

Effect of Calcination Temperatures on the Chemical, Microstructure, and Strength Characterisation of Borassus Ash-Mortar



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ABSTRACT: Studies have shown that biomass ashes from diverse agricultural residues exhibit pozzolanic characteristics, making them suitable for partial cement replacement in mortar production. However, limited studies have explored the feasibility of Borassus ash as a partial replacement of cement in mortar. Information on the material phase changes and microstructure under the varying calcination temperatures is not available in literatures. This study assessed the effect of calcination temperatures on the chemical, microstructure, and strength properties of mortar containing Borassus ash. The Borassus was calcined at four different temperatures: 500, 600, 700, and 800 °C. Mineralogical, chemical, and morphological characterization of the obtained Borassus ashes was conducted. Moreover, the influence of the Borassus ash on the setting time, density, and compressive strength properties of mortar were examined. The results revealed that calcination temperature influences the surface morphology, fineness, porosity, amorphous and crystalline phase of Borassus ash. Borassus ash calcined at a temperature of 600 °C provides a balance between crystalline and amorphous phases, and the highest SiO₂, Al₂O₃, and Fe₂O₃ combination of 82.1%, demonstrating potential to perform better in cement replacement applications, aligning with the ASTM C618 and IS 3812-1 standards requiring a minimum of 70% for pozzolanic materials. A mortar mix containing 15 % Borassus ash as a cement replacement achieved an optimum density and compressive strength of 2218 ± 6 kg/m³ and 14.93 ± 0.2 N/mm² at 28 days, which were 7.4 and 29.9 % higher than the control mix. The findings demonstrate Borassus ash as a viable alternative to cement in the production of environmentally friendly mortar mixes, providing value for the agro-sourced material.

KEYWORDS: Borassus Ash, Mortar, Microstructure, Compressive Strength, and Cement Replacement.

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I. INTRODUCTION

To promote sustainable development, environmental protection must be integrated into the development process rather than treated as a separate issue, as highlighted by the third principle of the Rio Declaration on Environment and Development (United Nations, 2012). This principle underscores the global commitment to tackling environmental challenges that threaten the planet's survival. As a result, various stakeholders are encouraged to reduce pollutants, particularly greenhouse gas emissions, associated with their activities, and to conserve natural resources (Henin & Uglione, 2022; Morin et al., 2024). In an effort to mitigate the building industry's negative environmental impact and support sustainable growth, the use of alternative materials in construction has garnered considerable attention lately. Plant ash/Biomass ash is one such substitute material that has been shown to have a number of qualities that allow it to be used as a partial replacement of cement in mortar (González-Kunz et al., 2017; He et al., 2020). Mortar plays a vital role in the construction industry, acting as a binding agent for materials such as bricks, stones, and concrete blocks (Arum et al., 2022; Ruano Gutiérrez et al., 2024). Cement, the key component of mortar, is crucial for the strength and durability of structures (Arum et al., 2022). However, cement production is energy-intensive and leads to significant carbon dioxide (CO₂) emissions, accounting for 7% to 8% of total global

anthropogenic CO₂ emissions (Firdissa et al., 2025; Singh et al., 2023). Studies show that buildings contribute to over a third of CO₂ emissions (Li et al., 2025; Kumar et al., 2024), making the construction sector the second-largest source of CO₂ emissions after electricity and heat industry (IPCC, 2022; Li et al., 2025; Nguyen, 2010). Since CO₂ is a major greenhouse gas responsible for global warming and climate change, contributing to the greenhouse effect (Zhong and Haigh, 2013), the building sector is often targeted for carbon emissions reductions.

In response, researchers have been exploring alternative materials to partially replace cement in mortar, and research studies have demonstrated that the partial replacement of ordinary portland cement with sustainable materials can bring numerous benefits like improved mechanical properties, durability, cost saving and environmental sustainability (Fode et al., 2023; Dey et al., 2023; Francioso et al., 2024; Hansted et al., 2022; Sequeira et al., 2023). One such material is ash derived from the Borassus aethiopum plant, commonly known as the African fan palm (Thomas et al., 2021; Koffi & Konin, 2024). which belongs to the Arecaceae family whose biomass ashes have demonstrated pozzolanic properties due to significant silica and alumina content (Thomas et al., 2021; Saki et al., 2020; Mandelot-Matetelot et al., 2025). Borassus aethiopum is a widely distributed tree species in West Africa, recognized for its medicinal and industrial applications (Mansur et al., 2021).

