

Assessment of Millet Husk Ash - Cement Blended Concrete for Sustainable Rigid Pavement Applications

Evaluación de hormigón con cemento parcialmente reemplazado por ceniza de cáscara de mijo para aplicaciones sostenibles en pavimentos rígidos

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Fecha de Recepción: 19/02/2026

Fecha de Aceptación: 26/07/2026

Fecha de Publicación: 06/08/2026

PAG: 1-13

Abstract

This study presents an evaluation of cement-millet husk ash (CMHA) concrete for sustainable rigid pavement applications using destructive and non-destructive testing techniques. Millet husk ash (MHA), obtained from controlled burning of agricultural waste, was used to replace ordinary Portland cement (OPC) at 0-20% (at 5% increment) by weight in two nominal mix proportions of 1:2:4 and 1:1.5:3. Fresh concrete properties were examined through slump and setting time tests, while hardened performance was assessed using compressive strength testing at 3, 7, 14, and 28 days. Complementary non-destructive tests, including rebound hammer and ultrasonic pulse velocity (UPV), were employed to characterize surface hardness, internal concrete quality, and microstructural integrity. Results showed that MHA replacement between 5 -10% improved workability, densification, and strength development due to enhanced pozzolanic activity and matrix refinement. This improvement was consistently reflected in both destructive and non-destructive indicators. However, higher replacement levels resulted in reduced performance, attributed to excessive dilution of cementitious compounds. The findings showed that MHA is a viable supplementary cementitious material for rigid pavement concrete and supports sustainable construction through reduced cement consumption and effective waste utilization, and an optimal replacement range of 5-10% is recommended for structural pavement applications.

Keywords: Destructive and Non-destructive Tests; Millet husk ash; Sustainable Rigid Pavement; Agricultural wastes.

Resumen

Este estudio presenta una evaluación del hormigón de cemento-ceniza de cáscara de mijo (CMHA) para aplicaciones sostenibles en pavimentos rígidos, utilizando técnicas de ensayo destructivas y no destructivas. La ceniza de cáscara de mijo (MHA), obtenida mediante la combustión controlada de residuos agrícolas, se utilizó como sustituto parcial del cemento Portland ordinario (OPC) en proporciones del 0 al 20 % (con incrementos del 5 %) en peso, empleando dos dosificaciones nominales de 1:2:4 y 1:1,5:3. Las propiedades del hormigón fresco se evaluaron mediante los ensayos de asentamiento (slump) y tiempo de fraguado, mientras que el comportamiento del hormigón endurecido se determinó mediante ensayos de resistencia a la compresión a los 3, 7, 14 y 28 días. Como complemento, se realizaron ensayos no destructivos, incluidos el martillo de rebote (Schmidt) y la velocidad de pulso ultrasónico (UPV), para caracterizar la dureza superficial, la calidad interna del hormigón y la integridad de su microestructura. Los resultados mostraron que una sustitución de MHA entre el 5 y el 10 % mejoró la trabajabilidad, la densificación y el desarrollo de la resistencia debido a una mayor actividad puzolánica y al refinamiento de la matriz. Esta mejora se reflejó de manera consistente tanto en los indicadores de los ensayos destructivos como en los no destructivos. Sin embargo, niveles de sustitución superiores provocaron una disminución del rendimiento, atribuida a la excesiva dilución de los compuestos cementantes. Los resultados demuestran que la ceniza de cáscara de mijo constituye un material cementante suplementario viable para el hormigón destinado a pavimentos rígidos y favorece la construcción sostenible mediante la reducción del consumo de cemento y el aprovechamiento eficiente de los residuos agrícolas. Se recomienda un rango óptimo de sustitución del 5 al 10 % para aplicaciones estructurales en pavimentos.

Keywords: Ensayos destructivos y no destructivos; ceniza de cáscara de mijo; pavimento rígido sostenible; residuos agrícolas.

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1. Introduction

The global increase in civil infrastructure has intensified the demand for durable, cost-effective, and environmentally sustainable pavement materials (Sharma et al., 2024; Tafida et al., 2024). Conventional Portland cement concrete is a dominant material in rigid pavement construction (Chore and Joshi, 2020; Kumar and Sharma, 2022; Okon and Ngene, 2025; Patil and Katare, 2023). It is associated with high energy consumption and significant emissions of carbon dioxide, contributing nearly 8% of global greenhouse gas emissions from industrial sources (Abdayem et al., 2024). In addition to environmental concerns, rising cement costs and depletion of natural resources pose economic challenges for developing countries striving to expand their road networks (Azubuike et al., 2023). These issues underscore the urgent need to explore alternative binders and supplementary cementitious materials that can reduce the ecological footprint of concrete while maintaining structural performance (Mudgal and Chellasamy, 2024; Ramachandran, 2021).

Agro-waste by-products have gained attention as sustainable alternatives due to their pozzolanic properties and potential to enhance concrete durability (Banu et al., 2020; He et al., 2020). Materials such as rice husk ash, palm oil fuel ash, and millet husk ash are rich in silica and alumina, which contribute to secondary hydration reactions that improve strength and reduce permeability (Olaiya et al., 2025). Millet husk ash, in particular, represents an underutilized resource in many developing regions (Mohammed et al., 2021). Its incorporation into concrete not only diverts agricultural waste from landfills but also supports circular economy principles by transforming residues into valuable construction inputs (Banu et al., 2020; Bheel et al., 2024). Recent studies have demonstrated that agro-waste ashes can improve compressive strength, durability, and resistance to chemical attack, making them promising candidates for rigid pavement applications (Alharthai et al., 2024; Charitha et al., 2021; He et al., 2020).

