INVESTIGATION ON THE PERFORMANCE BEHAVIOR OF SUSTAINABLE CONCRETE MADE WITH METAKAOLIN AS PARTIAL CEMENT REPLACEMENT AND RECYCLED COARSE AGGREGATE

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Abstract: This experimental research investigates the effect of utilizing metakaolin (MK) on the behavior of recycled aggregate concrete (RAC). The recycled coarse aggregate (RCA) originated from crushing construction and demolition waste. Investigated parameters were RCA and MK contents. Tests of workability and mechanical properties such as compressive strength, splitting tensile strength, f were conducted to evaluate the influence of MK on workability and mechanical behavior of RAC. In total, 19 mixes were prepared. These mixes are divided into four groups. Group zero (G0) includes a reference mix containing normal coarse aggregate (NCA) and 3 mixes made with 35%, 70%, and 100% of RCA. Each one of the other three groups (G1, G2, and G3) was made with one content of the three contents of RCA, and each group includes Three mixes made with the contents of and 20% of MK.

INTRODUCTION

Concrete production has increased markedly in recent decades due to its extensive use in construction. Global output now averages about one ton of concrete per person annually (Marie and Quiara, 2012). This high demand accelerates the depletion of natural aggregates, which make up 60–75% of concrete volume (Shi et al., 2016), leading many countries to face aggregate scarcity. Moreover, aggregate extraction and concrete manufacturing generate considerable CO_2 emissions, dust, and other pollutants, contributing to environmental degradation. (Rakesh Muduli, Bibhuti Bhusan Mukharjee,2019). Globally, construction and demolition (C&D) activities generate over three billion tons of waste each year, with China, India, and the United States contributing the majority. India alone produces about 14.5 million tons annually from the demolition and renovation of various civil structures. As a result, recycling C&D waste into recycled aggregates has emerged as an effective approach to conserve natural resources and improve waste management. Recycled coarse aggregates (RCA) are produced by cleaning and crushing demolished concrete and are used to manufacture recycled aggregate concrete (RAC) by partially or fully replacing natural aggregates. (Rakesh Muduli a, Bibhuti Bhusan Mukharjee,2020). Cement production has advanced significantly since its early use nearly 2000 years ago. Although cement has long been a key component of concrete, its industrial manufacturing began in the mid-19th century with shaft kilns, which were later replaced by rotary kilns that dominate today's industry. Current global cement production is about 2.8 billion tons per year and is projected to rise to nearly 4 billion tons, with major increases expected in China, India, the Middle East, and North Africa. (M. Schneider et al.,2011). From a chemical perspective, cement consists primarily of calcium silicates, aluminates, and ferrites. The main clinker phases include tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetra calcium alumina ferrite (C_4AF). When cement reacts with water, these compounds undergo hydration, forming calcium silicate hydrate (C-S-H) gel and calcium hydroxide, which collectively provide the strength and durability of hardened cement paste. The hydration process is exothermic and influences important engineering properties such as setting time, heat of hydration, and early-age strength development.

