

Metakaolin –A Partial Replacement of Cement in Concrete as Admixture

G. Ganesh*

Department of Civil Engineering, M.V.R. College of Engineering & Technology. Andhra Pradesh-521180

*Corresponding author email ID: ganeshgoddilla110@gmail.com

HIGHLIGHTS

- 10% metakaolin gives maximum strength across all tests.
- Workability decreases as metakaolin content increases.
- 10% is the optimum replacement level for best performance.

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ABSTRACT

The use of supplementary cementitious materials has become an important approach for improving the performance and sustainability of concrete. Among these materials, metakaolin – produced by controlled calcination of kaolin clay – offers high pozzolanic reactivity and the potential to enhance strength and durability. This study evaluates the influence of metakaolin as a partial replacement for ordinary Portland cement in M25 concrete. Replacement levels of 5%, 10%, 15%, and 20% were tested to determine their effects on workability and mechanical properties. Concrete specimens were prepared and subjected to slump and compaction factor tests in the fresh state, followed by compressive, split tensile, and flexural strength tests at 3, 7, and 28 days. Workability was found to decrease slightly with increasing metakaolin content, though all mixes remained workable. The mechanical test results showed a clear improvement in strength for mixes containing metakaolin, with the 10% replacement level providing the highest enhancement across all strength parameters. This improvement is attributed to the pozzolanic reaction, which reduces calcium hydroxide and forms additional C-S-H gel, resulting in a denser and stronger microstructure. Based on the findings, metakaolin can be considered an effective mineral admixture for producing stronger and more durable concrete. The study identifies 10% replacement as the optimum level for achieving maximum performance benefits while maintaining acceptable workability.

1 INTRODUCTION

Concrete is the most widely used construction material due to its high compressive strength, ease of mouldability, and suitability for diverse structural applications. However, conventional concrete is limited by its low tensile strength, vulnerability to microcracking, and reduced durability when exposed to aggressive environments. The hydration of

ordinary Portland cement (OPC) produces calcium hydroxide, a compound that contributes little to strength and may compromise long-term durability. Additionally, the production of OPC is energy-intensive and responsible for substantial CO₂ emissions, prompting the need for alternative and more sustainable construction materials (Hewlett, 1998; Lea, 1970). Global infrastructure demands

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and environmental concerns have intensified the search for materials that both improve performance and reduce environmental impact. Sustainable approaches in concrete production often involve lowering cement content and enhancing durability, thereby extending service life and reducing lifecycle costs. The partial replacement of cement with reactive mineral additives has emerged as an effective method to reduce permeability, mitigate chemical deterioration, and refine microstructure (Malhotra, 1983; Kosmatka, 1999).

Supplementary cementitious materials (SCMs) such as fly ash, silica fume, slag, and natural pozzolans have been widely studied for their ability to improve concrete properties. Their pozzolanic reaction with calcium hydroxide results in the formation of additional calcium silicate hydrate (C-S-H), which contributes to increased strength and reduced porosity. The beneficial effects of SCMs on durability, early-age strength, and microstructural densification have been documented extensively (Malhotra, 1986; Jiping & Gailius, 2009).

Metakaolin—produced by calcining kaolinite at controlled temperatures—has emerged as a highly reactive pozzolan offering superior performance compared with many traditional SCMs. Its finely divided aluminosilicate structure enables rapid reaction with calcium hydroxide, producing additional C-S-H and calcium aluminate hydrates. Prior research has demonstrated that metakaolin improves compressive strength, tensile strength, and resistance to chemical attack, while also reducing permeability (Ambroise et al., 1985; Dunster et al., 1999; Frias & Cabrera, 2000). Because metakaolin is an engineered material rather than an industrial by-product, its consistency and high purity provide reliable performance improvements, making it a promising candidate for high-performance, durable, and sustainable concrete.