Rigid pavements are designed to withstand heavy traffic loads and long service lives, requiring materials with superior mechanical and durability properties (Manjunatha et al., 2024). Ensuring the quality of such pavements demands rigorous evaluation techniques. Traditional destructive testing methods, for example, compressive strength tests, remain fundamental in concrete research, providing direct and reliable measurements of strength and durability parameters essential for validating material performance (Monteiro, 2006). Non-destructive testing (NDT) methods, including ultrasonic pulse velocity, rebound hammer and ground-penetrating radar, provide reliable alternatives for assessing concrete quality and durability without damaging the structure (Lencis et al., 2024). These methods enable continuous monitoring and facilitate performance-based design approaches in pavement engineering that align with modern infrastructure sustainability goals (Abdollahi-Mamoudan et al., 2025; Bertolini et al., 2023).

Despite growing interest in agro-waste utilization, limited research has focused specifically on millet husk ash as a partial cement replacement in rigid pavement applications, particularly evaluated through Non-Destructive Testing and Destructive Testing methods. This gap highlights the need for systematic investigation into the suitability of cement-millet husk ash concrete for sustainable pavement construction.

Therefore, this study aims to conduct a destructive and Non-Destructive Assessment of Millet Husk Ash-Blended Cement Concrete for Sustainable Rigid Pavement Applications. The methodology involves preparing concrete mixes with varying proportions of millet husk ash, subjecting them to standardized Non-Destructive Testing and Destructive Testing procedures, and analyzing their performance relative to conventional cement concrete. By addressing this research gap, the study contributes to advancing sustainable infrastructure development, reducing environmental impacts, and promoting innovative material practices in civil engineering.

The objectives of the study are to: (i) investigate the effects of partial replacement of ordinary Portland cement (OPC) with millet husk ash (MHA) at replacement levels of 0-20% (at 5% increment) on the fresh properties of concrete, including workability and setting characteristics; (ii) assess the compressive strength development of MHA-Cement concrete at different curing ages; (iii) examine the quality and integrity of the concrete using rebound hammer and ultrasonic pulse velocity (UPV) tests; and (iv) determine the optimum MHA replacement level capable of producing durable and structurally adequate concrete suitable for rigid pavement construction while promoting sustainable utilization of agricultural waste.

The remaining parts of this paper is organized as follows: Section 2 describes the materials used, preparation of millet husk ash, mix design, specimen preparation, and the experimental procedures adopted for both destructive and non-destructive testing. Section 3 presents and discusses the experimental results, including the fresh and hardened properties of millet husk ash-cement concrete, as well as the rebound hammer and ultrasonic pulse velocity evaluations. Lastly, Section 4 summarizes the major findings of the study, presents the conclusions, and

provides recommendations regarding the optimum use of millet husk ash as a supplementary cementitious material for sustainable rigid pavement applications.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC) conforming to BS EN 197-1 was used as the primary binder (British Standards Institution [BSI], 2011). Millet husk ash (MHA) was produced through controlled burning of millet husks, followed by grinding and sieving through a 75 μm sieve in accordance with ASTM C618 (ASTM 2023). River sand classified as Zone II and 20 mm crushed granite conforming to BS EN 12620 were used as fine and coarse aggregates, respectively (British Standards Institution [BSI], 2002). Potable water free from deleterious impurities was used throughout the study. Primary equipment included 150 mm steel cube moulds, a slump cone, Vicat apparatus, density bottles, a Universal Testing Machine (UTM), a digital rebound hammer, and an ultrasonic pulse velocity (UPV) tester.

Given that millet husk ash (MHA) is an agro-waste by-product whose chemical and physical properties may vary depending on the source of the husks and processing conditions, quality control measures were adopted to ensure consistency of the material used in this study. The millet husks were obtained from a single source and subjected to controlled burning under uniform conditions to minimize variations in ash composition and carbon content. The resulting ash was allowed to cool naturally, ground to improve fineness, and sieved through a 75 μm sieve in accordance with ASTM C618 requirements. These procedures were intended to produce a homogeneous pozzolanic material with consistent particle size distribution and reactivity. Also, physical characterization tests, including specific gravity and setting time determination, were conducted to verify the suitability of the ash for use as a supplementary cementitious material. Such quality control measures are essential for reducing variability in agro-waste-derived pozzolans and ensuring reliable performance in concrete applications (Mohammed et al., 2021; Charitha et al., 2021).

2.2 Mix Design and Sample Preparation

Two nominal mix ratios (1:2:4 and 1:1.5:3) were adopted, with OPC partially replaced by MHA at 0, 5, 10, 15, and 20% by volume. A constant water–cement ratio of 0.50 was maintained. Dry constituents were manually mixed to achieve uniformity, and fresh concrete was cast into 150 mm $\times$ 150 mm $\times$ 150 mm steel cube moulds in three layers, each compacted with 25 blows of a tamping rod, following standard concrete casting procedures (British Standards Institution [BSI], 2019). After 24 hours, specimens were demoulded and cured in clean water until testing at ages of 3, 7, 14, and 28 days.

2.3 Materials Characterization

Sieve analysis of aggregates was carried out in accordance with BS 812-103.1 (British Standards Institution [BSI], 1985), while specific gravity tests for cement, MHA, and sand were conducted using density bottles in line with the standard laboratory procedures (ASTM International, 2023). The setting time of cement–MHA pastes was determined using a Vicat apparatus in accordance with ASTM C191, using a constant binder mass of 400 g and a water-to-binder ratio of 0.28 (ASTM International, 2022).