Metakaolin (MK) is a highly reactive aluminosilicate material produced by the thermal activation of kaolinite-rich clays at temperatures between 650 °C and 900 °C. Compared to other mineral admixtures such as fly ash, silica fume, and ground granulated blast-furnace slag, MK offers superior consistency and controlled production, resulting in high purity and predictable chemical composition. Its fine particle size and high surface area provide significant pozzolanic reactivity, which improves both the mechanical properties and durability of concrete. The pozzolanic reaction occurs when MK's amorphous silica reacts with calcium hydroxide from cement hydration, forming additional calcium silicate hydrate (C–S–H) gel. This reaction refines the pore structure and densifies the cementitious matrix, leading to higher compressive strength, reduced permeability, and improved long-term durability. Several studies have highlighted the effectiveness of MK in concrete. Concrete with 5–15% MK replacement exhibited higher compressive and tensile strength and enhanced durability. (Mohamed Ahmed Ali Al mattar et al., 2009). (Bao Min Wang and Wei Liu (2010) demonstrated that 5–15% MK replacement enhanced compressive, tensile, and flexural strength, particularly at early ages, and improved toughness of high-performance concrete. Luma Ahmed Aday (2018) observed that MK refined pore structure, reduced absorption, and significantly enhanced compressive and flexural strength. More recently, Mohammed Najeeb Al-Hashem et al. (2022) reported up to 33% higher 90-day compressive strength for concrete containing 20% MK, although workability decreased with higher MK content. Overall, these studies suggest that partial replacement of cement with MK, typically in the range of 5–15% (and occasionally up to 20%), provides a beneficial balance between enhanced mechanical performance, improved durability, and environmental advantages through reduced cement consumption. (Yan L (2021) et al) To address these issues, research has focused on improving the quality and performance of recycled aggregates, including methods to reduce their porosity, remove old mortar, or modify the RAC mix design. Among various improvement techniques, the incorporation of supplementary cementitious materials—especially metakaolin, a highly reactive pozzolan—has shown notable effectiveness. Metakaolin enhances the microstructure of RAC by strengthening the interfacial transition zone, reducing water absorption and chloride penetration, and improving compressive and tensile strength. Thus, the literature indicates that the use of metakaolin-modified recycled aggregate concrete is a promising pathway for producing sustainable, durable, and high-performance concrete. Environmental concerns further highlight the need for recycled aggregates: producing 1 ton of natural aggregate emits 0.0046 MT CO_2, while recycled aggregates emit only 0.0024 MT CO_2, indicating substantial carbon savings. While the use of recycled aggregates may slightly increase shrinkage, creep, and porosity—leading to a 10–30% reduction in compressive strength—they significantly reduce life-cycle cost by 34–41% and CO_2 emissions by 23–28% compared to disposal. These benefits make recycled aggregates a vital component of sustainable construction practice.

NEED OF THE STUDY.

The global reliance on traditional concrete production is accelerating the depletion of natural aggregates and generating significant environmental burdens, including substantial CO_2 emissions and vast quantities of construction and demolition (C&D) waste. With output averaging one ton per person annually, the industry must fundamentally shift towards sustainable practices. This presentation explores a dual approach to mitigating these issues: integrating recycled coarse aggregates (RCA) from C&D waste into new concrete mixes, and leveraging metakaolin (MK), a high-purity mineral admixture, to overcome the typical performance limitations of recycled aggregate concrete (RAC). We will demonstrate how this innovative blend not only reduces waste and conserves natural resources but also enhances the mechanical performance and durability of the final product, providing a viable pathway to sustainable, high-performance construction.

The increasing demand for sustainable construction materials has encouraged the use of recycled aggregates and supplementary cementitious materials in concrete production. This study evaluates the performance of metakaolin-based concrete incorporating recycled coarse aggregate (RCA) as a partial replacement for natural coarse aggregate. Metakaolin (MK) was used as a cement replacement at varying percentages, while RCA replaced conventional aggregates at fixed levels. The mechanical properties, including compressive strength, were examined along with workability variations. Results indicate that the addition of metakaolin significantly enhances the strength and durability of RCA concrete by improving the microstructure and reducing porosity. However, higher RCA content reduces workability and strength, which can be effectively compensated by optimum MK replacement. The study concludes that a balanced combination of RCA and metakaolin can produce an eco-friendly, durable, and structurally reliable concrete mix suitable for practical applications. The findings contribute to sustainable material development and offer guidance for future research in green concrete technologies.

The sustainable development goal (SDG) 14 of the 2030 Agenda for Sustainable Development aims at protection, conservation, and management of coastal ecosystems and resources, including by strengthening their resilience, to avoid significant adverse impacts. Coastal/marine structures are exposed to aggressive environmental conditions, such as chloride laden environment. Deterioration of reinforced concrete structures located in a coastal/ marine setting can influence the safety, economic and sustainability aspects of the society. Hence, there is an increased need for sustainable materials with the ability to reduce the effects of chloride attack in concrete. This experimental study aims to investigate the engineering properties of metakaolin (MK) based concrete exposed to chloride attack. The investigation was conducted for different w/b ratios of 0.54–0.61. The MK, utilized as cementitious material, was varied from 0 to 20% with an increment of 5% and ages of concrete from 7 to 56 days were considered. The effects of the above-mentioned parameters on the various properties of concrete such as workability, compressive and flexural strength, durability, resistance to chloride attack and microstructure properties of the concrete samples were investigated. From the favorable strength and durability results that were observed during the experimental study (optimum compressive strength of 49.8 MPa for 10% MK and optimum flexural strength of 8.35 MPa for 5% MK), it can be concluded that MK is a feasible supplementary cementitious material for combatting chloride attack in coastal/marine concrete structures. The obtained results, in combination with the lack of carbon dioxide CO2 released during the MK manufacturing process, further highlights the positive influence of MK on improving the serviceability and sustainability states of coastal/marine structures.

