



Original Research Article

Performance Boundaries and Economic Viability of Cow Bone Ash and Metakaolin as Cement Replacements in High-Strength Concrete

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<http://doi.org/10.5281/zenodo.21046673>

ARTICLE INFORMATION

Article history:

Received 05 Apr. 2026

Revised 30 May 2026

Accepted 07 Jun. 2026

Available online 30 Jun. 2026

Keywords:

Cow bone ash

Metakaolin

Cementitious materials

High-strength concrete

Sustainable construction

ABSTRACT

The construction industry's high carbon footprint creates the need for development of sustainable cementitious materials. This study evaluates the performance boundaries and economic feasibility of cow bone ash (CBA) and metakaolin (MK) as partial cement replacements in high-strength concrete for rigid pavement applications. Replacement levels up to 30% were systematically evaluated through comprehensive testing of workability, compressive strength, split tensile strength, and economic viability. Five sets of concrete mixes were prepared, comprising control, 30% CBA, 20% CBA + 10% MK, 10% CBA + 20% MK, and 30% MK. Results revealed critical performance thresholds as CBA demonstrated acceptable behaviour as a bulk filler up to 30% replacement, achieving 75% of control compressive strength at 28 days, while enhancing workability. Metakaolin, however, showed negative effects beyond 10% replacement, with 30% MK reducing compressive strength to 51% of the control and compromising workability. Statistical analysis confirmed significant strength variations among mixtures. Economic assessment revealed substantial cost challenges as MK costs 5.71 times more than cement, and CBA costs 8.66 times more. Despite economic constraints, this study establishes crucial replacement boundaries showing that CBA is viable up to 30% for non-critical applications, while MK must be limited to 5-10% replacement levels. These findings provide essential guidance for optimizing ternary blends and preventing potential construction failures in sustainable concrete technology development.

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1. INTRODUCTION

Concrete is a major building material, widely used in many structural works and able to withstand high loads. However, rising cement costs and environmental impacts such as large carbon dioxide CO₂ emissions create the need for more sustainable alternatives. The global construction industry accounts

for approximately 8-10% of anthropogenic CO₂ emissions, with cement production alone contributing nearly 7% of total global emissions (Andrew, 2018; Monteiro et al., 2017). This environmental challenge, together with the depletion of natural resources and escalating cement costs, has led to research into sustainable alternatives and supplementary cementitious materials (SCMs) (Olutaiwo et al., 2017; Miller et al., 2016; Juenger and Siddique, 2015).

The concept of partial cement replacement addresses multiple sustainability dimensions including reducing greenhouse gas emissions, conserving natural resources, valorising industrial and agricultural waste streams, and potentially reducing construction costs (Snellings et al., 2012; Lothenbach et al., 2011). Among SCMs, metakaolin (MK) and cow bone ash (CBA) are widely studied for their pozzolanic action and local availability (Adanikin et al., 2021; Rashad, 2013).

Nigeria's construction sector faces challenges such as infrastructure deficits and increasing cement costs (National Bureau of Statistics, 2024). The country, however, generates substantial agricultural waste, including approximately 500,000 tonnes of cow bones annually from abattoirs and meat processing facilities (Federal Ministry of Agriculture and Rural Development, 2023). This waste causes environmental challenges and is a potential source for SCMs. Furthermore, despite growing interest in alternative SCMs, critical knowledge gaps persist.

Partial replacement of cement in rigid-pavement concrete can influence both fresh and hardened performance through two principal mechanisms. First, filler and packing effects, especially relevant to CBA can modify rheology and early densification by improving particle-size distribution within the paste. Second, pozzolanic reaction central to MK consumes portlandite to generate additional binding phases, potentially enhancing strength and durability when water demand is managed. Engineering success therefore depends on balancing constructability (workability at target w/c) with capacity (compressive and tensile performance linked to flexural behaviour).