2.3.1 Fresh Concrete Tests

Concrete workability was evaluated using the slump test in accordance with BS EN 12350-2, with slump values recorded immediately after mixing for all concrete mixes (British Standards Institution [BSI], 2019).

2.3.2 Hardened Concrete Tests

Compressive strength tests were performed using a Universal Testing Machine (UTM) in accordance with BS EN 12390-3 (British Standards Institution [BSI], 2019). For each mix and curing age, three cube specimens were tested, and the average compressive strength was reported. Non-destructive tests were also conducted on all cured specimens:

- Rebound Hammer Test: Surface hardness was assessed following BS 1881-202, with three readings taken per cube and averaged (British Standards Institution [BSI], 1986).
- Ultrasonic Pulse Velocity (UPV) Test: Internal concrete quality was evaluated using the direct transmission method in accordance with BS 1881-203 and ASTM C597 (ASTM, 2022; British Standards Institution [BSI], 1986).

2.3.3 Data Analysis

All results were averaged, tabulated, and plotted to evaluate the influence of MHA content and curing age on workability, setting time, compressive strength, and NDT parameters. Comparative interpretation was used to determine the optimum MHA replacement level for pavement-grade concrete.

3. Results and Discussion

3.1 Material Characterization Results

3.1.1 Aggregate Properties

The physical properties of fine and coarse aggregates were evaluated through sieve analysis and particle size distribution to confirm their compliance with standard specifications for concrete production. The results are indicated in Figure 1 and Figure 2 for fine and coarse aggregates, respectively.

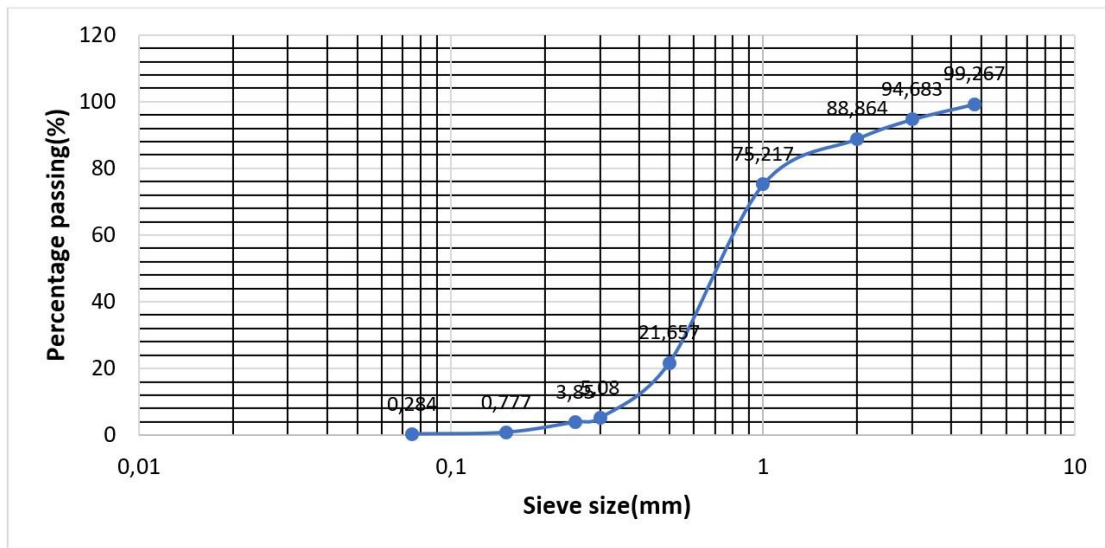


Figure 1. Sieve Analysis for fine aggregates.

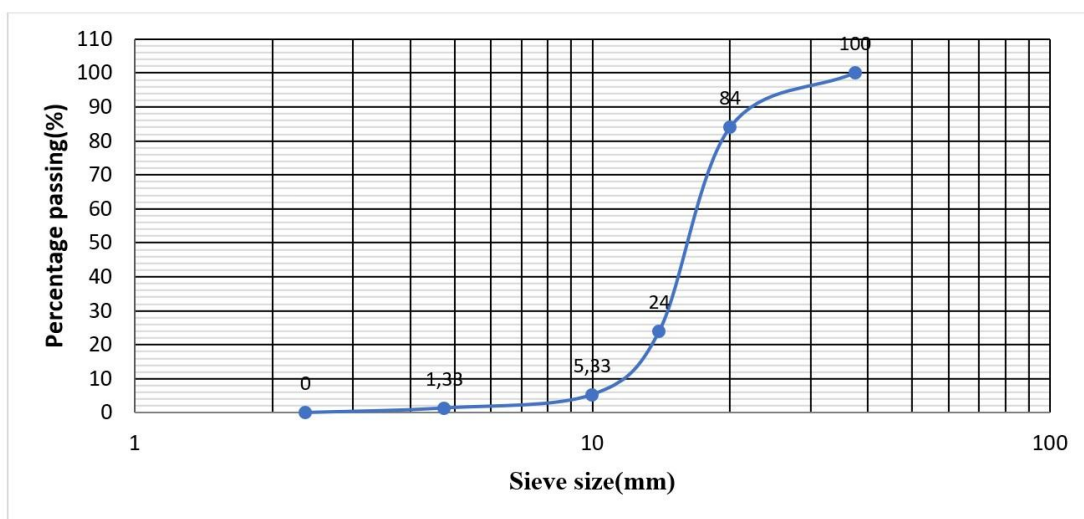


Figure 2. Sieve analysis for coarse aggregates.

