



An Experimental Investigation on Metakaolin Modified Concrete Paver Blocks

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Abstract: Concrete paver blocks are widely used in pavement applications due to their durability, ease of maintenance, and structural efficiency. However, conventional paver blocks manufactured using ordinary Portland cement (OPC) are associated with high carbon emissions and moderate durability performance under severe environmental exposure. This study investigates the influence of metakaolin as a partial replacement of cement on the fresh, mechanical, and durability properties of concrete paver blocks. Five concrete mixes were prepared with metakaolin replacement levels of 0%, 5%, 10%, 15%, and 20% by weight of cement while maintaining a constant water–cement ratio of 0.40. Fresh concrete properties were evaluated using slump tests, while hardened properties were assessed through compressive strength, flexural strength, split tensile strength, water absorption, and abrasion resistance tests. The results indicated that the incorporation of metakaolin reduced workability due to its high fineness and increased water demand. However, mechanical and durability properties improved significantly up to an optimum replacement level of 10%. The mix containing 10% metakaolin achieved the highest compressive strength of 48 MPa at 28 days, along with improved flexural and split tensile strengths. Water absorption and abrasion loss were reduced considerably, indicating enhanced durability performance. Beyond 10% replacement, strength and

durability properties declined due to reduced workability and dilution effects caused by excessive cement replacement. The study concludes that 10% metakaolin replacement provides the best balance between strength, durability, and workability, making it suitable for sustainable high-performance concrete paver block production.

Keywords: Metakaolin, Concrete paver blocks, Compressive strength, Durability, Sustainable concrete

1. Introduction

Concrete paver blocks are widely used in modern pavement systems such as pedestrian walkways, parking areas, industrial flooring, bus terminals, and low-volume roads because of their high durability, ease of maintenance, aesthetic flexibility, and superior load distribution characteristics. Compared with conventional rigid pavements, paver blocks provide advantages such as easy replacement, better crack resistance, and improved surface performance under repeated loading conditions. However, the long-term performance of concrete paver blocks is strongly dependent on the quality of the concrete matrix, particularly its compressive strength, abrasion resistance, and permeability characteristics. Conventional concrete manufactured using ordinary Portland cement (OPC) often suffers from limitations related to water absorption, surface wear, and durability under aggressive environmental exposure. Furthermore, cement manufacturing contributes



significantly to global carbon dioxide emissions and energy consumption, creating a strong need for sustainable and environmentally friendly construction materials (Mehta & Monteiro, 2014; Li et al., 2023).

In recent years, the use of supplementary cementitious materials (SCMs) has emerged as an effective approach for enhancing concrete performance while reducing cement consumption. SCMs such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), and metakaolin have been widely investigated due to their ability to improve strength, reduce permeability, and enhance resistance to chemical attack and abrasion. Among these materials, metakaolin has attracted considerable attention because of its high pozzolanic reactivity, ultrafine particle size, and ability to refine the microstructure of concrete (Sabir, Wild, & Bai, 2001). Metakaolin is produced by the calcination of kaolin clay at temperatures between 600°C and 800°C, resulting in an amorphous aluminosilicate material capable of reacting with calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This reaction improves the density and compactness of the concrete matrix, thereby enhancing both mechanical and durability properties (Justice, Kurtis, & Monteiro, 2005).

Several recent studies have confirmed the effectiveness of metakaolin in improving concrete performance. Zhang et al. (2022) reported that metakaolin significantly enhanced compressive strength and chloride resistance by refining pore structure and reducing microcracks in concrete. Similarly, Sharma and Gupta (2023) observed that the inclusion of metakaolin improved abrasion resistance and reduced water absorption in pavement concrete mixtures due to improved particle packing and pozzolanic reactions. Research by Kumar et al. (2024) further demonstrated that metakaolin-modified concrete exhibited superior durability under wet–dry cycles and mechanical loading conditions compared with conventional OPC concrete. These improvements are primarily attributed to the formation of additional C–S–H gel and the strengthening of the interfacial transition zone between aggregate and cement paste.

