Effect of High-Volume Metakaolin Replacement on the Performance of Fibre Reinforced Concrete with Manufactured Sand

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***Abstract*: This study investigates the effect of high-volume metakaolin replacement on the performance of fibre reinforced concrete incorporating manufactured sand. Concrete mixes were prepared with varying metakaolin replacement levels while maintaining constant fibre dosage and water–binder ratio. Fresh concrete properties were evaluated through workability and slump loss tests, whereas hardened properties were assessed using compressive, split tensile, flexural, bond, and shear strength tests. The results indicated that workability decreased with increasing metakaolin content; however, satisfactory performance was achieved using a superplasticizer. Mechanical properties improved significantly up to an optimum replacement level of 20% metakaolin, beyond which marginal reductions were observed. Fibre reinforcement effectively enhanced crack resistance and load transfer, compensating for strength loss at higher replacement levels. Overall, the combined use of metakaolin, manufactured sand, and steel fibres provides a sustainable and structurally efficient concrete solution.**

Keywords: Metakaolin; Fibre reinforced concrete; Manufactured sand; High-volume cement replacement; Mechanical properties; Sustainable concrete

I. INTRODUCTION

Fibre reinforced concrete (FRC) has proved to be a proper structural material because it has enhanced tensile resistance, crack resistance, ductility, and post-cracking behaviour than the conventional concrete. Addition of discrete steel fibres improves the load transfer mechanisms and energy absorption to make FRC applicable in applications where there are flexural, shear, and impact loads [13]. Nevertheless, the quality of cementitious matrix and interfacial bond between fibre and concrete is the key factor affecting the performance of FRC.

High energy consumption and emission of carbon dioxide which is of great significance during production of Ordinary Portland Cement, has been a serious environmental concern increasing the demand of the latter. To overcome these issues, many supplementary cementitious materials (SCMs) like metakaolin have been explored widely as partial substitutes of cement [4–6]. Metakaolin is a very active pozzolanic substance that is the result of the kaolinitic clay that is calcined under controlled temperatures. It reacts with calcium hydroxide emitted during the hydration of cement to produce more calcium silicate hydrate (C-S-H) which increases the strength of concrete, decreases porosity and improves the concrete durability [7-9].

Some researches have indicated that metakaolin enhances the mechanical properties of concrete especially when used in replacement of up to 15 percent. As noted by Dinkar et al. [1], the perfect compressive strength was obtained when the replacement level was 10 percent, with replacement levels of above that level leading to lower strength. Sabir et al. [9] noted that metakaolin enhances the pore structure and resistance to ingressive harmful ions. It was shown by Guneyisi et al. [2] that the use of steel fibre and metakaolin combined was very effective in increasing compressive, flexural, and bond strengths of concrete. Likewise, Bhalchandra and Shirale [3] reported improvement that was observed when fibres are used to enhance the strength properties of metakaolin concrete.

Besides cement substitution, depletion of natural river sand has made the replacement with manufactured sand (M-sand) to be a sustainable alternative fine aggregate. Manufactured sand has a controlled grading, better shape of the particles as well as better packing density which can have a positive impact on the concrete strength and durability provided it has the right proportion [10,11]. Past studies have demonstrated that concrete that uses manufactured sand has the ability to perform equal or better results compared to natural sand concrete.

- Although the study of metakaolin and fibres has been intensively researched, and the research on manufactured sand has been conducted extensively, research has not been done on the joint effect of metakaolin and fibre reinforced concrete. Specifically, the behaviour of high-volume metakaolin replacement in fibre reinforced concrete using manufactured sand has not been investigated well with most of the available studies establishing moderate metakaolin replacement levels. In addition, little has been done in bond and shear behaviour, which are important in structural applications. The proposed study will fill these gaps by experimentally assessing fresh and hardened properties, and structural performance of fibre reinforced concrete, with high volume metakaolin replacement and manufactured sand. The significant findings of this study are as follows:
- An experimental investigation is carried out on fibre reinforced concrete incorporating high-volume metakaolin replacement, extending beyond the commonly studied moderate replacement levels.
- The combined influence of metakaolin and manufactured sand on the fresh and hardened properties of fibre reinforced concrete is systematically evaluated.
- The study examines not only conventional strength parameters but also bond strength and shear behaviour, which are less explored in metakaolin-based fibre reinforced concrete.