The sieve analysis results indicated that the fine aggregates were well graded and fell within Zone II of BS 882 (1992), confirming their suitability for concrete work. The coarse aggregates exhibited a continuous and uniform grading pattern, ensuring efficient particle packing and minimal voids in the mix. The use of river sand, with its rounded particles, contributed to improved workability, while the angular texture of crushed granite enhanced interlocking and bond strength. These results align with BS 812: Part 103.1 requirements.

3.1.2 Chemical and Oxide Composition of Cement and MHA

Table 1 shows the oxide composition of Ordinary Portland Cement (OPC) and MHA as obtained from Mohammed et al. (2021). Based on the oxide composition reported, the MHA contained a high silica (SiO_2) content of 64.22%, together with alumina (Al_2O_3) and iron oxide (Fe_2O_3), giving a combined value of 71.42%, which satisfies the minimum 70% requirement specified by ASTM C618 for natural pozzolans.

Table 1. Oxide Composition of Cement and MHA.

<i>Oxides</i>	<i>Cement</i>	<i>MHA</i>
<i>SiO₂</i>	12.01	64.22
<i>Al₂O₃</i>	3.03	3.71
<i>Fe₂O₃</i>	4.14	3.49
<i>CaO</i>	74.06	6.55
<i>MgO</i>	1.4	2.81
<i>SO₃</i>	2.05	1.56
<i>Na₂O</i>	-	0.86
<i>K₂O</i>	1.27	6.01
<i>P₂O₅</i>	-	4.06
<i>Cl</i>	0.1	1.05
<i>TiO₂</i>	0.33	0.71
<i>Cr₂O₃</i>	-	-
<i>Mn₂O₃</i>	-	0.09
<i>ZnO</i>	-	0.09
<i>SrO</i>	0.49	0.06
<i>LoI</i>	1.04	4.54

Source: Mohammed et al. (2021)

The high silica content promotes secondary pozzolanic reactions with calcium hydroxide released during cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel that enhances matrix densification and strength development (Monteiro, 2006; Charitha et al., 2021). This explains why concrete mixes containing 5-10% MHA exhibited comparable or slightly improved compressive strength, rebound hammer values, and ultrasonic pulse velocity (UPV) results relative to the control mix.

The relatively low calcium oxide (CaO) content of MHA (6.55%) compared with cement (74.06%) indicates that MHA functions primarily as a supplementary cementitious material rather than a self-cementing binder. Consequently, at higher replacement levels (15-20%), there will be an observed reduction in available cementitious compounds, leading to dilution effects, slower hydration, and lower strength development, a trend similarly reported for other agricultural ashes such as rice husk ash and palm oil fuel ash (Givi et al., 2010).

The loss on ignition (LOI) value of 4.54% indicates relatively low unburnt carbon content and suggests that the controlled burning process produced a reasonably reactive ash. Nevertheless, the reviewer's concern regarding the variability of agro-waste ashes is justified because factors such as burning temperature, residence time, and milling conditions can significantly influence the chemical composition and reactivity of MHA (Mohammed et al., 2021).

3.1.3 Specific Gravity Results

The specific gravity of cement, millet husk ash (MHA), and fine aggregates was determined to evaluate their relative densities and suitability for concrete production, and the results are shown in Figure 3.

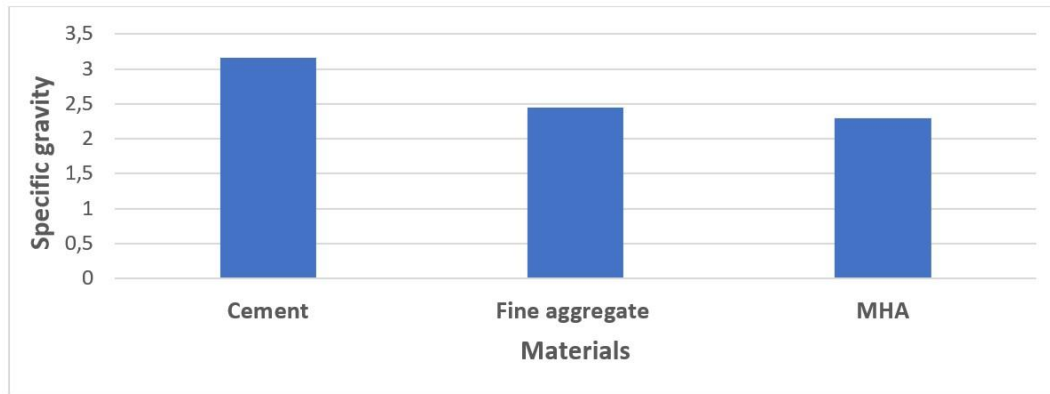


Figure 3. Specific gravity of materials.

As shown in Figure 3, millet husk ash (MHA) exhibits a lower specific gravity than Ordinary Portland Cement (OPC), confirming that MHA is a lighter and less dense material. This lower specific gravity implies that, for the same mass replacement level, MHA occupies a larger volume than OPC, thereby increasing the paste volume and total surface area within the concrete matrix. Consequently, mixes incorporating MHA tend to exhibit higher water demand and reduced workability, as more water is required to coat the finer and more porous ash particles. In the hardened state, the increased solid volume and improved particle packing associated with low-density pozzolans may enhance pore refinement and contribute to strength development at later curing ages through pozzolanic reactions. However, at higher MHA replacement levels, the pronounced difference in specific gravity observed in Figure 3 may lead to cement dilution, which can adversely affect early-age compressive strength. Similar trends have been reported for other low-specific-gravity agro-waste pozzolans such as rice husk ash and palm oil fuel ash (Neville, 2011; Monteiro, 2006; Givi et al., 2010).