Despite the growing interest in metakaolin-based concrete, relatively limited studies have specifically focused on concrete paver blocks. Paver blocks are subjected to unique service conditions involving repeated traffic loading, abrasion, moisture exposure, and surface wear, which differ significantly from conventional structural concrete applications. Therefore, the behavior of metakaolin in paver block systems requires dedicated investigation. Moreover, inconsistencies remain regarding the optimum replacement level of metakaolin, as excessive replacement may reduce workability and adversely affect compaction quality. Some studies report optimum performance at 10% replacement, whereas others suggest different replacement levels depending on curing conditions, aggregate grading, and mix composition (Patel et al., 2022; Singh & Verma, 2024).

The present study aims to experimentally investigate the influence of metakaolin as a partial replacement of cement on the fresh, mechanical, and durability properties of concrete paver blocks. Different replacement levels of metakaolin were considered to identify the optimum dosage capable of providing the best balance between workability, strength, abrasion resistance, and water absorption. The study evaluates slump, compressive strength, flexural strength, split tensile strength, water absorption, and abrasion resistance of paver blocks prepared with varying metakaolin contents. The findings of this study are expected to contribute toward the development of sustainable and high-performance concrete paver blocks suitable for modern pavement infrastructure.

2. Materials and Methodology

2.1 Materials Used

The experimental investigation was carried out using ordinary Portland cement (OPC), fine aggregate, coarse aggregate, metakaolin, and potable water. Ordinary Portland Cement (OPC 43 Grade) conforming to IS 8112 was used as the primary binding material due to its consistent hydration characteristics and suitability for pavement applications. Cement plays a critical role in strength development and durability of concrete paver blocks through the formation of calcium silicate hydrate (C–S–H) gel during hydration (Neville, 2011).

Natural river sand conforming to Zone II grading as per IS 383 was used as fine aggregate. The sand was clean, free from organic impurities, and properly graded to ensure adequate workability and particle packing. Crushed angular coarse aggregates of nominal maximum size 10 mm were used to achieve improved



interlocking and strength characteristics suitable for paver block applications. Potable water free from harmful impurities was used for both mixing and curing purposes in accordance with IS 456 recommendations.

Metakaolin was used as a supplementary cementitious material due to its high pozzolanic reactivity and ultrafine particle size. Metakaolin reacts with calcium hydroxide released during cement hydration and forms additional C–S–H gel, which refines pore structure and improves mechanical and durability properties of concrete (Sabir, Wild, & Bai, 2001). The material also contributes to filler effects by reducing internal voids and improving the compactness of the cement matrix (Justice, Kurtis, & Monteiro, 2005).

The physical properties of the materials used in this investigation are presented in Table 1.

Table 1: Physical Properties of Materials

Material	Property	Value
Cement	Specific Gravity	3.15
Fine Aggregate	Specific Gravity	2.65
Coarse Aggregate	Specific Gravity	2.70
Metakaolin	Specific Gravity	2.50
Water	pH	7.0

2.2 Mix Proportions

Five concrete mixes were prepared with varying percentages of metakaolin as partial replacement of cement by weight. The replacement levels considered in this study were 0%, 5%, 10%, 15%, and 20%. The control mix without metakaolin was designated as M0, while the modified mixes were designated as M5, M10, M15, and M20, respectively.

The total binder content and water–cement ratio were maintained constant throughout the investigation to ensure that variations in performance could be attributed solely to the metakaolin content. A constant water–cement ratio of 0.40 was adopted to achieve adequate strength and durability characteristics for concrete paver blocks. Previous studies have shown that metakaolin replacement levels between 5% and 15% generally produce significant improvements in concrete performance due to enhanced pozzolanic activity and microstructural refinement (Zhang, Liu, & Chen, 2022). The detailed mix proportions adopted for the study are presented in Table 2.

Table 2: Mix Proportions

Mix	Metakaolin (%)	Cement (kg/m ³)	Metakaolin (kg/m ³)	Water–Cement Ratio
M0	0	400	0	0.40
M5	5	380	20	0.40
M10	10	360	40	0.40
M15	15	340	60	0.40
M20	20	320	80	0.40

2.3 Experimental Procedure

The experimental procedure involved batching, mixing, casting, compaction, curing, and testing of concrete paver block specimens. Initially, dry materials including cement, metakaolin, fine aggregate, and coarse aggregate were thoroughly mixed to ensure uniform distribution of constituents. Water was then added gradually and mixing was continued until a homogeneous concrete mix was obtained.