Metakaolin is a highly reactive pozzolanic material produced by calcining kaolin clay at temperatures between 650-850°C (Rashad, 2013). Its amorphous aluminosilicate structure reacts with calcium hydroxide (Ca(OH)₂) liberated during cement hydration to form additional calcium silicate hydrate (C-S-H) gel, enhancing concrete properties (Wild et al., 1996). Studies reveals MK's benefits such as improved compressive strength, enhanced durability, reduced permeability, and superior resistance to chemical attack at optimal percentages (Geu et al., 2026; Al-Hashem et al., 2022). However, MK significantly increases water demand due to its high specific surface area (10,000-15,000 m²/kg), potentially compromising workability at higher replacement levels (Justice & Kurtis, 2007).

Cow bone ash (CBA) is an emerging SCM produced by calcining cow bones at 800-1000°C (Ajayi et al., 2023). The calcination process converts hydroxyapatite [Ca₁₀(PO₄)₆(OH)₂] into calcium oxide (CaO) and calcium phosphates, yielding a material with potential cementitious properties (Awoyemi et al., 2023). Studies suggest CBA can serve as a partial cement replacement, though its performance characteristics and optimal dosage ranges remain inadequately defined (Edun et al., 2023; Elinwa et al., 2008). The chemical composition of CBA typically includes 50-60% CaO, 30-40% P₂O₅, and minor constituents, differing substantially from conventional pozzolanic materials.

While literature suggests optimal MK replacement levels of 5-15% (Guneyisi et al., 2008; Poon et al., 2006), studies on behaviour beyond these thresholds are limited. Understanding failure mechanisms at higher replacement levels is important for preventing construction failures. Comprehensive data on CBA's performance as a cement replacement, particularly in high-strength concrete applications, is also limited. Most existing studies focus on low-to-medium strength concrete (Awoyemi et al., 2023; Edun et al., 2023). The effects of CBA-MK binary blends are poorly understood, yet such combinations could enhance concrete performance while managing costs. Few studies also integrate economic analysis with technical performance assessment, despite cost being a primary determinant of material adoption in developing countries (Flower & Sanjayan, 2007). Studies have also advocated for the need for Nigeria-specific data on SCM performance, accounting for local material characteristics and economic constraints (Olonade et al., 2023). Considering all these, this study investigates mechanical and

economic effects when up to 30% of cement is replaced by various CBA/MK proportions for high-strength concrete.

2. MATERIALS AND METHODS

2.1. Materials and Preliminary Characterization

Portland limestone cement was used with natural river sand and 20-mm nominal granite. CBA was obtained from locally sourced cow bones that were cleaned, calcined to ash, ground, and sieved to 75 μm . MK was produced by calcining purified kaolin at approximately 800 °C for 60 minutes to achieve dihydroxylation and pozzolanic reactivity. Preliminary tests conducted included sieve analysis of the sand and specific gravities for aggregates and cement. Chemical compositions for CBA and kaolin-derived MK were sourced from published studies.

2.2. Mix Design and Specimen Preparation

A Road Note 4-based proportion of 1:1.5:3 (cement:sand:granite) with $w/c = 0.40$ was adopted. Five binders were prepared, namely a 100% cement control and four modified mixes with 30% total binder replacement distributed between CBA and MK (CBA30MK0, CBA20MK10, CBA10MK20, CBA0MK30). Mixing followed a standardized sequence in a drum mixer to ensure homogeneity. Immediately after mixing, slump was measured. For hardened testing, 150-mm cubes were cast for compressive strength and 150×300-mm cylinders for split-tensile strength. Moulds were cleaned, lightly oiled, and filled in three layers with 25 tamping strokes per layer. Specimens were then struck off, labelled, and left undisturbed for 24 hours.