3.2 Effect of HMA on Setting Time and Density

3.2.1 Results of the Setting Time Test

The effect of millet husk ash (MHA) on the setting times of cement paste was evaluated using the Vicat apparatus in accordance with BS EN 196-3:2016. Figure 4 illustrates the variation of initial and final setting times with increasing MHA replacement levels (0-20%).

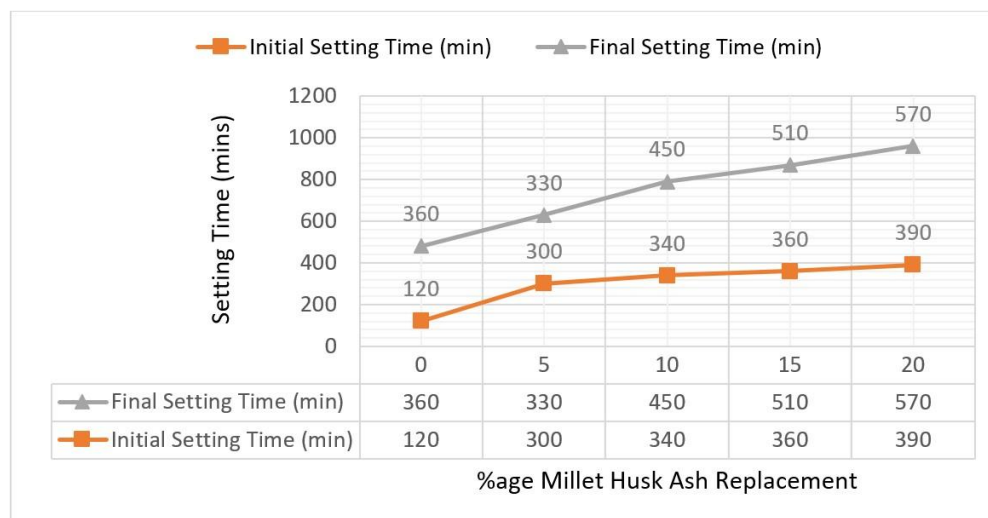


Figure 4. Variation of Initial and Final Setting Time with MHA Replacement.

Figure 4 shows a steady increase in both initial and final setting times as the proportion of MHA increased. The control mix (0% MHA) recorded an initial set of 2 hours and a final set of 6 hours, while at 20% replacement, the initial and final sets extended to 6.5 hours and 9.5 hours,

respectively. This delay confirms that MHA acts as a set-retarding pozzolanic additive. Its high silica content reacts slowly with calcium hydroxide released during cement hydration, forming secondary calcium silicate hydrates (C-S-H) at later ages, thereby reducing the rate of early stiffening. Similar trends have been reported for other agricultural pozzolans such as rice husk ash and palm bunch ash, where increased replacement levels prolong setting due to reduced early reactivity (Givi et al., 2010).

Despite the observed delays, all values remained within the acceptable limits prescribed by ASTM C191 and BS EN 196-3, which require an initial set of not less than 45 minutes and a final set not exceeding 10 hours. This confirms that cement-MHA blends are suitable for general-purpose concrete applications.

3.2.2 Density of Concrete Cubes

The results presented in Figures 5 and 6 showed the variation of cube mass and density for both mix ratios (1:2:4 and 1:1.5:3) at different levels of Millet husk ash (MHA) replacement. The density of concrete decreased consistently with increasing MHA replacement for both mix ratios. This reduction is directly related to the lower specific gravity of millet husk ash (2.30) compared to that of cement (3.16). The introduction of MHA into the binder reduces the overall mass per unit volume of the concrete, thus lowering its density.

At all curing ages, the control samples (0% MHA) exhibited the highest densities, while the 20% replacement samples recorded the lowest. This pattern is observed for both 1:2:4 and 1:1.5:3 mixes. Additionally, densities increased progressively with curing age for all mixtures. This can be attributed to the continued hydration and pore refinement that occur over time, leading to a denser and more compact matrix.

At 10% MHA replacement, the densities of both mixes remained within the range commonly acceptable for structural concrete (2200-2600 kg/m³), indicating that MHA substitution up to this level does not significantly affect the load-bearing capacity. However, beyond 15% replacement, the reduction in density became more noticeable, suggesting possible limitations for structural use at higher replacement levels. The density results reflect that MHA can be effectively used as a partial cement replacement (up to 10%) without compromising the essential properties of normal-weight concrete.



Figure 5. Line graph of density vs. MHA replacement (1:2:4 Mix).



Figure 6. Line graph of density vs. MHA replacement (1:1.5:3).

From the results presented in Figures 5 and 6, it was observed that the 1:1.5:3 mix demonstrates a similar trend. Densities decreased gradually as MHA replacement increased, but the values were consistently higher than those of the 1:2:4 mix. This is due to the richer binder content in the 1:1.5:3 mix, which produces denser and more cohesive concrete. Figures 5 and 6 further confirms that 10% MHA yields comparable densities to the control mix, while 15% and 20% levels lead to more notable reductions. At lower replacement levels (5 - 10%), strength values were comparable to or slightly higher than the control mix, indicating that MHA contributes to the development of additional calcium-silicate-hydrate (C-S-H) gel at later ages. However, at higher replacement levels (15% and 20%), the dilution of cement led to slower hydration and reduced strength.