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Several studies have shown that biomass ashes from diverse agricultural residues exhibit pozzolanic characteristics, making them suitable for partial cement replacement in mortar production. Villar-Cocina et al. (2011) calcined bamboo leaf ash at a temperature of 600 °C for 2 hr. Their X-ray fluorescence analysis (XRF) analysis result revealed 80.4 % silica, 5.06 % CaO, 1.22 % Al₂O₃, and LOI of 8.04 %, demonstrating a high presence of notable oxides for pozzolanic reaction. Frias et al. (2012) showed that bamboo leaf ash increased the water demand of concrete by 19 and 49 %, when it substituted cement at 10 and 20 %, respectively. Cordeiro and Sales (2016) and Cordeiro and Sales (2015) reported that elephant grass ash calcined at 600 °C for 3 hrs demonstrated pozzolanic activity similar to rice husk ash and sugarcane bagasse ash. Concrete containing 20 % of the elephant grass ash as a cement substitute, exhibited similar compressive strength, water absorption, and Young's modulus to the control concrete (Cordeiro and Sales, 2016). A study conducted by Kanning et al. (2014) on the influence of plantain leaf ash on concrete performance showed 25 % and 10 % strength gain for concrete containing 10 % and 20 % plantain leaf ash.

Binici et al. (2008) noted that corn cob ash as a replacement for fine aggregate could make concrete more homogenous with dense microstructure, thereby improving the durability properties. However, untreated corncob could increase the porosity and permeability of concrete due to the presence of potassium oxide, which negatively affects cement hydration, resulting in low compressive strength and high chloride ion penetration (Shakouri et al., 2020). Adesanya and Raheem (2009) reported 8 % corn cob ash as the optimum replacement level, and the concrete must be cured for 120 days to achieve an enhanced strength performance. Studies have shown that wheat straw ash, olive waste ash, banana leaf ash, corncob ash, and rice straw ash exhibited significant pozzolanic reactivity, with combined SiO₂, Al₂O₃, and Fe₂O₃ contents ranging from 70% to 85%, satisfying ASTM C618 Class N requirements (Rosello et al., 2017; Pandey et al., 2020; Pinheiro et al., 2018; Al-akhras et al., 2002; Biricik et al., 2000). The pozzolanic mechanism involves the reaction of amorphous silica in the ash with calcium hydroxide liberated during cement hydration, producing additional calcium silicate hydrate (C-S-H) gel that densifies the microstructure and refines pore networks (Thomas et al., 2021).

Despite the extensive studies confirming biomass ashes from various palm species (e.g., oil palm fuel ash, olive waste ash, banana leaf ash, corncob ash, date palm leaf ash) as pozzolanic supplementary cementitious materials, no published literature to date has experimentally evaluated the chemical composition, pozzolanic activity index, or mechanical performance of *Borassus aethiopum* ash as a partial cement replacement, representing a critical knowledge gap in sustainable construction material research. Furthermore, no study has demonstrated the influence of calcination temperature on the chemical composition, phase transformation, mineralogy, and microstructure of *Borassus* ash, hence, this study.

The purpose of this study is to assess the suitability and sustainability of using unconventional materials like *Borassus*

leaf ash as a partial substitute for cement in mortar. The influence of different calcination temperatures on the chemical composition, phase transformation, mineralogy, and microstructure of *Borassus* ash were analysed. Furthermore, mortar mixes were produced with *Borassus* ash incorporated as a partial replacement for cement, and the setting time, density, and compressive strength were examined. The findings provide insights on the phase structure of *Borassus* at different temperature, and performance of mortar containing *Borassus* ash as cement replacement. Also, it assists in conserving non-renewable resources, recycling agricultural waste in an environmentally friendly manner, and reducing the cost of mortar production by incorporating *Borassus* ash in mortar mix.