MATERIAL PROPERTIES

Metakaolin (MK) is widely recognized as a sustainable and highly reactive supplementary cementitious material that enhances the performance of ultra-high-performance concrete (UHPC). Research highlights that the physical and chemical properties of MK—such as particle size, surface morphology, and oxide composition— directly influence its pozzolanic activity and its ability to refine concrete microstructure. Studies by Zhan et al. [72] show that MK derived from kaolin transforms significantly during calcination at 600–800 °C, where the kaolinite structure loses hydroxyl groups and forms more reactive tetra- and penta-coordinated aluminum units. Further grinding produces nano metakaolin (NMK), which exhibits a 2–8 times larger surface area and smoother plate-like morphology, improving its filling ability and reactivity. NMK contains high Si O_2 (45.5–89.6%) and Al_2 O_3 (18.9–42.3%), which accelerate hydration and reduce setting time. These properties make MK and NMK effective in enhancing UHPC strength, durability, and overall performance. (R. Muduli, 2020).

Materials	Cao	Sio_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	SO_3	Loss on Ignition
OPC	64.2	20.46	5.83	3.23	1.23	.46	.64		2.23	1.72
MK	.03	53.56	41.5	1.38	.25	.18	.76	1.54		.85

RESEARCH METHODOLOGY

The methodology section outlines the plan and method that how the study is conducted. This includes Universe of the study, sample of the study, Data and Sources of Data, study's variables and analytical framework. The details are as follows; The preparation of metakaolin-modified recycled aggregate concrete (MK-RAC) involved a systematic sequence of material processing, proportioning, mixing, casting, and curing to ensure uniformity and accuracy across all test specimens. The overall methodology followed relevant IS, BS, and ASTM standards and aligns with practices described in Adebanjo et al. (2021).

MATERIAL SELECTION

1. Binder - In this research, the cementitious system was formulated using two primary materials: Ordinary Portland Cement (OPC) of 43 grade and a highly reactive metakaolin (MK). The OPC, conforming to the requirements of IS 8112, was procured freshly from a regional supplier to avoid variations arising from storage conditions and to ensure stable performance throughout the experimental program. The supplementary material, metakaolin, was obtained from Kaomin Industries located in Gujarat, India, and was selected due to its proven reactivity and compatibility with blended cement systems. Prior to its use, both OPC and MK were subjected to routine characterization tests recommended by the relevant Indian Standards in order to verify their suitability for concrete production and to establish baseline properties for comparison. The metakaolin incorporated in the study demonstrated a specific gravity of 2.64 and a fineness value of 12,600 cm^2/g, indicating the presence of extremely fine particles capable of improving packing density within the cement matrix. Additionally, the measured pH of 6.8 suggests that the material is mildly acidic, which is consistent with highly processed kaolinitic clays. These characteristics collectively point to MK's enhanced pozzolanic potential, enabling it to react more effectively with calcium hydroxide released during cement hydration. As a result, when blended with OPC, the metakaolin contributes to the formation of additional calcium silicate hydrate (C–S–H) gel, ultimately improving the microstructure and performance of the composite binder.