The principal objective of this study is to investigate the effects of metakaolin as a partial replacement for ordinary Portland cement on the workability and mechanical performance of M25 grade concrete. Drawing upon earlier research that highlights the significant pozzolanic activity and performance benefits of metakaolin, this study evaluates replacement levels of 5%, 10%, 15%, and 20% to determine the optimum proportion that maximizes compressive, tensile, and flexural strength while maintaining acceptable fresh concrete properties. Through a systematic experimental programme, the study aims to assess whether metakaolin can function

as a reliable and sustainable supplementary cementitious material for enhancing concrete durability and overall structural performance.

2 MATERIAL AND METHODS

This study follows an experimental research design aimed at evaluating the influence of metakaolin as a partial replacement for ordinary Portland cement (OPC) on the fresh and hardened properties of M25 grade concrete. Four replacement levels—5%, 10%, 15%, and 20% by weight of cement—were selected based on previous literature indicating effective pozzolanic activity within this range (Ambroise et al., 1985; Frias & Cabrera, 2000). A control mix with 0% metakaolin was prepared for comparison. The pavement models used solid hexahedral elements with 8-point integration and quadratic shape functions for accurate strain and displacement estimation. Mesh refinement was applied in loaded areas with a minimum size of 20 mm, gradually coarsening to 40 mm near boundaries. All materials were assumed homogeneous, isotropic, and linearly elastic, except the sand-filled joints between blocks. These joints were modelled with elastic-plastic behaviour to capture nonlinear load transfer and interlocking effects, providing a realistic representation of the block pavement system under traffic loads.

2.1 Research Design

This study follows an experimental research design aimed at evaluating the influence of metakaolin as a partial replacement for ordinary Portland cement (OPC) on the fresh and hardened properties of M25 grade concrete. Four replacement levels—5%, 10%, 15%, and 20% by weight of cement—were selected based on previous literature indicating effective pozzolanic activity within this range (Ambroise et al., 1985; Frias & Cabrera, 2000). A control mix with 0% metakaolin was prepared for comparison.

2.2 Materials

2.2.1 Cement

Ordinary Portland Cement (OPC) of 53 Grade conforming to IS 12269:1987 was used. The cement was fresh, free of lumps and stored under dry conditions. Standard tests—including fineness, standard consistency, initial and final setting times, and specific gravity—were conducted to ensure compliance with IS specifications.

2.2.2 Metakaolin

Commercially manufactured metakaolin with high aluminosilicate purity was used as a cement replacement material. Its physical properties (specific

gravity, fineness, and colour) and chemical composition (SiO_2 , Al_2O_3 , Fe_2O_3 content) were verified as per IS 3812 (Part 1):2003. The metakaolin used was off-white and highly reactive.

2.2.3 Fine Aggregates

Locally available river sand conforming to Zone III grading under IS 383:2016 was used. Specific gravity, bulk density, and fineness modulus were determined as per IS 2386 (Part I & III).

2.2.4 Coarse Aggregates

Crushed angular aggregates of maximum nominal size 20 mm, conforming to IS 383:2016, were used. Aggregate impact value, crushing value, abrasion value, and specific gravity were tested according to IS 2386 (Part III & IV).

2.2.5 Water

Clean potable water free from contaminants was used for mixing and curing, conforming to IS 456:2000 requirements.

2.3 Concrete Mix Design

The mix proportions were designed for M25 grade concrete in accordance with IS 10262:2019 and IS 456:2000. A water-cement ratio of 0.45 was adopted. The control mix proportions were calculated based on density, workability requirements (slump 50–75 mm), and aggregate grading.

Metakaolin was incorporated at 0%, 5%, 10%, 15%, and 20% by weight of cement, maintaining constant total binder content across all mixes.

2.4 Mixing and Casting Procedure

2.4.1 Mixing

Concrete was mixed in a tilting drum mixer following a three-stage procedure:

1. **Dry Mixing:** Cement, metakaolin, and fine and coarse aggregates were dry-mixed for 2–3 minutes to ensure uniform distribution.
2. **Wet Mixing:** Approximately 80% of the required water was added and mixed for another 2 minutes.