The fresh concrete was cast into standard paver block moulds and compacted using vibration to eliminate entrapped air and improve density. Proper compaction is essential because insufficient compaction can increase porosity and reduce strength and durability characteristics of concrete (Neville, 2011). After casting, the specimens were demoulded after 24 hours and cured in water for curing periods of 7, 14, and 28 days under controlled laboratory conditions.

The overall experimental methodology adopted in the present study is illustrated in Figure 1.

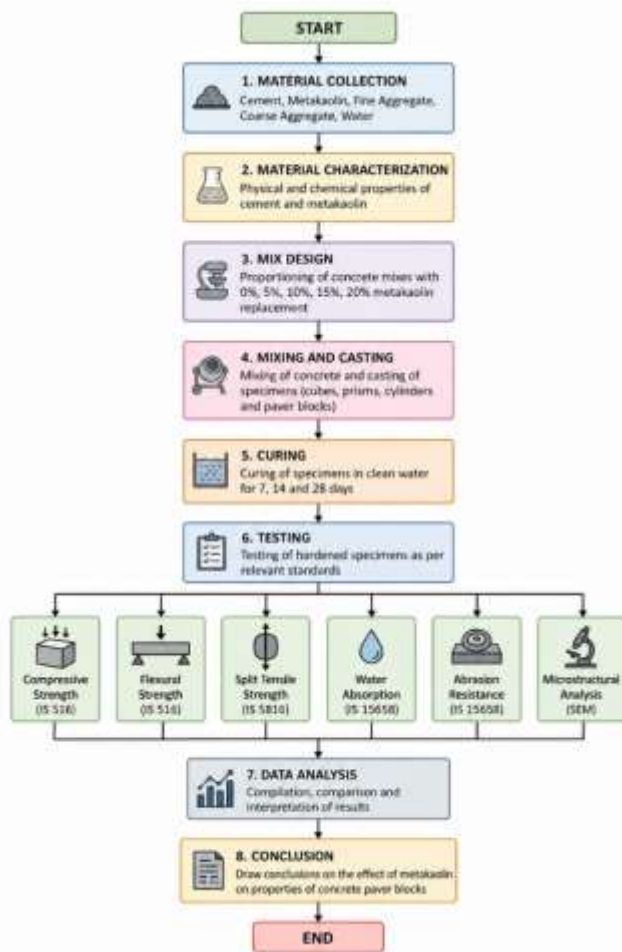


Figure 1: Experimental Flowchart

3. Results and Discussion

3.1 Workability

The workability of concrete mixes containing different percentages of metakaolin was evaluated using the slump test in accordance with IS 1199. The slump values obtained for the control mix (M0) and metakaolin-modified mixes are presented in Table 3, while the variation in slump with increasing metakaolin content is illustrated in Figure 2. The results show a gradual decrease in slump as the percentage of metakaolin increased. The control mix recorded the highest slump value of 80 mm, whereas mixes M5, M10, M15, and M20 recorded slump values of 75 mm, 70 mm, 65 mm, and 60 mm, respectively. This reduction in slump indicates that the incorporation of metakaolin decreases the workability of concrete mixes.

The reduction in workability is mainly attributed to the high fineness and increased specific surface area of metakaolin particles, which increase the water demand of the concrete mix. The ultrafine metakaolin particles absorb more water and reduce the amount of free water available for lubrication between aggregates, resulting in a stiffer mix (Sabir, Wild, & Bai, 2001). Similar findings were reported by Zhang et al. (2022), who observed that higher metakaolin replacement levels significantly reduce slump due to enhanced pozzolanic activity and particle packing effects. Although reduced workability may improve cohesiveness and reduce segregation, excessive reduction in slump can adversely affect compaction and increase internal voids. Therefore, proper dosage of metakaolin is necessary to maintain a balance between workability and hardened concrete performance.