3.3 Fresh Concrete Properties

3.3.1 Resu Workability (Slump Test) Results

The workability of cement–millet husk ash (MHA) concrete was evaluated using the slump test in accordance with BS EN 12350-2. Figure 7 presents the variation in slump values for the 1:2:4 and 1:1.5:3 mix ratios at different levels of MHA replacement.



Figure 7. Slump Values for Mix 1:2:4 and 1:1.5:3 at Varying MHA Contents.

The slump test results revealed a gradual decline in workability as the percentage of MHA increased for both mix ratios. At 20% replacement, slump values decreased by more than 35% compared with the control mix, indicating reduced ease of mixing and placing. In the 1:2:4 mix, slump reduced from 65 mm to 40 mm, while in the 1:1.5:3 mix, it decreased from 75 mm to 48 mm. The richer binder content in the 1:1.5:3 mix helped maintain slightly better workability compared to the leaner 1:2:4 mix.

The reduction in slump is attributed to the fine and highly absorbent nature of MHA particles, which increase water demand and limit the free water available for lubrication in the mix. Similar observations have been reported for other agro-waste pozzolans such as rice husk ash and palm oil fuel ash (Givi et al., 2010; Salam et al., 2018), where higher replacement levels reduce workability due to increased surface area and porosity.

Despite the decline, all mixes exhibited satisfactory consistency for construction purposes and remained suitable for rigid pavement applications. The results suggest that MHA can be safely incorporated up to 20% replacement, although adjustments such as water reducers or plasticizers may be beneficial at higher replacement levels to maintain desired workability.

3.4 Hardened Concrete Properties

3.4.1 Compressive Strength Test Results

Figures 8 and 9 present the variation in compressive strength with curing age and MHA content for 1:1.5:3 and 1:2:4, respectively.

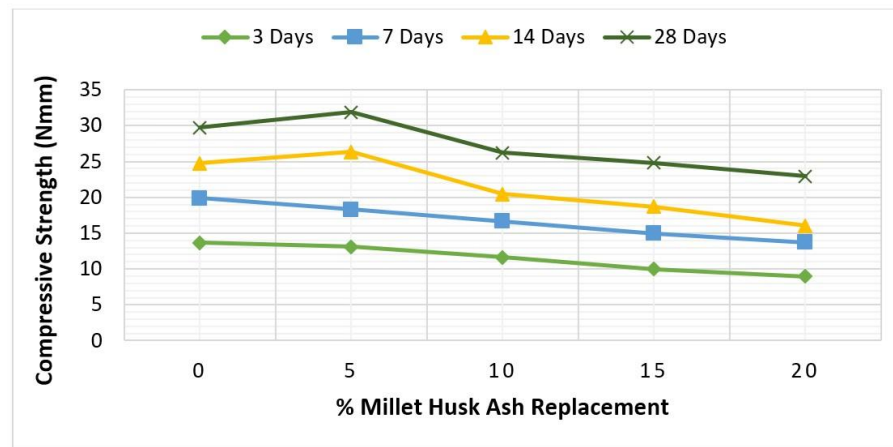


Figure 8. Compressive strength Vs MHA replacement for mix 1:1.5:3.

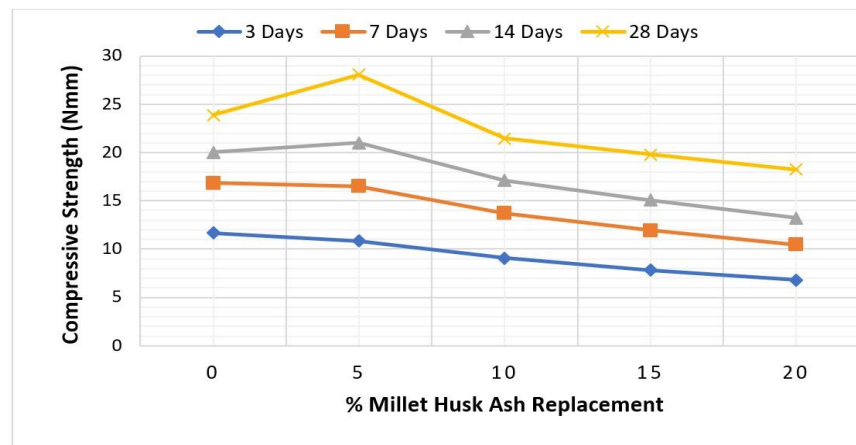


Figure 9. Compressive strength Vs MHA replacement for mix 1:2:4.

Results from Figures 8 and 9 showed that compressive strength increased with curing age for all mixes, but decreased progressively with higher MHA replacement. The richer 1:1.5:3 mix consistently achieved higher strengths than the 1:2:4 mix due to its greater cement content. At 5% MHA, strength values were comparable to or slightly higher than the control, indicating beneficial pozzolanic activity. At 10% replacement, early-age strength was slightly lower but improved steadily with curing, reflecting delayed pozzolanic contribution. Beyond 10%, strength declined significantly, with 20% MHA recording the lowest values, attributed to reduced cementitious compounds and slower hydration.

The optimum replacement level was observed between 5-10% MHA, where strength remained acceptable for rigid pavement applications. These findings confirm that limited incorporation of MHA can enhance sustainability without compromising structural performance, while excessive replacement reduces strength below desirable levels.