3. **Final Adjustment:** Remaining water was added to achieve the required workability.

2.4.2 Casting

Fresh concrete was cast into:

- **Cubes** (150 × 150 × 150 mm) for compressive strength
- **Cylinders** (150 × 300 mm) for split tensile strength
- **Beams** (100 × 100 × 500 mm) for flexural strength

Concrete was placed in moulds in three layers, each compacted using a tamping rod or vibration table depending on the specimen.

2.5 Curing

Specimens were demoulded after 24 hours and transferred to a curing tank containing clean water at $27 \pm 2^\circ\text{C}$. Curing durations were 3, 7, and 28 days for mechanical strength tests. Fresh specimens were kept moist at all times to ensure proper hydration.

2.6 Testing of Fresh Concrete

2.6.1 Slump Test

The workability of each mix was measured using the slump cone test according to IS 1199:1959. Slump height was recorded in millimetres.

2.6.2 Compaction Factor Test

Low-workability behaviour was evaluated using the compaction factor apparatus as per IS 1199:1959, suitable for mixes where slump does not provide adequate sensitivity.

2.7 Testing of Hardened Concrete

2.7.1 Compressive Strength Test

Cube specimens were tested under axial compression following IS 516:1959. The ultimate load at failure was recorded and compressive strength was calculated using:

$$f_c = \frac{P}{A}$$

2.7.2 Split Tensile Strength Test

Cylindrical specimens were tested using the diametral compression method (IS 5816:1999) to evaluate tensile resistance.

2.7.3 Flexural Strength Test

Beam specimens were tested using a third-point loading arrangement as per IS 516:1959 to determine modulus of rupture.

3 EXPERIMENTATIONS

This chapter presents the experimental procedures adopted to evaluate the influence of metakaolin as a partial replacement for cement in M25 concrete. The study involved preparation of concrete specimens with varying metakaolin percentages (0%, 5%, 10%, 15%, and 20%) and conducting a series of fresh and hardened concrete tests. The objective was to determine suitable mixture proportions, evaluate workability, and assess strength parameters under controlled laboratory conditions.

3.1 Tests on Fresh Concrete

The workability of each concrete batch was assessed immediately after mixing, in accordance with IS 1199:1959. Two standard tests were conducted:

1. **Slump Test**
2. **Compaction Factor Test**

Care was taken to ensure that no loss of concrete occurred during sampling. If the consistency test required remixing before casting, the material was homogenized with minimal delay to avoid segregation or loss of water.

3.1.1 Slump Test (Workability)

The slump test was carried out to determine the ease of flow and consistency of fresh concrete. The test followed the procedure specified in IS 1199:1959 using a slump cone and tamping rod (Figure 1).

Procedure

- i. Clean the internal surface of the cone and apply a thin layer of oil.
- ii. Place the mould on a rigid, smooth, non-absorbent horizontal base.
- iii. Fill the cone in four equal layers of fresh concrete.

- iv. Compact each layer with 25 uniform strokes using the rounded end of the tamping rod.
- v. Strike off the top surface to level it with the mould.
- vi. Lift the cone vertically and steadily without lateral movement.
- vii. Measure the vertical settlement between the cone height and highest point of the slumped concrete.
- viii. Report the value as **slump (mm)**.

Reporting

If the sample collapses or shears laterally, the test is considered invalid and repeated. If repetition yields shear again, the slump is recorded with notation of "shear slump".



Figure 1. Slump Test

3.1.2 Compaction Factor Test

The compaction factor test was used to evaluate the workability of concrete with relatively low or medium workability, following IS 1199:1959 (Figure 2).

Procedure

- i. Fill the upper hopper with freshly mixed concrete.
- ii. Open the trap door to allow concrete to fall freely into the lower hopper.
- iii. Open the second trap door so that concrete falls into the cylindrical mould.
- iv. Cut off excess concrete level with the top of the cylinder.
- v. Weigh the partially compacted concrete.
- vi. Refill the cylinder with a fresh sample and fully compact it using vibration.
- vii. Weigh the fully compacted concrete.

