. Variation of 28-day compressive strength with metakaolin replacement

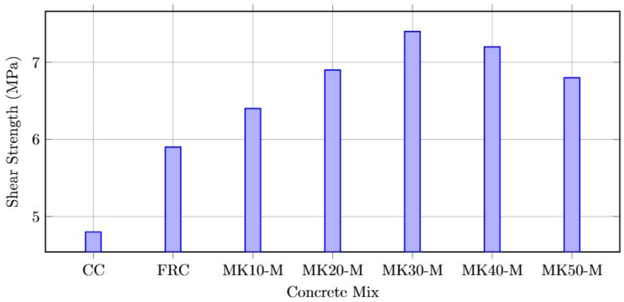

Fig. 3. Shear strength comparison of control and metakaolin-based FRC mixes

The use of manufactured sand (M-sand) mainly applies to better particle packing and mechanical interlocking. Angular form and uneven texture of surface of M-sand particles help in enhancing transfer of loads in the concrete matrix which enhances compressive, tensile, and shear strengths. M-sand can be used with metakaolin to create a high-grade and high-density composite matrix.

Steel fibers provide the post-cracking response of concrete with significant effects with the help of crack bridging and stress transfer. Fibers inhibit crack propagation, re-distribute tensile stresses, and increase the ability to absorb energy. This is evidently expressed in split tensile, flexural, bond, and shear strengths which were recorded as better in Tables 4 7. The overall performance of these mechanisms can be attributed to the high and balanced performance of the metakaolin-based fiber reinforced concrete as was witnessed in the current study.

V. CONCLUSIONS

This study investigated the influence of metakaolin and manufactured sand on the fresh and hardened properties of fiber reinforced concrete. The experimental results demonstrated that the incorporation of metakaolin as a partial replacement of cement, along with manufactured sand as a replacement for natural fine aggregate, significantly enhances the mechanical performance of fiber reinforced concrete. While the workability of concrete decreased with increasing metakaolin content and fiber inclusion, satisfactory workability was achieved through the use of superplasticizer. The hardened property results revealed notable improvements in compressive, split tensile, flexural, bond, and shear strengths for metakaolin-based fiber reinforced concrete compared to control and conventional fiber reinforced mixes.

Enhancement of strength was noted to high degrees of metakaolin replacement up to moderate and high levels where there was slight decline as a result of low cementitious content. The concrete with the most balanced performance and the one that was found to be the best mix had an approximation of 30% metakaolin and manufactured sand. The enhancement in performance was explained by combined activities of pozzolanic reaction and filler activity of metakaolin, better packing of particles through manufactured sand and the successful crack bridging and stress transfer through steel fibers. All in all, the findings substantiate that the combination of metakaolin, manufactured sand, and steel fibers be used as a viable and sustainable method to produce high strength fiber reinforced concrete that can be used in structural applications.

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