3.5 Non-Destructive Tests

3.5.1 Rebound Hammer Test Results

The rebound hammer test was conducted in accordance with BS 1881-202 to evaluate the surface hardness of cement–millet husk ash (MHA) concrete. Figure 10 presents the variation in rebound values for the 1:2:4 and 1:1.5:3 mixes at different replacement levels and curing ages.

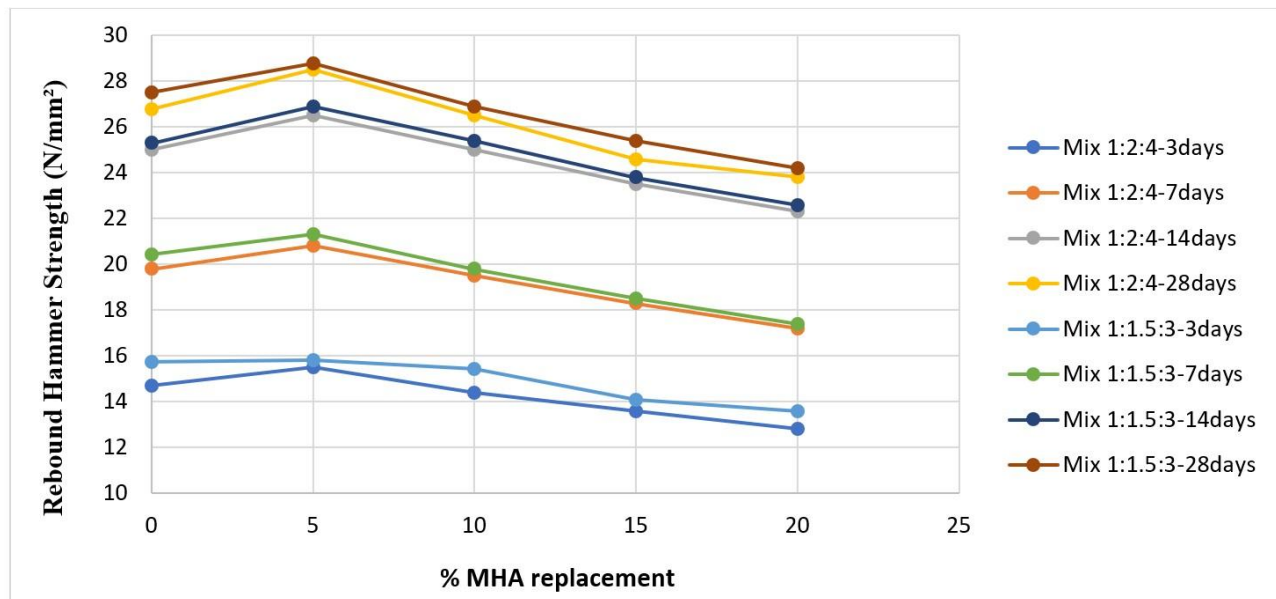


Figure 10. Rebound Hammer Strength Vs %age MHA for 1:1.5:3 and 1:2:4 mixes at all curing ages.

The results show that rebound values generally increased up to 5% MHA replacement, with 28-day strengths surpassing the control mix. This indicates that limited incorporation of MHA enhances surface hardness and compactness. At 10% replacement, values remained within acceptable ranges, though slightly lower than the optimum. Beyond 10%, rebound numbers declined, reflecting reduced cementitious content and slower hydration.

Comparing with BS 1881-202 classifications, mixes containing 0-10% MHA consistently fell within the good-quality concrete range, confirming their suitability for rigid pavement applications. The richer 1:1.5:3 mix exhibited higher rebound values than the 1:2:4 mix across all ages, owing to its greater binder content and denser matrix. At 15-20% replacement, rebound values dropped but remained above the minimum threshold for structural concrete, indicating that even at higher replacement levels, surface integrity was not critically compromised. The optimum replacement level lies between 5-10% MHA, where rebound hammer results confirm improved surface strength and compliance with BS 1881 standards. This demonstrates that MHA can be safely used in moderate proportions to enhance the durability and quality of pavement-grade concrete.

3.5.2 Ultrasonic Pulse Velocity (UPV) Test Results

The ultrasonic pulse velocity (UPV) test was conducted in accordance with BS 1881-203 and ASTM C597 to assess the internal quality and uniformity of cement-millet husk ash (MHA) concrete. Figure 11 presents the variation in pulse velocity values for the 1:2:4 and 1:1.5:3 mixes at different replacement levels and curing ages.