2. Admixtures – Metakaolin: The metakaolin utilized in the current work was a commercial type produced by the BASF Company of chemicals. It is a reactive mineral admixture in the form of very fine white powder. The average particle size of the metakaolin is around 1µm. High reactivity metakaolin (HRM), produced by calcining purified kaolin clay at temperatures between 700–800 °C, was used in this study as a partial replacement for cement. The controlled calcination process transforms kaolinite into a highly amorphous and reactive aluminosilicate material, enhancing its pozzolanic activity. Owing to its ultrafine particle size and high reactivity, metakaolin improves the microstructure of the cement matrix and contributes positively to the mechanical and durability properties of the concrete mixes investigated. (H. Younis et al., 2020)

3. Recycled Aggregate – Coarse Aggregate: For the present experimental study, the natural coarse aggregate used was locally available crushed granite with a nominal size of 20 mm. The recycled coarse aggregates (RCA) were sourced from the roof slab of a collapsed building in the nearby locality. To produce RCA, the embedded reinforcement was first removed, and the concrete debris was manually sorted to eliminate unwanted materials such as wood, leaves, and wires. The cleaned concrete fragments were then transported to a local crusher, where they were processed into smaller particles with a maximum size of 20 mm. Prior to use in the concrete mix, the RCA was thoroughly washed and air-dried to remove dust and fine particles generated during crushing. The processed aggregates were further sieved to obtain clean 20 mm RCA suitable for the experimental investigations.

4. Fine Aggregate (FA) Fine aggregate used in this study consisted of locally available river sand conforming to IS 383. Fine aggregate plays a critical role in concrete by filling voids between coarse aggregates, improving workability, and contributing to the overall density of the mix. The selected sand was naturally sourced, well-graded, and free from harmful contaminants such as clay lumps, silt, mica, and organic matter that could adversely affect cement hydration or bond strength. Before batching, the sand was oven-dried to eliminate surface moisture and ensure accurate proportioning by weight. Sieve analysis confirmed that the sand satisfied the grading requirements for Zone II, making it suitable for structural concrete. The nominal maximum size of 4.75 mm ensured good packing characteristics and contributed to stable, cohesive mixes required for recycled aggregate concrete.

5. Chemical Admixture – Superplasticizer (PCE-based) A high-range water-reducing admixture (HRWRA) based on polycarboxylate ethene (PCE) technology, complying with IS 9103, was used to improve workability without increasing the water–cement ratio. PCE superplasticizers disperse cement and metakaolin particles through electrostatic and steric hindrance mechanisms, resulting in improved particle separation and reduced flocculation. This enhances fluidity, reduces internal friction, and promotes better compaction—particularly important in mixes containing recycled aggregates, which tend to absorb more water and reduce workability. Water Potable water, suitable for drinking and conforming to IS 456 specifications for mixing and curing of concrete, was used throughout the investigation. The water was clear, colorless, and free from harmful quantities of oils, acids, alkalis, or organic matter. Consistent water quality was ensured to avoid any variation in hydration behavior and concrete performance. The same water source was used for both mixing and curing to maintain uniformity across all test specimens.

Properties of Natural Fine aggregate, Natural Coarse aggregate, and Recycled Coarse aggregate

Properties	NCA	RCA	NFA
Specific gravity	2.85	2.35	2.63
Loose bulk density (Kg/m^3)	1577	1336	1548
Compact bulk density (Kg/m^3)	1792	1505	1666
Water absorption (%)	0.36	4.92	0.8
Free surface moisture (%)	0.25	1.56	0.5
Fineness modulus	6.95	7.00	3.21
Flakiness index (%)	6.53	1.82	–
Elongation index (%)	18.62	16.28	–
Impact value (%)	14.3	20.23	–
Crushing value (%)	20.5	29.2	–
Abrasion value (%)	17.28	32.4	–

Material	Specific Gravity	Fineness	Water Absorption	Size
Cement	3.15	225	30 %	<75μm
Metakaolin	2.6	776	Very reactive	<45μm
Coarse Agg.	2.46	N.A.	30-40 %	4.75-20mm
Fine Agg.	2.65	N.A.	10-20 %	<4.75mm

Chemical Composition of Binding Material

Materials	Cao	Sio$_2$	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	SO_3	Loss on Ignition
OPC	64.2	20.46	5.83	3.23	1.23	.46	.64		2.23	1.72
MK	.03	53.56	41.5	1.38	.25	.18	.76	1.54		.8