- The role of steel fibres in compensating for strength reduction at higher metakaolin replacement levels is experimentally demonstrated.
- An optimum range of metakaolin replacement is identified based on mechanical and structural performance, providing practical guidance for sustainable and high-performance concrete applications.

II. Materials and Methods

A. Materials

1) Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 was used as the primary cementitious material in this study. Physical properties like standard consistency, initial and final setting time, and compressive strength were tested on the cement in conformity with the applicable Indian Standards. The reason behind choosing OPC 53 grade was to reduce the lack of early-age strength development especially when substitution of cement with supplementary cementitious material on large volumes is adopted [12].

2) Metakaolin

Metakaolin was used as a partial replacement for cement. It is an extremely reactive pozzolanic substance that is produced as a result of controlled calcination of refined kaolinitic clay by temperatures that vary between 600 C and 750 C. The presence of silica and alumina in metakaolin make it more pozzolanic, and thus, calcium hydroxide is used and forms other calcium silicate hydrate (C–S–H) gel. It results in densification of the matrix, increased strength, and creation of durability properties of concrete [1315].

3) Manufactured Sand

Manufactured sand (M-sand) was used as a replacement for natural river sand. It was obtained through crushing of hard granite rock and refined to attain appropriate grading. The physical characteristics of manufactured sand including the specific gravity, water absorption, and particle size distribution were identified before use. The manufactured sand has enhanced interlocking of the particles and controlled grading which are contributing factors to the enhanced strength and elimination of reliance to the natural sand resources [16], [17].

4) Coarse Aggregate

Crushed angular coarse aggregates of nominal maximum size 20 mm were used in the concrete mixes. The aggregates were analyzed in regard to specific gravity, water absorption and gradation according to the applicable IS requirements. Angular coarse aggregates were used to increase the mechanical interlock and load carrying capacity of the fibre reinforced concrete [12].

5) Steel Fibres

Crimped steel fibres conforming to ASTM A820 Type I were used in this investigation. The fibres were made out of high tensile cold-drawn steel wire. Having crimped steel fibres can be used to boost tensile strength, crack resistance and post-cracking ductility due to the presence of useful crack-bridging effects of the fibres, and the better energy absorption capacity [14], [18].

6) Superplasticizer

A sulphonated naphthalene formaldehyde (SNF)-based high-range water-reducing admixture was used to improve the workability of concrete mixes containing metakaolin and steel fibres. The superplasticizer is based on IS 9103 and the content was incorporated in the correct proportions to ensure that the workability desired was not compromised by adding more water to the binder ratio. The chemical admixtures are imperative in the metakaolin-based concretes because the metakaolin is very fine and requires a lot of water [15], [19].

7) Water

Potable water free from impurities was used for mixing and curing of concrete. The water used satisfied the requirements specified in IS 456, ensuring that it did not adversely affect the hydration process or the durability of concrete [12].

B. Mix Proportions

Concrete mixes were designed for high-strength fibre reinforced concrete with varying levels of metakaolin replacement. A control mix without metakaolin and steel fibres was prepared for comparison. Cement was partially replaced with metakaolin at different replacement levels, including high-volume replacement, while maintaining a constant water-to-binder ratio across all mixes. Different metakaolin replacement levels and fibre dosages considered in this investigation are shown in Fig. 1.

Fig. 1. Mix proportions and material constituents for different metakaolin replacement levels.

Manufactured sand was used consistently as the fine aggregate in all mixes to isolate the effect of metakaolin replacement. The volume fraction of steel fibres was kept constant to determine their effects on the mechanical and structural performance. The fibre aspect ratio was chosen to make sure that the cracks are bridged and the dispersion of the fibres is even throughout the concrete matrix. Finalisation of mix proportions was done on trial mixes to get sufficient workability and even distribution of fibres [13], [18].

C. Specimen Preparation and Curing

1) Mixing Procedure

Mixing of concrete was done by the use of a mechanical mixer in order to distribute all the constituents uniformly. First, cement, metakaolin, manufactured sand were dry mixed to become homogenous. Gradually, the dry mix was then added with steel fibres to avoid balling. A slow addition of water and the necessary dosage of superplasticizer was done and it was mixed until an even and workable concrete mix was achieved [14], [19].