2.3. Curing and Test Procedures

After demoulding at 24 h, specimens were water-cured to the specified ages as shown in Figure 1 after which slump tests were conducted. Compressive strength was measured on cubes at 7 and 28 days (Figure 2). Split-tensile strength was measured at 28 days on cylinders (Figure 3). The compressive-strength loading rate and strengths were computed from peak load and specimen area, with results reported as the mean of three specimens for each age and mix.



Figure 1: Curing of concrete cubes prior to mechanical testing



Figure 2: Compressive strength test setup for concrete cubes



Figure 3: Split tensile strength test setup for concrete cylinders

2.4. Statistical and Economic Analysis

A one-way ANOVA was performed on the 28-day compressive strengths to test for between-mix differences at $\alpha = 0.05$ using triplicate results per mix. The study also compiled a market price snapshot for cement, MK (including processing), and CBA to contextualize cost implications through a simple cost-performance ratio. Cost-performance indices were calculated according to equation (1).

$$\text{Cost-Performance Index} = (\text{Material Cost per m}^3) / (\text{28-day Compressive Strength}) \quad (1)$$

This metric enables quantitative comparison of economic efficiency across mixtures.

3. RESULTS AND DISCUSSION

3.1. Concrete Workability

Workability results revealed variations among mixtures as shown in Table 1. The control mixture (CTRL) exhibited a slump of 20 mm, indicating low workability suitable for rigid pavement applications. CBA incorporation significantly enhanced workability, with CBA30MK0 achieving 32 mm slump (60% increase), suggesting CBA's role as a lubricating agent due to its smooth particle morphology. This aligns with the findings of Keerio et al. (2021), who revealed that CBA can maintain or improve fresh properties when its particle grading reduces the overall water demand of the mix.

Table 1: Slump test results for all concrete mixtures

Mix ID	Mix Composition	Slump (mm)	Change from Control (%)	Workability Classification
CTRL	100% Cement	20	-	Very Low / Stiff
CBA30MK0	70% Cement + 30% CBA + 0% MK	32	+60%	Low
CBA20MK10	70% Cement + 20% CBA + 10% MK	18	-10%	Very Low / Stiff
CBA10MK20	70% Cement + 10% CBA + 20% MK	8	-60%	Extremely Stiff
CBA0MK30	70% Cement + 0% CBA + 30% MK	5	-75%	Extremely Stiff / Harsh

However, as shown in Table 1, metakaolin (MK) incorporation drastically reduced workability. CBA20MK10 (10% MK) showed a 10% reduction in slump (18 mm), while CBA10MK20 (20% MK)

and CBA0MK30 (30% MK) produced nearly unworkable concrete with slumps of 8 mm and 5 mm, respectively. This behaviour is primarily due to MK's extremely high specific surface area and platelet morphology, which dramatically increases water demand for particle wetting (Justice & Kurtis, 2007). Bheel et al. (2024) also noted that workability decreases significantly as MK content increases, particularly when substituted as a binder fraction, due to the high reactivity and fineness of the powder. The binary blends demonstrated that MK's negative impact on workability dominates over CBA's beneficial effects. At 10% MK (CBA20MK10), workability remained marginally acceptable, but higher MK contents rendered the mixtures practically unworkable without the use of superplasticizers, consistent with recommendations by Keerio et al. (2021) to limit MK dosage or adjust water/powder ratios to maintain flow.

3.2. Compressive Strength Performance

Early-age strength results, as shown in Table 2, revealed distinct performance patterns. The control mixture achieved 23.16 MPa at 7 days, representing 61% of its 28-day strength. CBA30MK0 attained 16.82 MPa, indicating slower early strength development. This is a characteristic of pozzolanic materials, which require extended curing for the secondary reaction between silica and calcium hydroxide ($\text{Ca}(\text{OH})_2$) to occur (Wild et al., 1996). Higher MK contents for CBA10MK20 and CBA0MK30 resulted in progressively lower 7-day strengths of 11.95 MPa and 9.87 MPa, respectively. This decline is attributed to the dilution effect, where the replacement of reactive Portland cement clinker with slower-reacting pozzolans reduces the initial concentration of calcium silicate hydrate (C-S-H) phases (Singh et al., 2019).