EXPERIMENT WORK

• **General design Mix:** - For this study, in case of design, mix of specimens, IS 10262:2009 were being considered. The Metakaolin was replaced by Cement in three different proportions i.e., 5%,15%,20%, and there were 11 design mix in which different proportion of Mk and RCA are taken and a simple design mix also considered for the comparison purpose and the targeted Design Mix is M45.The W/C ratio were considered b/w .42-.45. Design mix calculations as per **IS 10262:2009** involve selecting suitable proportions of cement, water, fine aggregate, coarse aggregate, and admixtures to achieve the desired workability, durability, and strength while minimizing variability in concrete performance. The procedure typically includes determining the target mean strength, selecting the water–cement ratio, estimating water and cement content, and then calculating aggregate proportions based on grading and specific gravities. Estimated material quantities are further adjusted through trial mixes to meet required slump and strength criteria. When **metakaolin is used as a partial cement replacement**, it is incorporated into the design by reducing a portion of the cement content—usually between 5% and 15%—and modifying water demand or superplasticizer dosage accordingly, as metakaolin improves pozzolanic reaction, enhances strength, and reduces permeability.

PROCESSING OF RECYCLED COARSE AGGREGATES (RCA)

I. Collection of demolished concrete:

Recycled coarse aggregates were obtained from the roof slab of a collapsed building. Large concrete pieces were manually sorted to remove embedded reinforcement, wood, plastic, and other debris.

II. Crushing:

The cleaned concrete fragments were transported to a local crushing unit and reduced to desired sizes (maximum 20 mm), consistent with procedures.

III. Sieving and grading:

The crushed material was sieved to obtain aggregates within the 9.5-20 mm size range, ensuring compliance with IS 383 grading requirements.

IV. Washing and SSD conditioning:

The RCA was thoroughly washed to remove adhered fines and dust generated

During crushing. Aggregates were then soaked and brought to a Saturated Surface Dry (SSD) condition to minimize excess water absorption during mixing.

PREPARATION OF METAKAOLIN (MK)

I. Raw kaolin acquisition:

Raw kaolin was collected from a kaolin mining site and milled to pass through a 75 µm sieve.

II. Calcination:

The kaolin powder was calcined in an electric furnace at 700-800°C to obtain high-reactivity metakaolin, matching the range documented in the literature and the uploaded paper.

III. Characterization:

The metakaolin's physical and chemical properties-specific gravity (2.64), fineness (12,600 cm²/g), and pH (6.8) were assessed in accordance with IS standards.

IV. Proportioning of Concrete Mix

Concrete mix proportions were determined based on IS: 10262 and BRE mix design guidelines.

Metakaolin was used as a partial replacement of cement.

RCA was used as a full or partial replacement of natural coarse aggregates.

Mixes included control concrete (0% MK, natural aggregate) and modified mixes with varying MK contents (5-20%).

MIXING PROCEDURE
The mixing procedure was standardized for all batches:

1. Dry mixing:
Cement, metakaolin, fine aggregates, and coarse aggregates (NCA or RCA) were dry-mixed for 2 minutes to ensure uniform distribution.

2. Addition of water and admixture:
70% of the mixing water was added gradually while the remainder (mixed with superplasticizer) was added to adjust workability.
7. Testing of Fresh and Hardened Concrete

3. Final mixing:

Wet mixing continued for 3-4 minutes until a uniform and homogeneous mix was achieved.

CASTING OF SPECIMENS

I. Fresh concrete was placed in steel cube moulds (150 x 150 x 150 mm) and cylindrical moulds (150x300 mm).

II. Concrete was filled in three layers, each compacted using a tamping rod or vibrating table to eliminate air voids.

III. The top surface was finished smoothly using a trowel.

4. Curing Procedure

I. After 24 hours of initial setting, all specimens were demoulded.

II. Specimens were then cured in clean potable water at room temperature until their designated testing ages.

TESTS FOR SAMPLE SPECIMENS

1. Slump Test:
Conducted according to IS 1199 to determine workability.

2. Compressive Strength Test:
Cube specimens were tested at 7, 28, days using a compression testing machine following IS 516