2) Casting and Compaction

Fresh concrete was placed into pre-cleaned and oiled moulds in layers. Each layer was compacted using an electrically operated table vibrator to remove entrapped air and ensure proper compaction. Care was taken to avoid segregation and fibre alignment during compaction. The top surface of the specimens was finished using a trowel to obtain a smooth and level surface [12].

3) Curing Regime

After casting, the specimens were covered to prevent moisture loss and demoulded after 24 h. The demoulded specimens were cured in potable water at room temperature until the time of testing. All specimens were tested at specified curing ages to evaluate the influence of metakaolin replacement and fibre reinforcement on the fresh and hardened properties of concrete [15], [17]. The specimen preparation and curing procedure adopted in the present study is shown in Fig. 2.

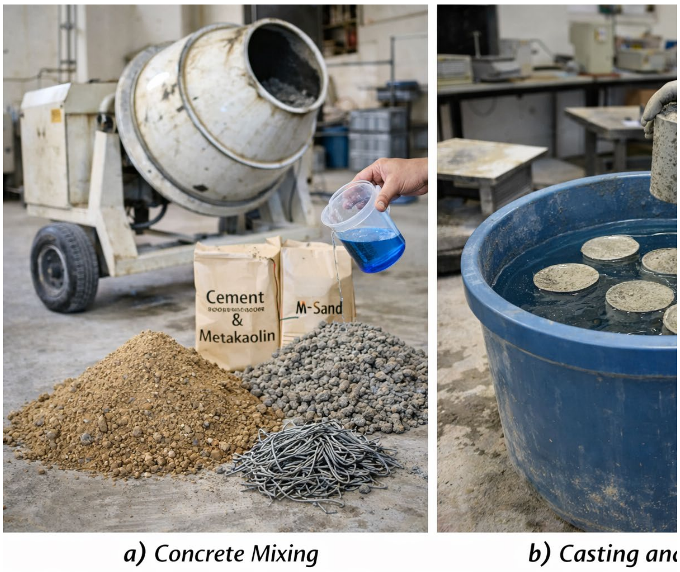

Fig. 2. Specimen preparation and curing: (a) concrete mixing, (b) casting and water curing.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Fresh Concrete Properties

The workability characteristics of fibre reinforced concrete mixes incorporating different levels of metakaolin are presented in Table 4.1. As shown in Table 1, the initial slump value decreased progressively with an increase in metakaolin replacement. The control mix exhibited the highest slump, whereas the MK40 mix showed the lowest workability.

The data on the higher percentage of slump loss with high amounts of metakaolin in Table 1 may be explained by the fact that the metakaolin particles have high fineness and large surface area which is more demanding of water. The introduction of steel fibres also helped to decrease slump because of a higher level of friction and contact between the fibre and the aggregate. Even though there was a decline in workability, all mixes fell within acceptable range of fibre reinforced concrete in the event that an appropriate dosage of superplasticizer was taken.

TABLE I. SLUMP AND SLUMP LOSS OF FIBRE REINFORCED CONCRETE MIXES

Mix ID	Metakaolin (%)	Initial Slump (mm)	Slump Loss (%)
Control	0	90	6.5
MK10	10	85	9.2
MK20	20	78	12.6
MK30	30	70	16.8
MK40	40	62	21.4

B. Compressive Strength

The compressive strength results of all concrete mixes are summarized in Table 2. It is evident that compressive strength increased significantly with metakaolin replacement up to 20%, beyond which a marginal reduction was observed.

TABLE II. COMPRESSIVE STRENGTH OF CONCRETE MIXES

Mix ID	Metakaolin (%)	Compressive Strength (MPa)
Control	0	42.5
MK10	10	48.3
MK20	20	51.6
MK30	30	49.2
MK40	40	45.7

The maximum compressive strength has been seen in the MK20 mix meaning that there is an optimal replacement level. The benefits of the strength increase at the moderate levels of replacement are much explained by the pozzolanic reaction between metakaolin and filler effect which makes the cementing matrix more dense and enhances the interfacial transition zone. At the increased replacement (MK30 and MK40), the strength diminishes, which can be explained by the dilution of the cementitious material and the consequent limitation of primary hydration products. The tendency of compressive strength variation verses metakaolin content is well illustrated in Fig. 3 which validates the fact that there is optimum replacement range.