The **compaction factor** = (Weight of partially compacted concrete) / (Weight of fully compacted concrete).



Figure 2. Compaction Factor Test

Table 1. Workability Test Results

Replacement Level (%)	Slump (mm)	Compaction Factor
0	60	0.92
5	58	0.92
10	54	0.91
15	50	0.9
20	48	0.89

3.2 Tests on Hardened Concrete

Two categories of hardened concrete tests are typically used:

- i. **Non-Destructive Tests (NDT)**
- ii. **Destructive Tests (DT)**

Although NDT methods such as Rebound Hammer and Ultrasonic Pulse Velocity were listed, the present study utilized *only destructive tests* for evaluating mechanical strength.

Destructive tests conducted:

- Compressive Strength Test
- Split Tensile Strength Test
- Flexural Strength Test

All tests were performed using a Universal Testing Machine (UTM).

3.3 Operation of Universal Testing Machine (UTM)

Apparatus

- Universal Testing Machine
- Concrete specimens
- Vernier Calipers
- Measuring scale

Machine Description

A UTM consists of:

- **Loading Unit:** Upper and lower crossheads, test table

- **Controls:** Load application system, dial indicators, grips, bending devices

General Procedure

- i. Prepare the specimen and measure its dimensions at multiple points.
- ii. Insert the appropriate jaws or supports for the type of test.
- iii. Position the specimen centrally within the grips or supports.
- iv. Apply load gradually without impact.
- v. Record the yield point (if applicable) and ultimate load at failure.
- vi. Note fracture pattern and mode of failure.

3.4 Strength Tests on Concrete

3.4.1 Compressive Strength Test

The compressive strength test provides a direct measure of concrete's load-carrying capacity. The test followed IS 516:1959.

Procedure

1. Remove cube from curing tank at the selected age (3, 7, 28 days).
2. Wipe surface water and measure weight and dimensions.
3. Clean platen surfaces of the compression testing machine.
4. Place cube centrally on the lower platen.
5. Apply load at a uniform rate until failure.
6. Record maximum load (P).
7. Compute compressive strength:

$$f_c = \frac{P}{A}$$

where A is the loaded area.

Split Tensile Strength Test

The splitting tensile test was carried out on 150 mm × 300 mm cylinders following IS 5816:1999.

Formula

$$f_t = \frac{2P}{\pi DL}$$

where

P = load at failure,

D = diameter,

L = length of specimen.

Table 2. Compressive Strength test Results

Replacement Level (%)	3 Days	7 Days	28 Days
0%	1.27	2.97	11.88
5%	1.34	3.12	12.48
10%	1.63	3.89	15.56
15%	1.4	3.26	13.04
20%	1.31	3.05	12.2

3.4.2 Flexural Strength Test (Modulus of Rupture)

Flexural strength measures a beam specimen's resistance to bending, conducted per IS 516:1959 under third-point loading.

Specimen Size

100 × 100 × 500 mm beams.

Procedure

1. Prepare and oil the mould; cast and compact the beam in 2-3 layers.
2. Cure the beams until testing age.
3. Place the beam on two supporting rollers with correct span length.
4. Apply load symmetrically at one-third points.
5. Increase load gradually until fracture.
6. Record maximum load (P).

Calculation

$$f_s = \frac{PL}{bd^2} \text{ (if fracture occurs at mid-span)}$$

or

$$f_s = \frac{3Pa}{bd^2} \text{ (if fracture occurs off-centre)}$$

where

L = span length, a = distance from support to fracture line, b = width, d = depth.