Table 2: Compressive strength development (7 and 28 days)

Mix ID	7-day strength (MPa)	28-day strength (MPa)	7-to-28-day strength gain (%)	Strength development ratio
CTRL	23.16	38.00	64.13	0.61
CBA30MK0	16.82	28.45	69.20	0.59
CBA20MK10	14.23	26.22	84.32	0.54
CBA10MK20	11.95	22.80	90.63	0.52
CBA0MK30	9.87	19.38	96.40	0.51

The 28-day compressive strength results show critical performance boundaries for both SCMs. The control mixture achieved 38.00 MPa, exceeding the target strength of 30 MPa. The result of the CBA at the 28th day shows that CBA30MK0 achieved 28.45 MPa, representing a 25% strength reduction. This 25% strength reduction aligns with studies by Bheel et al. (2024), which found that high substitution levels of binder with CBA above 10-15% typically lead to mechanical strength reduction due to lower pozzolanic reactivity compared to cement. However, the absolute strength still exceeds the 25 MPa requirement for rigid pavements (ACPA, 2020). This suggests CBA's viability as a bulk filler for non-critical applications. The strength reduction could be attributed to CBA's limited pozzolanic reactivity and potential dilution effect from replacing highly reactive cement with less reactive material (Elinwa et al., 2008). The metakaolin comprehensive strength performance shows that the 30% MK replacement (CBA0MK30) yielded only 19.38 MPa, representing a significant 49% strength loss. This result contradicts the common perception that more pozzolan equals better performance and highlights the critical importance of optimal dosage. The decrease in strength could be attributed to factors such as excessive water demand, which leads to poor compaction and increased porosity. It may also result from insufficient cement to provide $\text{Ca}(\text{OH})_2$ for pozzolanic reactions and from the formation of poorly crystallized reaction products at high MK contents (Ambroise et al., 1994).

The binary blend performance using the strength development ratio as shown in Table 2 reveals that the values decreased progressively from 0.61 (CTRL) to 0.51 (CBA0MK30). This shows the diminished early strength contribution in mixes with higher replacement levels. The reduction in early strength can

be attributed to the dilution of Portland cement clinker phases, which delays the formation of calcium silicate hydrate (C-S-H). However, the subsequent increase in strength gain percentage reflects the gradual activation of MK's pozzolanic reactivity, consuming calcium hydroxide and forming secondary C-S-H and aluminosilicate hydrates. CBA, being less reactive, primarily acts as a microfiller, contributing to matrix densification but not significantly enhancing strength. The combined effect of MK and CBA therefore results in lower absolute strength but higher relative strength development over time. This suggests that excessively high SCM contents limit strength development potential, likely due to insufficient cement for sustained hydration and pozzolanic reactions. These findings therefore shows that while CBA/MK blends compromise early strength limiting their suitability for applications requiring rapid load-bearing capacity, they may offer long-term durability benefits through continued pozzolanic activity and refined pore structure.

3.3. Split Tensile Strength Performance

The split tensile strengths of the mixes at 28 days are presented in Table 3. The control achieved 3.07 MPa. Substitution of 30% CBA (CBA30MK0) resulted in a proportional decrease (2.18 MPa). MK-dominated mixes (CBA10MK20, CBA0MK30) reached much lower tensile strengths of 1.76 MPa and 1.52 MPa, respectively. This trend of decreasing split tensile strength with increasing ash-based replacement is consistent with findings on concrete incorporating ash where 10-30% replacement of fine aggregate led to reductions in 28-day split tensile strength (Wan Ibrahim et al., 2015). Similarly, concrete with high levels of bottom ash and fly ash has been shown to maintain compressive strength at later ages but to exhibit more sensitive flexural and splitting tensile responses at higher replacement levels (Rafieizonooz et al., 2016).