Table 3: Slump Values

Mix ID	Metakaolin (%)	Slump (mm)
M0	0	80
M5	5	75
M10	10	70
M15	15	65
M20	20	60

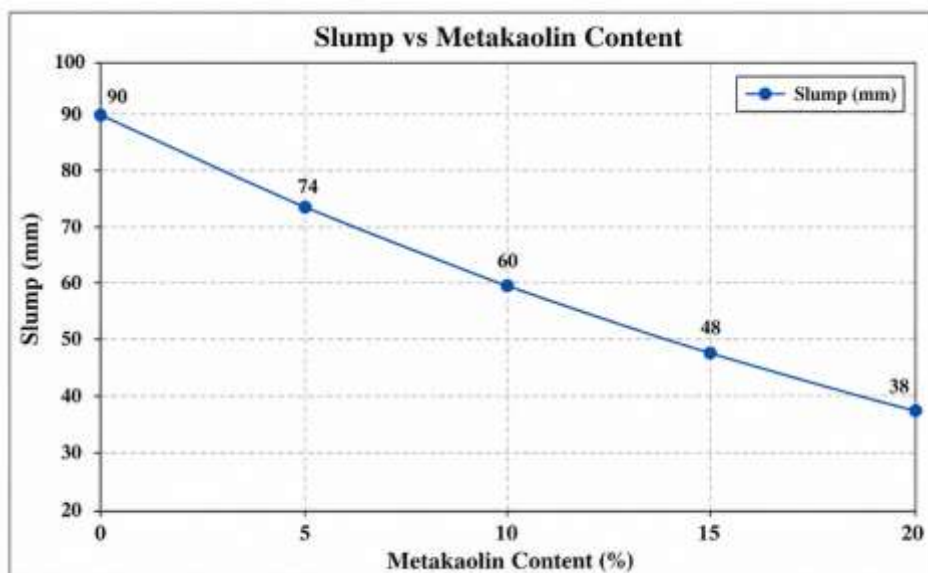


Figure 2: Slump Variation with Metakaolin Content

3.2 Compressive Strength

The compressive strength of concrete paver blocks was evaluated at curing ages of 7, 14, and 28 days to assess the influence of metakaolin on strength development. The results obtained are presented in Table 4, while the variation in 28-day compressive strength is illustrated in Figure 3. The results indicate that compressive strength increased progressively with curing age for all mixes. The control mix (M0) achieved compressive strengths of 28 MPa, 35 MPa, and 40 MPa at 7, 14, and 28 days, respectively. With the incorporation of metakaolin, compressive strength improved significantly up to 10% replacement. The M10 mix exhibited the highest 28-day compressive strength of 48 MPa, representing a substantial improvement compared with the control mix. However, beyond 10% replacement, a gradual decline in strength was observed, with the M15 and M20 mixes recording 46 MPa and 42 MPa, respectively.

The improvement in compressive strength is mainly attributed to the pozzolanic reaction and filler effect of metakaolin. Metakaolin reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H) gel, which densifies the cement matrix and improves the bond between aggregate and paste (Justice, Kurtis, & Monteiro, 2005). Furthermore, the ultrafine particles of metakaolin fill microvoids within the concrete matrix, resulting in improved particle packing and reduced porosity. Similar findings were reported by Sharma and Gupta (2023), who observed significant enhancement in compressive strength of metakaolin-modified pavement concrete up to an optimum replacement level of 10%. The reduction in strength beyond 10% replacement may be attributed to the dilution effect caused by excessive replacement of cement and reduced workability, which adversely affects compaction quality and internal density of concrete.



Table 4: Compressive Strength Results

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
M0	28	35	40
M5	30	38	44
M10	33	41	48
M15	31	39	46
M20	29	36	42