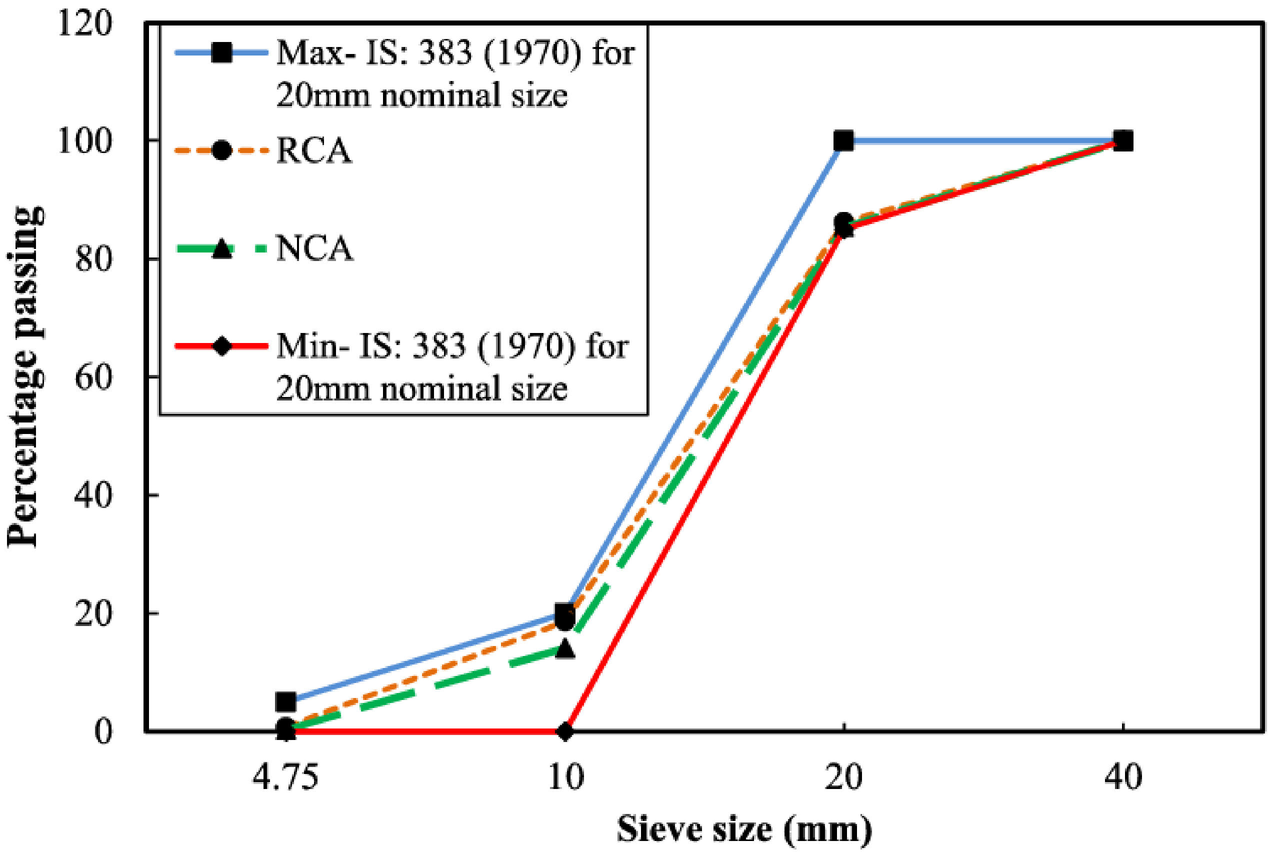
IV. RESULTS AND DISCUSSION

4.1 Results of Descriptive Statics of Study Variables

4.2 Result Table

	7 Days (MPA)	28 Days (MPA)	Notes
RM 0-0	31	45	Normal m45 control mix
RM 0-5	33	48	MK improves strength
RM 0-10	35	51	Peak strength zone
RM 50-0	28	41	RCA 50% reduces strength
RM 50-5	30	44	MK compensates loss
RM 50-10	32	46	MK improves further
RM 100-15	33	47	Slight improvement
RM 100-5	26	38	100% RCA reduces strength significantly
RM 100-10	28	40	MK gives some improvement
RM 100-15	29	41	Slightly more improvement
RM 100-20	27	39	Too much MK reduction