Table 3: Split tensile strength results

Mix ID	28-day tensile (MPa)	28-day as % of control
CTRL	3.07	100%
CBA30MK0	2.18	71%
CBA20MK10	2.01	65%
CBA10MK20	1.76	57%
CBA0MK30	1.52	49%

The split tensile strength findings show the important effect of binder composition in determining concrete's resistance to indirect tensile failure. In this study, control concrete exhibited high tensile properties, while increasing substitution levels of both CBA and MK resulted in a decrease in split tensile strength at 28 days. This behaviour aligns with findings on ash-based cementitious replacements, where increasing bone powder beyond an optimum typically causes reductions in both compressive and split tensile strengths (Teshome et al., 2019; Wan Ibrahim et al., 2015). This suggests that low pozzolanic replacement levels may only slightly enhance tensile properties by densifying the matrix and improving interfacial bonding. MK is known to enhance microstructural development and bond strength when used at optimal dosages.

This also aligns with studies indicating peak tensile strength at 10-15% metakaolin replacement, with strength declining at higher contents (Ghughe et al., 2018; Vipat and Kulkarni, 2016). However, excessive MK may reduce available calcium hydroxide for pozzolanic reactions and lead to lower particle packing efficiency. These microstructural limitations manifest as increased micro-cracking and diminished tensile performance at high replacement levels, a trend observed in this study's high-MK mixes. CBA, while moderately improving particle packing and fostering internal curing at lower dosages, likewise demonstrates diminishing returns beyond optimal substitution rates. The observed reduction in split tensile strength at higher CBA contents mirrors the behaviour of concretes with elevated coal bottom ash contents, where increased porosity and weaker interfacial transition zones have been linked to lower tensile capacity (Rafieizonooz et al., 2016; Wan Ibrahim et al., 2015). The

reduction in split tensile strength with higher CBA and MK contents shows that sustainable replacement levels must be carefully controlled to ensure concrete durability performance.

3.4. Statistical Analysis

One-way ANOVA revealed statistically significant differences in 28-day compressive strength among the five mixtures. The ANOVA summary is presented in Table 4.

Table 4: ANOVA results for 28-day compressive strength

Source of variation	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	F-statistic	P-value	F-critical
Between Groups	578.92	4	144.73	892.45	0.0001	3.24
Within Groups	1.62	10	0.162			
Total	580.54	14				

The calculated F-statistic (892.45) is much greater than the critical value (3.24), and the p-value (0.0001) is well below the typical significance threshold (0.05), indicating highly significant differences among group means. Thus, the null hypothesis that no statistically significant difference exists between the mean compressive strengths of the mixes is rejected. The use of ANOVA to distinguish between mixtures is consistent with statistical approaches applied to metakaolin concretes. Response surface methods and variance analysis have been used to quantify the influence of metakaolin content and water-binder ratio on compressive and splitting tensile strengths (Al-Alaily and Hassan, 2016).

The study by Khan et al. (2025) showed that split tensile and compressive strengths are highly sensitive to mix-design variables. Their study confirms that binder composition and water-cement ratio produce statistically significant shifts in the mechanical performance of concrete. Their findings align with this study's findings that changes in CBA and MK levels produce performance differences rather than random variation. Li et al. (2023) in their study revealed that metakaolin content, curing age, and binder proportions significantly influence splitting tensile strength. The study used machine-learning models for the statistical analysis. This aligns with this study's ANOVA results, which confirm that the observed reductions in strength at higher CBA and MK replacement levels reflect material behaviour. The study by Garcia et al. (2024) further supports the statistical significance of SCM-induced strength changes. Their modelling of metakaolin concrete mixes showed that even small variations in MK dosage produce measurable and statistically meaningful differences in splitting tensile strength. This supports the need for variance analysis when evaluating SCM replacement thresholds as done in this study.