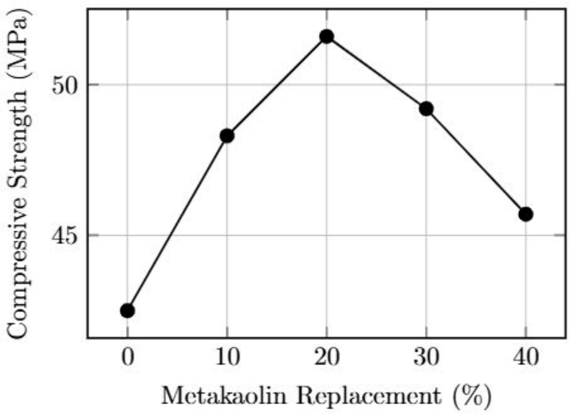

Fig. 3. Variation of compressive strength with metakaolin replacement

C. Split Tensile Strength

The results of the split tensile strengths are given in Table 3. The results in Table 3 indicate that all the mixes of metakaolin based fibre reinforced concrete depicted a greater tensile strength than the control mix. This has been achieved through the split tensile strength improvement caused by crack-bridging effect of the steel fibres and enhanced densification of the matrix by addition of metakaolin. The MK20 was the highest split tensile strength mix as compared to the compressive strength findings. Above this point, there was a slight decline in replacement percentages on higher percentages but the figures were higher than the control mix.

TABLE III. SPLIT TENSILE STRENGTH OF CONCRETE MIXES

Mix ID	Metakaolin (%)	Split Tensile Strength (MPa)
Control	0	3.4
MK10	10	3.9
MK20	20	4.3
MK30	30	4.1
MK40	40	3.7

D. Flexural Strength

The obtained results of flexural strength tests with a two-point load are summarized in Table 4. The Table 4 results show that flexural strength of fibre reinforced mixes with metakaolin is significantly improved over those of conventional concrete.

TABLE IV. FLEXURAL STRENGTH OF FIBRE REINFORCED CONCRETE

Mix ID	Metakaolin (%)	Flexural Strength (MPa)
Control	0	4.8
MK10	10	5.6
MK20	20	6.2
MK30	30	6.0
MK40	40	5.3

This improvement in flexural strength may be explained by the efficient transfer of stress across cracks by steel fibre and better bonding in the cementitious matrix. MK20 mix had the highest flexural strength with a slight decrease in MK30 and MK40 mixes following the same trend as compressive and tensile strength results.

E. Bond Strength (Pull-Out Test)

Results of bond strength tests are given in Table 5. Table 5 clearly shows that the addition of metakaolin greatly helped in increasing the bond strength between steel reinforcement and concrete. It is explained by the fact that the refinement of the interfacial transition zone with the help of metakaolin and reinforcement and the surrounding concrete interlocking increases the bond performance. The MK20 mix showed the best bond strength meaning to have better stress transfer ability. Marginal decrease in bond strength was recorded at higher replacement levels though the values were still better than the control mix.

TABLE V. BOND STRENGTH OF CONCRETE MIXES

Mix ID	Metakaolin (%)	Bond Strength (MPa)
Control	0	6.2
MK10	10	7.1
MK20	20	7.8
MK30	30	7.5
MK40	40	6.8

F. Shear Strength (Push-Off Test)

The table of results of push-off tests of shear strength is presented in Table 6. Table 6 indicates that the fibre reinforced concrete mixes with metakaolin had a higher shear strength as compared to the control mix. The improvement in shear strength is explained by a concerted effect of steel fibres that limit the expansion of cracks in the shear plane and metakaolin, which improves the strength of the matrix and interfacial bonding. MK20 mix demonstrated maximum shear strength with those having higher levels of replacement being slightly lower because of less cementitious content.

TABLE VI. SHEAR STRENGTH OF FIBRE REINFORCED CONCRETE

Mix ID	Metakaolin (%)	Shear Strength (MPa)
Control	0	5.6
MK10	10	6.4
MK20	2020	7.1
MK30	30	6.8
MK40	40	6.1

The analysis of every outcome of the tests through comparative evaluation reveals that moderate substitution of cement with metakaolin by a substantial margin improves the fresh and hardened characteristic of fibre reinforced concrete. The MK20 mix offered the best performance, as always witnessed in, compressive tensile flexural bond, and shear strength.

Even though increased replacement levels caused diminished workability and slight decrease in the strength, the existence of steel fibre effectively alleviated the consequences by enhancing tensile and post-cracking behaviour. These findings show that fibre reinforced concrete using manufactured sand and metakaolin can be practically employed in structural applications with the best replacement range.