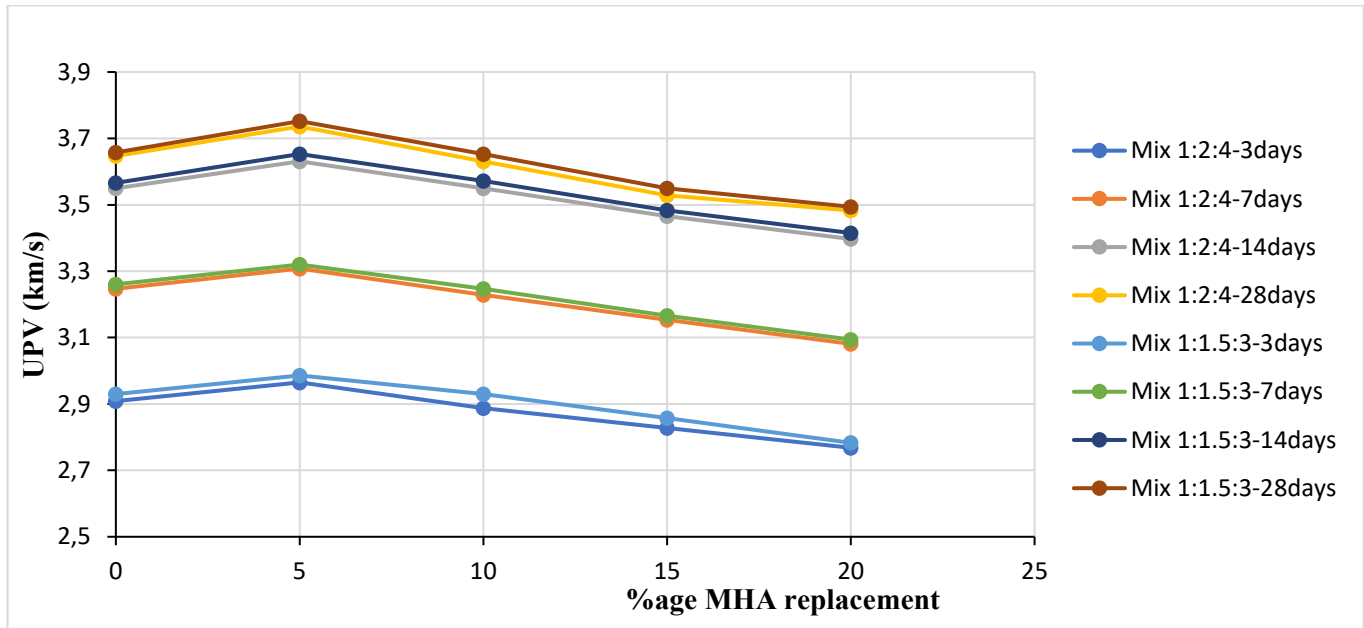


Figure 11. UPV Vs %age MHA for 1:1.5:3 and 1:2:4 mixes at all curing ages.

The UPV results followed a similar trend to the rebound hammer outcomes. Pulse velocities increased at 5-10% MHA replacement, reaching a value of 3.75 km/s, which classifies the concrete as good to very good according to BS 1881-203 and ASTM C597. This improvement reflects denser microstructures and enhanced internal compactness at moderate replacement levels. At higher replacements (15-20%), UPV values declined but still remained within the medium to good quality range, indicating that excessive MHA reduces uniformity but does not critically compromise concrete integrity.

Across both mix ratios, the richer 1:1.5:3 mix consistently achieved higher pulse velocities than the 1:2:4 mix, owing to its greater binder content and stronger paste-aggregate bond. The results confirm that 5-10% MHA provides optimal internal quality, producing concrete that meets or exceeds the control mix in terms of soundness and durability, while remaining compliant with BS 1881-203 and ASTM C597 standards for pavement-grade applications.

4. Conclusions

This paper presents an experimental investigation into the performance of millet husk ash-based concrete as a partial replacement for ordinary Portland cement for application in sustainable rigid pavement, through both destructive and non-destructive methods of testing. From the results, the following conclusions are drawn:

The ash obtained from controlled burning and finer grinding exhibited the necessary pozzolanic properties and can be used as an additive cementitious material. The addition of MHA resulted in an increase in the initial and final setting times, which further revealed that MHA has set retarding properties, and the values are within the ranges specified by the ASTM and BS standards. The workability values decreased with an increase in MHA content due to the higher fineness and absorbency of MHA, but all values were within the ranges specified for rigid pavement work.

Compressive strengths increased with curing ages for all mix proportions, indicating increased hydration processes in addition to pozzolanic activity. Mixes containing 5-10% MHA were able to attain higher strengths than that of the control mix, while beyond 5-10%, that is, 15-20%, low

strengths were not uncommon because of dilution of cementing material combined with low early hydration rates. The richer 1:1.5:3 mix consistently outperformed the 1:2:4 mix, highlighting the influence of binder content.

The rebound hammer and ultrasonic pulse velocity tests indicated a trend similar to the compressive strength result. The moderate replacement levels of MHA (5-10%) resulted in an improvement in surface hardness and quality of inner concrete structure, termed as good to very good concrete as per BS and ASTM standards. Higher replacement levels resulted in reduced rebound numbers and pulse velocities but still indicated structurally sound concrete suitable for pavement use. The destructive and non-destructive evaluation results ensure that the millet husk ash can be used as a supplementary cementitious material for making rigid pavement concrete. Its use contributes to reduced cement consumption, lower environmental impact, and beneficial utilization of agricultural waste, aligning with circular economy and sustainable infrastructure goals. Therefore, the optimal dosage of MHA in MHA-Cement blended concrete as a replacement in rigid pavement construction was established between 5-10%, where optimum workability, strength, and concrete performance can be obtained without affecting the performance of concrete in rigid pavements. It is recommended that further research be conducted to test the long-term performance of MHA blended concrete in terms of resistance to shrinkage, fatigue resistance, and abrasion resistance. Also, XRF, XRD, SEM, and EDS tests on HMA should be included for deeper characterization, and life-cycle and techno-economic assessment should be carried out.

5. Declaration of Generative AI and AI-assisted Technologies

In the course of preparing this manuscript, the authors used AI-assisted technologies such as ChatGPT and Grammarly to improve the style, support the structuring of the text, improve clarity, readability, and presentation.. After using this tools/services, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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