II. MATERIALS AND METHODS

A. Materials

Cement, fine aggregate (sand), water, and *Borassus* leaf are the materials used in this study. The type of cement used for this study was ordinary Portland cement (CEM II 42.5N grade), conforming to BS EN 197-1 (2011) and NIS 444:1 (2014), locally manufactured by BUA Cement Company, Nigeria. Its specific gravity, bulk density, blaine surface area and median size are 3.07, 1462.08 kg/m³, 446 m²/g and 21.57 µm, respectively (Kareem et al., 2023 and Ogodo et al., 2021).

The river sand used as fine aggregate was locally obtained from an ongoing construction site at the University of Ilorin, Ilorin, Nigeria. In this study, sand conforming to BS 882:1992 was used. The fine aggregates that passed the 2.36mm BS 410 test sieve with no coarser material were considered as sand for the study. The maximum diameter, specific gravity, bulk density and water absorption values of river sand are 2.36 mm, 2.71, 1859 kg/m³ and 14.83%, respectively.

The *Borassus* leaves used to produce the ash were obtained from Gaa Akanbi, Kwara State, Nigeria. It was harvested fresh and sundried for 48 hours to remove moisture. The ash from *Borassus* leaves was used as a partial replacement for cement in this study.

B. *Borassus* Ash Preparation and Chemical Analysis

The leaves of the *Borassus aethiopum* used in this study were harvested fresh and sundried for 48 h at ambient temperature to reduce the moisture content and reduce the volatile compounds in the plant that can vaporize during calcination. Thereafter, the leaves were shredded using an electric blender into smaller sizes for easy calcination, as seen in Figure 1. The ashes were obtained by calcining the dried and shredded *Borassus* leaves in a muffle furnace for 2 hours at different temperatures of 500, 600, 700, and 800 °C. The temperature variation used was due to the amount of heat needed to form ash from the *Borassus* leaf as reported by Ikubanni et al. (2023). The ash was cooled for 24 hours before being pulverized for 30 mins at 35 rpm in a ball mill to further reduce the size. Afterwards, the ash was sieved through a 0.075mm mesh with a sieve shaker, and fine ash passing through the sieve was used as a partial replacement for cement in the study. The influence of the different temperatures employed in the calcination process on the chemical characterisation and morphology of the *Borassus* leaf ash was

examined. Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analysis were conducted to evaluate the chemical composition of the ash and assess its suitability as a pozzolan.