This statistical validation confirms that the observed strength reductions at higher replacement levels are statistically significant, reinforcing the boundary-defining nature of the study. The statistically significant reductions at specific CBA and MK contents align with optimisation studies that identify narrow SCM dosage ranges for balanced strength and durability performance (Al-Alaily & Hassan, 2016; Li et al., 2023), supporting the reliability of the recommended limits.

3.5. Economic Analysis

Economic analysis, as shown in Table 5, revealed substantial cost implications of SCM utilization. Despite reducing cement consumption by 30%, SCM-containing mixtures exhibited higher costs due to expensive SCM procurement and processing.

CBA0MK30	₦1,107 (\$0.72)	51%	8.18
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The result reveals that at ₦1,200/kg (\$0.78) ($5.71 \times$ cement cost), metakaolin's price severely limits economic viability, particularly given its detrimental effects at high replacement levels. Despite

utilization as waste material, CBA costs ₦1,818/kg (\$1.18) ($8.66\times$ cement cost) due to energy-intensive calcination and grinding requirements. Current processing costs make CBA economically uncompetitive at small production scales.

Table 5: Economic analysis of concrete mixtures (2024 market prices)

Mix ID	Material Cost per kg of Binder	Performance (% of Control)	Cost-Performance Ratio
CTRL	₦210 (\$0.14)	100%	1.00
CBA30MK0	₦693 (\$0.45)	75%	3.30
CBA20MK10	₦831 (\$0.54)	69%	4.53
CBA10MK20	₦969 (\$0.63)	60%	6.08

Industrial-scale production with optimized energy efficiency and mechanized grinding could potentially reduce CBA costs by 60-70%, improving economic viability (Habert et al., 2010). Mixes with higher CBA and MK content had strongly elevated cost-performance ratios. While control concrete was the least expensive per unit performance, cost per strength achieved rose with increasing replacement, especially for MK-rich mixes. Studies by Yang et al. (2015), however, show that while direct economic analysis favours conventional cement, comprehensive life-cycle assessment incorporating environmental factors may change the economic balance toward SCMs. The observed MK performance aligns with established literature. Kashyap and Supe (2024) reported optimal MK replacement at 10-15%, with strength reductions at higher levels. Justice and Kurtis (2007) documented severe workability issues beyond 15% MK, consistent with this study's findings. The constant tensile-compressive strength ratio (0.100) across all mixtures aligns with Atis (2003), who reported that pozzolanic admixtures maintain this fundamental relationship.

4. CONCLUSION

This study's investigation of cow bone ash and metakaolin as partial cement replacements in high-strength concrete establishes critical performance boundaries and economic benchmarks for sustainable construction applications. The following conclusions are drawn:

- i. CBA demonstrates acceptable performance up to 30% replacement, while MK exhibits catastrophic failure beyond 15% replacement, with 30% MK achieving only 51% of control strength.
- ii. Metakaolin's high specific surface area causes severe workability deterioration, rendering concrete practically unworkable at 30% replacement. CBA conversely enhances workability.
- iii. Current SCM costs make these materials uneconomic, so larger-scale production and local sourcing are required for viability.
- iv. CBA is viable for non-critical applications such as pavement sub-bases, mass concrete at less than 30% replacement with MK limited to 5-15% replacement for any application. Exceeding these boundaries poses significant structural risks.
- v. Despite current economic constraints, these materials offer significant environmental benefits such as waste valorisation, CO₂ reduction, resource conservation that may justify adoption with appropriate policy support and technological advancement.

The primary contribution of this research lies in establishing evidence-based performance boundaries that define practical application limits for CBA and MK. These findings provide essential guidance for future optimization studies and prevent potential structural failures from inappropriate SCM dosages.

5. ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and contributions of the laboratory staff of Department of Civil Engineering, University of Lagos toward the success of this work.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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