Table 3. Flexural Strength test results (MPa)

Replacement Level (%)	3 Days	7 Days	28 Days
0%	1.48	3.45	13.38
5%	1.7	3.97	15.88
10%	2.06	4.81	19.24
15%	1.89	4.42	17.68
20%	1.58	3.69	14.76

4 RESULTS AND DISCUSSION

The compressive strength values for all mixes were obtained from 150 × 150 × 150 mm cubes tested at 3, 7, and 28 days. The control mix containing 100% cement served as the reference for comparison. The results revealed that the mix with 5% metakaolin did not exhibit a significant improvement in compressive strength over the control. This limited enhancement can be attributed to the relatively small quantity of metakaolin available to react with the calcium hydroxide released during cement hydration, resulting in only partial formation of additional calcium silicate hydrate (C-S-H). In contrast, the mix containing 10% metakaolin demonstrated consistently higher compressive strengths at all ages. The graph in

Fig. 6.1 clearly illustrates that the 10% replacement level produced the maximum strength development, indicating an optimal balance between available calcium hydroxide and the reactive metakaolin content. As the replacement level increased to 15% and 20%, the compressive strength declined. This reduction is likely due to the excess metakaolin present in the mix, which remains unreacted because the available calcium hydroxide becomes insufficient. As a result, the formation of additional cementitious compounds is limited, leading to reduced strength performance.

The split tensile strength results, obtained from 150 mm × 300 mm cylindrical specimens, follow a trend similar to that of compressive strength. The control mix again served as the benchmark, and the incorporation of metakaolin at different replacement levels showed noticeable variations in tensile performance. The mix with 10% metakaolin displayed the highest tensile strengths at 3, 7, and 28 days, achieving 1.63 MPa, 3.89 MPa, and 15.56 MPa respectively. These values were substantially higher compared with the mixes containing 5% and 15% metakaolin, as well as the control concrete. The 5% mix produced moderate improvements, while the 15% mix showed reduced performance at later ages, indicating diminishing effectiveness when metakaolin exceeds the optimal quantity. The observed reduction beyond 10% replacement suggests that excessive metakaolin does not contribute to further strength gain, as the available calcium hydroxide becomes insufficient to sustain additional pozzolanic reactions. Consequently, the concrete matrix does not experience adequate densification, leading to relatively lower tensile strength in higher replacement mixes.

The flexural strength behaviour, measured through beam specimens of size 100 × 100 × 500 mm, further confirms the trend observed in compressive and tensile strength. The flexural results indicate that the mix containing 10% metakaolin achieved the most favourable performance across all curing ages, with maximum strengths of 2.06 MPa at 3 days, 4.81 MPa at 7 days, and 19.24 MPa at 28 days. These values demonstrate a clear improvement over both the 5% and 15% mixes, which performed better than the control but did not reach the levels attained by the 10% mix. At 20% replacement, the flexural strength values showed a noticeable decline, further supporting the conclusion that the pozzolanic reaction becomes limited when the metakaolin content exceeds the available calcium hydroxide in the system. The

improved flexural behaviour at 10% can be attributed to the refinement of the interfacial transition zone (ITZ) and the additional formation of secondary gels, which enhance the overall bending resistance of the concrete (Figure 3).

Across all three strength parameters—compressive, tensile, and flexural—the consistent observation is that concrete incorporating 10% metakaolin exhibits the highest mechanical performance. While small improvements are observed at 5% replacement, the gains are not substantial enough to surpass those at 10% (Table 2,3). Conversely, replacements above 10% adversely affect strength due to insufficient calcium hydroxide available for reaction, resulting in unreacted metakaolin and a weaker matrix. The outcome suggests that metakaolin used in this study possesses high purity and reactivity, making 10% replacement sufficient to maximize beneficial pozzolanic reactions and significantly improve concrete strength.