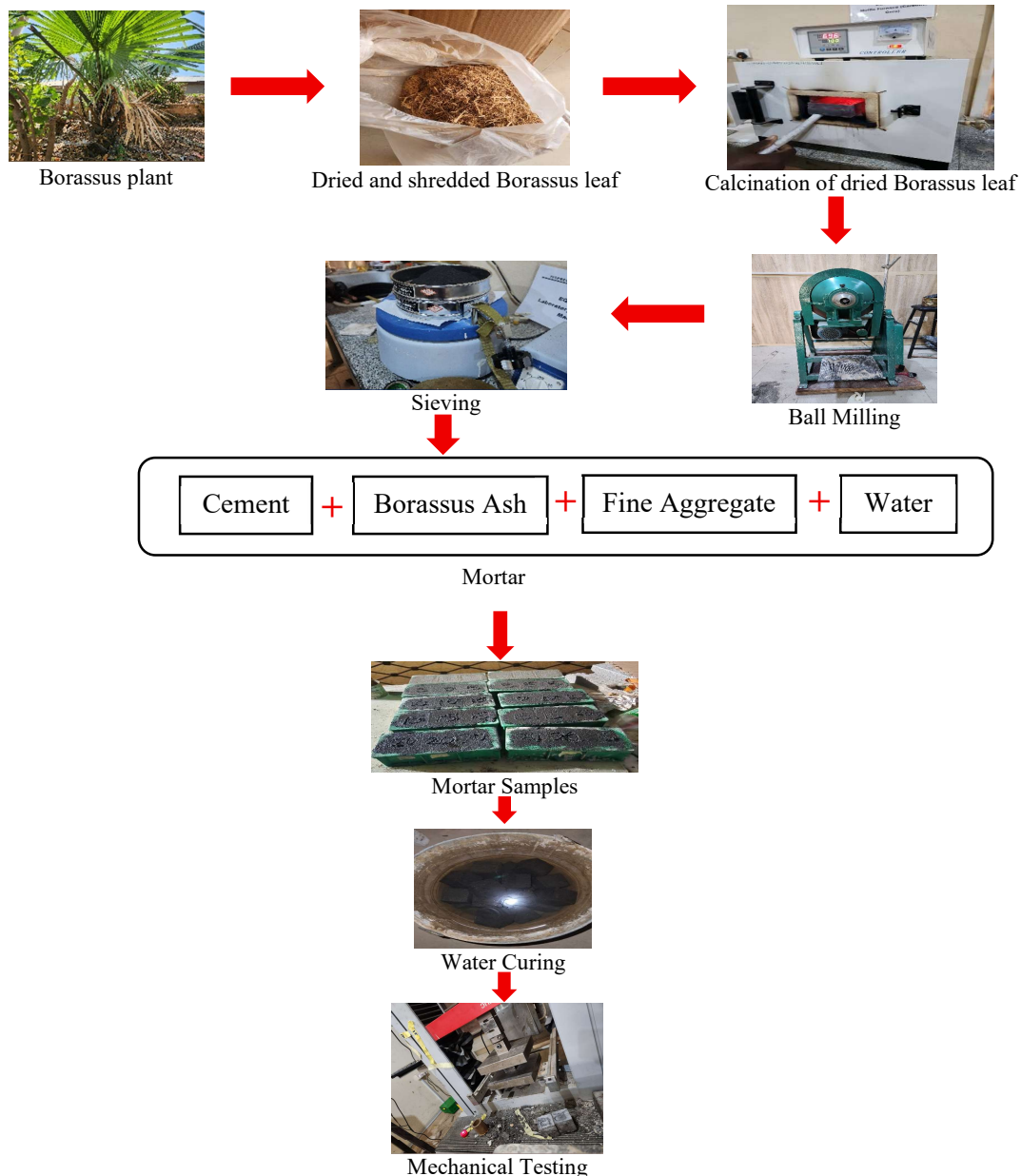


Figure 1: Methodology Workflow for Mortar Containing Borassus Ash

1) Scanning Electron Microscopy (SEM)

The morphology of the *Borassus aethiopum* ash obtained from the four different calcination temperatures of 500, 600, 700, and 800 °C was studied using SEM. The objective was to characterize the microstructural changes that have occurred at each calcination temperature. SEM equipment Model: JEOL-JSM 760F, Japan, with a high vacuum mode of 20 kV accelerating voltage was used in the study.

2) Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis is used to identify organic, polymeric, and in some cases, inorganic materials. It works by obtaining an infrared spectrum of absorption, emission, photoconductivity, or Raman scattering of a solid, liquid, or gas. It was used to identify the presence of silicate (Si-O-Si), aluminate (Al-O), and other functional groups. These groups are crucial for the pozzolanic activity because they react with calcium hydroxide to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). Sample of the *Borassus* ash calcinated at four different temperatures of 500, 600, 700, and 800 °C was mixed with KBr powder in the ratio of 1:10.

Afterwards, it was placed in a holder and compacted for 2 mins under a compaction load of 40 MPa. Then, the sample was transferred into the compartment, and the major functional group in the Borassus ash was estimated. The FTIR spectra for the samples were recorded in the range $4000 - 400 \text{ cm}^{-1}$ at a resolution of 4 cm^{-1} .

3) X-ray Diffraction (XRD) Analysis

XRD analysis was used to identify the mineral phases, assess reactivity, and determine the crystal structures of the Borassus ash sample. XRD informs the ash's ability to react with cement and form hydration products, which affect the mortar's microstructure and properties. This analysis was used to verify that the ash meets relevant standards for Supplementary Cementitious Material (SCM). A PANalytical Empyrean diffractometer was employed to observe the phases in the Borassus ash obtained at different temperatures of 500, 600, 700, and 800°C . The X-ray diffractometer, having Cu K_α radiation = $1.5406\text{\AA}$ at an acceleration voltage of 45 kV and a current of 40mA from a scan range of 2θ $4 - 70^\circ$ at a scan speed of $0.026^\circ/\text{min}$ was employed for the analysis. The X'Pert High-score Plus software attached to the PANalytical diffractometer was used to match the obtained peaks with mineral phases.