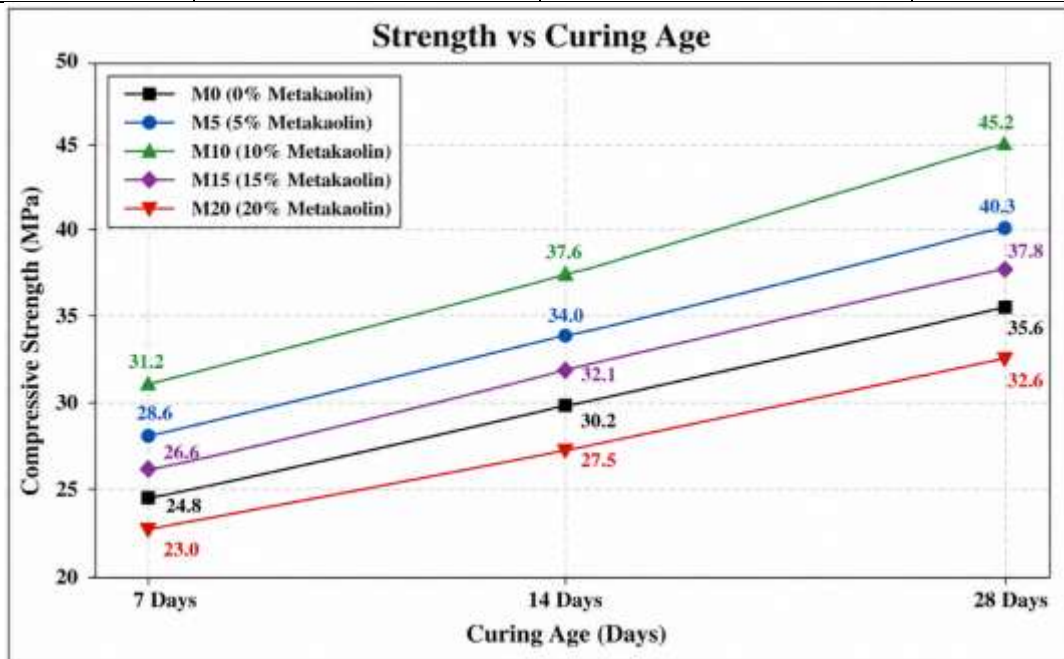


Figure 3: 28-Day Compressive Strength

3.3 Flexural Strength

Flexural strength is an important parameter for concrete paver blocks because it indicates the ability of concrete to resist bending stresses and crack formation under service loading conditions. The 28-day flexural strength results for different mixes are presented in Table 5. The results show that the incorporation of metakaolin improved the flexural strength of concrete up to 10% replacement. The control mix (M0) recorded a flexural strength of 5.2 MPa, whereas the M5 and M10 mixes achieved strengths of 5.6 MPa and 6.1 MPa, respectively. However, beyond the optimum replacement level, the flexural strength decreased slightly, with M15 and M20 mixes recording values of 5.8 MPa and 5.4 MPa, respectively.

The improvement in flexural strength is mainly attributed to the enhanced bonding between aggregate and cement paste due to the pozzolanic activity of metakaolin. The additional calcium silicate hydrate (C–S–H) gel formed during hydration refines the pore structure and strengthens the interfacial transition zone, thereby improving resistance to bending stresses (Sabir, Wild, & Bai, 2001). Similar findings were reported by Patel et al. (2022), who observed that metakaolin significantly enhances the flexural performance of concrete paving blocks due to improved matrix densification and reduced microcracking. The reduction in flexural strength beyond 10% replacement may be due to excessive cement replacement and reduced workability, which negatively affect compaction and internal concrete structure.

**Table 5: Flexural Strength Results**

Mix ID	28-Day Flexural Strength (MPa)
M0	5.2
M5	5.6
M10	6.1
M15	5.8
M20	5.4

3.4 Durability Properties

Durability properties of concrete paver blocks were evaluated through water absorption and abrasion resistance tests, as these parameters directly influence the long-term performance of pavement materials under environmental and traffic exposure. The durability test results are presented in Table 6. The results indicate that water absorption decreased significantly with the incorporation of metakaolin up to 10% replacement. The control mix recorded the highest water absorption value of 6.5%, whereas the M10 mix showed the lowest value of 5.1%. Similarly, abrasion loss decreased from 3.8 mm for the control mix to 2.9 mm for the M10 mix, indicating improved resistance to surface wear.

Table 6: Durability Test Results

Mix ID	Water Absorption (%)	Abrasion Loss (mm)
M0	6.5	3.8
M5	5.8	3.3
M10	5.1	2.9
M15	5.4	3.1
M20	5.9	3.5

The improved durability performance is mainly attributed to pore refinement and reduced permeability caused by the formation of additional calcium silicate hydrate (C–S–H) gel. The pozzolanic reaction of metakaolin fills capillary voids and produces a denser concrete matrix, thereby reducing water penetration and improving abrasion resistance (Justice, Kurtis, & Monteiro, 2005). Similar observations were reported by Sharma and Gupta (2023), who found that metakaolin-modified concrete exhibited lower permeability and higher abrasion resistance due to enhanced microstructural compactness. However, at higher replacement levels beyond 10%, the durability properties showed slight deterioration, which may be associated with reduced workability and incomplete hydration caused by excessive cement replacement.