GRADATION CURVE FOR NCA AND RCAGRADATION CURVE FOR NCA AND RCA



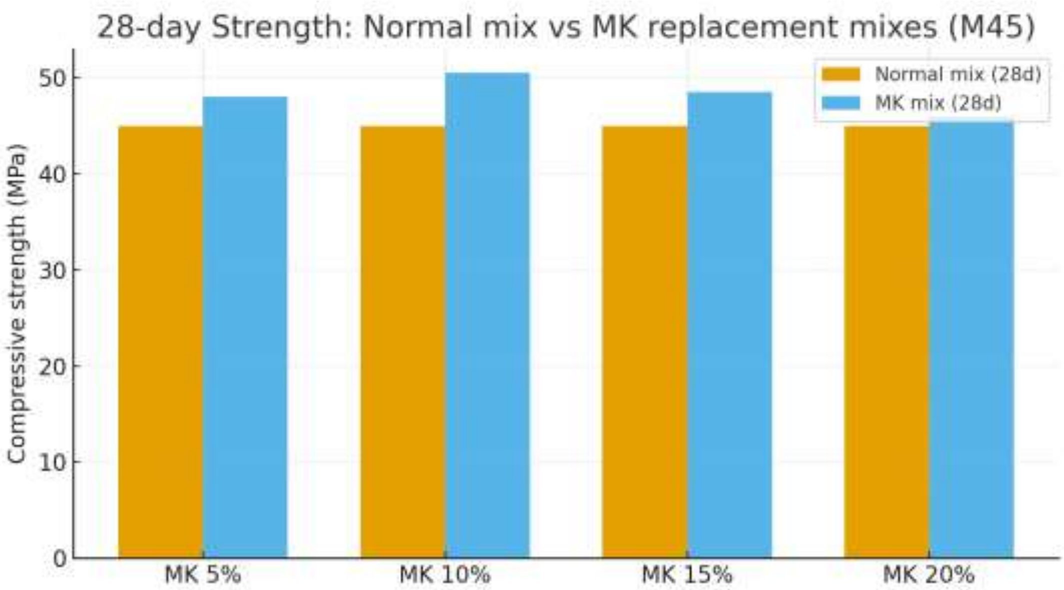
RESULTS

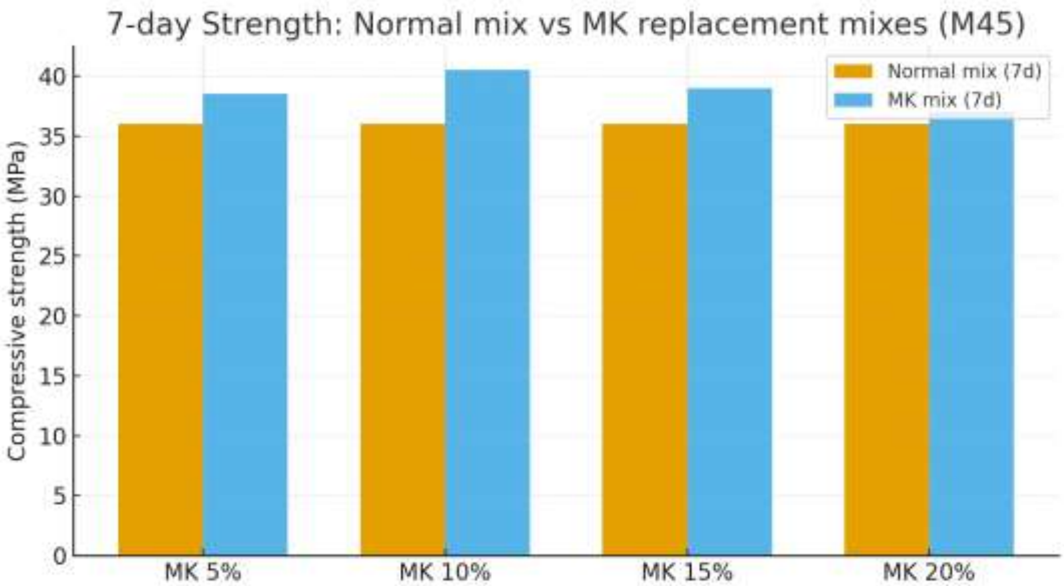
Cube size = 150 x 150 x 150 mm, average of 3 cubes per result.RM
Number of cubes = 33
Standard water curing (immersion) until test age.
Control Mix 28-day characteristic = 45.0 MPa (M45).