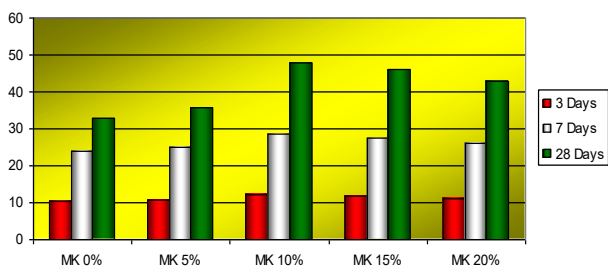


Figure 3: Graph showing Compression Strength at various proportions of Metakaolin

The combined analysis of compressive, tensile, and flexural strength results confirms that 10% metakaolin is the optimum replacement level. This percentage consistently demonstrated superior performance at all testing ages, indicating an ideal balance between reactivity, gel formation, and microstructural densification. Replacement levels above 10% resulted in diminished performance due to unreacted metakaolin and insufficient CH availability, while levels below 10% did not provide adequate reactive material to produce the full benefits of pozzolanic enhancement. Therefore, 10% replacement can be recommended as an effective and economical proportion for producing high-performance metakaolin concrete.

A comparison between metakaolin concrete and the control mix reveals that the incorporation of metakaolin significantly enhances the mechanical properties of concrete when applied at the appropriate dosage. Ordinary concrete exhibited lower

compressive, tensile, and flexural strengths compared with the 10% metakaolin mix at all testing ages. This performance enhancement arises from the improved microstructural characteristics, including denser packing, reduced porosity, and refined ITZ obtained due to metakaolin's pozzolanic activity. Although the 5% and 15% metakaolin mixes produced moderate improvements relative to the control, they did not outperform the 10% mix. The 20% replacement level resulted in strength values comparable to or slightly lower than ordinary concrete, highlighting the importance of controlling metakaolin dosage to avoid adverse effects caused by excess unreacted material.

The workability results reveal a gradual decrease in slump and compaction factor values as the metakaolin content increases. This reduction can be attributed to the high fineness and angular particle shape of metakaolin, which increases the surface area and consequently the water demand of the mix. Although workability decreases, all mixes remained workable and suitable for casting with standard compaction methods. In addition to workability, a noteworthy functional observation during curing was the appearance of a white powdery deposit on the top surfaces of some cube specimens. This deposit is identified as efflorescence, which likely results from the migration of calcium hydroxide and extremely fine metakaolin particles toward the surface through capillary pores. During early hydration, the concrete matrix remains relatively porous, allowing trapped air and dissolved CH to migrate upward. As water seeps into the pores, some CH dissolves and carries fine metakaolin particles toward the surface, where they deposit and crystallize as a white residue. This behaviour is consistent with the highly reactive and fine characteristics of metakaolin.

5 CONCLUSION

The study investigated the influence of metakaolin as a partial replacement for Ordinary Portland Cement in M25 grade concrete, focusing on workability and mechanical properties. The results clearly show that metakaolin affects both fresh and hardened concrete behaviour, with its effectiveness largely dependent on the percentage of replacement. Workability tests indicated a gradual reduction in slump with increasing metakaolin content from 5% to 20%. This decline is attributed to the high fineness and surface area of metakaolin, which increases water demand. Despite reduced workability, all mixes remained adequately workable for normal placement and compaction. Mechanical performance was strongly

influenced by the replacement level. The 10% metakaolin mix consistently achieved the highest compressive, tensile, and flexural strengths at all ages. This improvement results from the pozzolanic action of metakaolin, which reacts with calcium hydroxide to form additional C-S-H gel, refining the microstructure. At replacement levels above 10%, strength decreased due to insufficient calcium hydroxide for complete pozzolanic reaction, leaving excess metakaolin unreacted. The 5% replacement level produced only marginal strength enhancement compared to the control. When compared to ordinary concrete, the 10% metakaolin mix outperformed the control in all strength parameters, while 5% and 15% replacements showed moderate benefits. The 20% replacement exhibited strength comparable to or slightly lower than the control. The study identifies 10% metakaolin as the optimum replacement level, offering improved strength, durability potential, and microstructural quality without severely compromising workability. Metakaolin thus proves to be an effective and sustainable supplementary cementitious material for enhancing concrete performance.

Author Contributions:

GG: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software. GG: Validation, Visualization, Writing – original draft.

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