4. Discussion

The experimental results clearly indicate that metakaolin significantly improves the overall performance of concrete paver blocks when used at an optimum replacement level. Among all the mixes investigated, the M10 mix containing 10% metakaolin exhibited the best overall performance, achieving the highest compressive strength, flexural strength, and split tensile strength while also recording the lowest water absorption and abrasion loss values. The compressive strength increased from 40 MPa for the control mix to 48 MPa for the M10 mix at 28 days, while flexural strength improved from 5.2 MPa to 6.1 MPa. Similarly, water absorption decreased from 6.5% to 5.1%, indicating a denser and less permeable concrete matrix. These findings demonstrate that the incorporation of metakaolin can effectively enhance both the mechanical and durability characteristics of concrete paver blocks. Similar improvements in concrete performance due to metakaolin incorporation were also reported by Zhang et al. (2022) and Sharma and Gupta (2023).

The improvement in performance can primarily be attributed to the pozzolanic reaction of metakaolin and the formation of additional calcium silicate hydrate (C–S–H) gel within the concrete matrix. Metakaolin reacts with calcium hydroxide generated during cement hydration and converts it into secondary C–S–H gel, which enhances the density and compactness of concrete. In addition, the ultrafine particles of metakaolin improve particle packing and reduce capillary pores, leading to lower permeability and improved abrasion resistance. The refinement of pore structure also strengthens the interfacial transition zone between aggregate and cement paste, which contributes significantly to the improvement in compressive and flexural strengths. Justice et al.



(2005) similarly observed that metakaolin enhances microstructural compactness and improves bonding characteristics in cement-based materials.

However, the results also indicate that replacement levels beyond 10% resulted in reduced performance. The M15 and M20 mixes showed lower strength and durability compared with the M10 mix. This reduction may be attributed to the excessive replacement of cement, which decreases the amount of cement available for hydration and leads to the dilution effect. Furthermore, higher metakaolin contents significantly reduced workability, as observed from the slump test results. Reduced workability can adversely affect compaction quality and increase internal voids within the concrete matrix, ultimately lowering strength and durability performance. Therefore, although metakaolin is highly beneficial as a supplementary cementitious material, its dosage must be carefully optimized to achieve a balance between workability, strength, and durability properties of concrete paver blocks.

5. Conclusions

The present study investigated the influence of metakaolin as a partial replacement of cement on the fresh, mechanical, and durability properties of concrete paver blocks. The experimental results demonstrated that the incorporation of metakaolin significantly affected the performance of concrete. Workability decreased progressively with increasing metakaolin content due to the high fineness and increased water demand of metakaolin particles. However, mechanical properties such as compressive strength, flexural strength, and split tensile strength improved considerably up to an optimum replacement level of 10%. Among all mixes, the M10 mix exhibited the best performance, achieving the highest 28-day compressive strength of 48 MPa along with improved flexural and tensile strengths. The enhancement in mechanical performance was mainly attributed to the pozzolanic reaction of metakaolin, formation of additional calcium silicate hydrate (C–S–H) gel, improved particle packing, and refinement of the concrete microstructure.

The durability properties of concrete paver blocks also improved significantly with metakaolin incorporation. Water absorption and abrasion loss values decreased notably up to 10% replacement, indicating a denser and less permeable concrete matrix with improved resistance to surface wear. The M10 mix recorded the lowest water absorption and abrasion loss among all the mixes, confirming that 10% metakaolin replacement provides the optimum balance between workability, strength, and durability characteristics. However, replacement levels beyond 10% resulted in reduced performance due to lower workability and dilution effects caused by excessive cement replacement. Overall, the findings of this study demonstrate that metakaolin can be effectively utilized as a sustainable supplementary cementitious material for the production of high-performance and durable concrete paver blocks suitable for pavement applications.

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