G. Comparative Discussion

An evaluation was conducted to compare the performance of the fibre reinforced concrete mixes using metakaolin to the control concrete. The change in the main mechanical properties (as a percentage) of the control mix was computed to give a clear measure of the influence of metakaolin substitution.

All metakaolin-based fibre reinforced concrete mixes (Table 7) showed a high level of mechanical performance in comparison with the control mix at a replacement level of up to 20%. The MK20 mixture depicted the highest improvements in compressive, split tensile, flexural, bond and shear strengths. This is possible through the synergistic action of pozzolanic reaction, filler action through metakaolin and crack-bridging capacity of steel fibres.

TABLE VII. PERCENTAGE CHANGE IN MECHANICAL PROPERTIES WITH RESPECT TO CONTROL CONCRETE

Mix ID	CS (%)	STS (%)	FS (%)	BS (%)	SS (%)
MK10	+13.6	+14.7	+16.7	+14.5	+14.3
MK20	+21.4	+26.5	+29.2	+25.8	+26.8
MK30	+15.8	+20.6	+25.0	+21.0	+21.4
MK40	+7.5	+8.8	+10.4	+9.7	+8.9

In addition to the point of replacement greater than 20 percent, the marginal strength decrease was recorded in mixes of MK30 and MK40 but their performance was better than control concrete. This implies that fibre reinforcement is effective to overcome the dilution effect of high-volume metakaolin replacement.

The current trends that were observed in the study (Fig. 4) are in line with those observed by previous studies. Past research has demonstrated that replacement level of metakaolin (10-20 percent) increases compressive and tensile strength as a result of the improvement of hydration kinetics and pore refinement. Likewise optimum replacement rates were reported in high performance concrete based on metakaolin and fibre reinforced concrete systems.

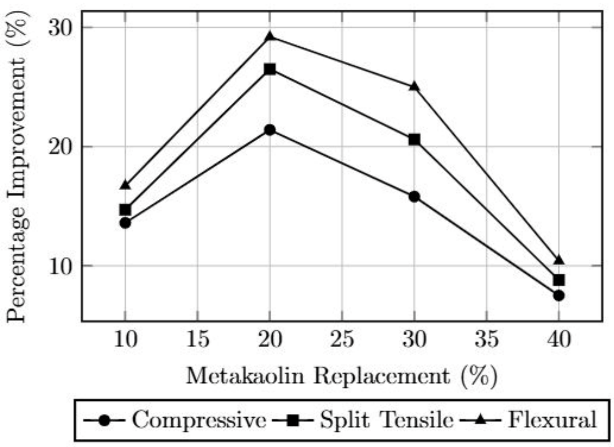

Fig. 4. Comparative improvement in strength properties relative to control concrete

This loss of strength at elevated replacement levels has also been found in agreement with the earlier studies whose results are explained by decreased access to calcium hydroxide, and erosion of cementitious phases at high metakaolin content. Nevertheless, the current study reduced this decrease due to the steel fibre content that increased tensile resistance, bond behaviour and shear capacity, which previously was not a major concern in previous research on plain concrete.

IV. CONCLUSIONS

This study examined the effect of high-volume metakaolin replacement on fibre reinforced concrete incorporating manufactured sand through a comprehensive experimental program. The results indicated that increasing metakaolin content reduced workability due to its high fineness; however, acceptable fresh concrete properties were maintained using an appropriate superplasticizer. Mechanical performance improved significantly with metakaolin replacement up to an optimum level, with the mix containing 20% metakaolin exhibiting the highest compressive, split tensile, flexural, bond, and shear strengths. These enhancements are attributed to the pozzolanic reaction and filler effect of metakaolin, which densified the concrete matrix and improved interfacial bonding.

Higher replacement level showed a marginal decrease in strength as a result of cement dilution; however, the existence of steel fibre practically overcame decrease by means of strengthening the tensile resistance, crack management, and mechanisms of load transfer. All in all fibre reinforced concrete with metakaolin and manufactured sand performed better than the control concrete in all performance indicators which proves that a moderate replacement of 20 percent by metakaolin provides a balance in performance of concrete in strength, structural and sustainability, and higher replacement levels can be considered as the possibilities of eco-efficient construction application.

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