In above calculation all the quantities were taken in kgs and the slump of the design mix were taken 105mm. To compare the mechanical and physical properties like compressive strength of the design mix we also use some specimens in which natural aggregates are used. The estimated quantities shown in the table were obtained using the design mix procedure specified in IS 10262:2009. Based on the required grade of concrete, the proportions of cement, water, fine aggregate, and coarse aggregate were calculated step-by-step, and the final values reflect the adjustments made during the mix design process. In this mix, a part of the cement was also replaced with metakaolin, so the cement quantity was reduced accordingly, and the equivalent metakaolin content was added. The table therefore represents the final material quantities used for preparing the concrete mix with metakaolin modification.

- Metakaolin (MK) was used as a partial cement replacement at 5%, 10%, 15%, and 20% in M45 grade concrete.
- Workability remained acceptable for all mixes, with a slump value of about 105 mm, indicating MK does not adversely affect placement up to 20%.
- All MK mixes showed higher compressive strength than the normal mix at both 7 and 28 days, except at 20% replacement.
- Strength improvement is attributed to the pozzolanic reaction of metakaolin, which refines the microstructure and densifies the cement matrix.
- At 7 days, 10% MK showed the highest compressive strength, followed by 5% MK.
- 15% MK performed better than the control mix but was inferior to 10% MK.
- 20% MK resulted in reduced early-age strength due to lower cement content and reduced early hydration.
- At 28 days, 10% MK again showed the maximum compressive strength.
- Long-term strength gain confirms that MK improves both early and later-age strength up to an optimum level.
- Excess MK (20%) increased water demand and reduced effective cementitious material.
- The optimum replacement level of metakaolin is 10% for M45 grade concrete.
- MK enhances strength through:
- Improved C–S–H gel formation
- Reduced porosity
- Improved interfacial transition zone (ITZ)
- MK replacement should not exceed 15% when strength is the primary performance criterion.

- 10% MK OUTPERFORMED THE NORMAL MIX BY THE WIDEST MARGIN AT BOTH CURING AGES.





FINAL OBSERVATIONS

1. Effect on 7-Day Compressive Strength

The early-age strength showed an improvement for all MK percentages compared to the normal mix. This increase is primarily due to the highly reactive pozzolanic nature of MK, which accelerates the formation of C–S–H gel at early ages. Among all variations: 10% MK exhibited the highest 7-day strength, followed by 5% MK. 15% MK still performed better than the control mix, but the improvement was lower than the 10% mix. 20% MK showed a decline compared to other MK mixes, indicating that excessive MK reduces early hydration due to lower cement content.

2. Effect on 28-Day Compressive Strength

The long-term strength gain was significantly improved by MK incorporation. A similar trend to the 7-day results was observed: 10% MK replacement produced the maximum 28-day strength, showing the highest overall densification of the matrix. 5% and 15% MK also performed better than the control concrete. 20% MK again showed a reduction, likely due to increased water demand and reduced effective cementitious material. This confirms that MK enhances both early and long-term strength up to an optimum percentage, after which the benefits start decreasing.

3. Overall Optimum Percentage of Metakaolin

Based on the comparison of normal mix vs. MK mixes (for both 7 and 28 days): 10% Metakaolin is the optimum replacement level. It consistently produced: The highest 28-day compressive strength Superior microstructural densification due to the pozzolanic reaction Reduced porosity and improved interfacial transition zone (ITZ)

4. Influence of High MK Replacement (20%)

Higher replacement levels led to: Reduced workability Increased water demand Lower strength gain Possible incomplete hydration due to reduced cement quantity This confirms that MK should not exceed 15% for M45 grade concrete when strength is the primary performance indicator.

5. Comparison With Normal Mix Across all mixes

All MK mixes except 20% exhibited higher strength than the normal mix. 10% MK outperformed the normal mix by the widest margin at both curing ages.

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