4) X-ray Fluorescence (XRF) Analysis

The elemental compositions of the calcined Borassus ash obtained at different temperatures of 500, 600, 700, and 800°C were determined using X-ray Fluorescence (XRF) analysis. A Herzog Gyro-mill (Simatic C7-621) was used to pulverise each sample for 60 s after it was crushed with an electric crusher. A 20g of the pulverized sample was grinded with 0.4 g of stearic acid for 60 s to produce pellets (Ikubanni et al., 2020). At the end of each grinding, the Gyro-mill was cleaned to avoid contamination. Meanwhile, an aluminium cup was used to weigh 1 g of the stearic acid as a binder. Then, the sample was filled into the cup, reaching the level point. Afterwards, pressure was applied for 60 s to pelletise the sample in the cup using a pelletizing equipment with a capacity of 2000 kN. The 2 mm pellets were placed in the sample holder of the XRF (Phillips PW – 1210) for analysis, at 40 kV and 25 mA of voltage and current, respectively. The resulting spectrum described the elemental composition of the material.

C. Batching and Preparation of Cement Mortar Mix

A fixed mortar mix design of 1:3 was used in this study, which implies that for every 1kg of cement, 3kg of fine aggregate will be used in the mix. Based on the chemical analysis conducted, Borassus ash calcined at 600°C gave the better pozzolanic properties, which was selected for incorporation in the mortar mix. Cement was partially substituted with the Borassus ash at 0, 5, 10, 15, and 20 % by weight in mortar mix. A total of five mortar mixes were prepared with a constant water-cement ratio of 0.5 for all the mixes, conforming to BS EN 998-2. For each batch of cement mortar, the same amount of sand, water, and binder were used. Table 1 presents the proportions of mortar mixtures employed in this study. The dry mortar constituents were thoroughly mixed after batching, and water was added to the mixture, and

thoroughly mixed in line with BS 1881 – 125 (2013). The initial and final setting times were conducted on the mortar mixes containing 0%, 10%, and 20% of Borassus ash to determine the period it takes for the mortar to transition from a workable (fluid state) to a hardened (solid state). The $50 \times 50 \times 50 \text{ mm}$ cube moulds were filled with the mixture after it was lubricated for easy removal. The moulds were rammed using a rod to ensure proper distribution of the paste, and the surface of the mortar was smoothed. The specimens were produced and placed in the open air in the laboratory for 24 hours at a room temperature of 25°C , as shown in Figure 1. After the 24-hour casting duration, the mortars were removed from the mould gently to avoid any damage. The specimens were then cured for 7 and 28 days using the water curing method.

Table 1 Mix proportion of the mortar batches

Mix ID	Cement (kg/m^3)	Borassus ash replacement (%)	Borassus ash (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Water/Binder ratio
M1	487	0	-	1461	244	0.5
M2	463	5	24	1461	244	0.5
M3	438	10	49	1461	244	0.5
M4	414	15	73	1461	244	0.5
M5	390	20	97	1461	244	0.5

2.4 Testing Methods

The hardened density test was carried out on the mortar samples, in accordance with BS EN 12390-7 (2019). Three samples from each mix were tested at the ages of 7 and 28 days. The density measured as the ratio of the mass of the mortar cube to the volume, is expressed in kg/m^3 . The compressive strength test was performed on the $50 \times 50 \times 50 \text{ mm}$ cubic samples in accordance with BS EN 12390-3 (2019). The samples were tested after being cured for 7 and 28 days. The samples were taken out, wiped dry and tested using a Testometric Universal Testing Machine with a load capacity and a loading rate of 100 kN and 0.4 kN/s , respectively. Axial load was applied centrally to each sample at a uniform rate, as shown in Figure 1. Failure load was noted, and compressive strength was calculated based on the average of three cubes produced for each mix.

III. RESULTS AND DISCUSSIONS

A. Morphological and Chemical Analysis

1) Scanning Electron Microscopy (SEM)

Figure 2 (a- d) shows the surface morphology of Borassus ash calcined at temperatures of 500, 600, 700, and 800°C , respectively. The particles of Borassus ash calcined at 500°C appear relatively larger and less porous, as shown in Figure 2 (a). The surface seems to have more irregular and coarse structures, which suggests incomplete decomposition of organic matter in the Borassus ash at lower calcination temperatures, resulting in larger particle sizes. These larger and irregular particles observed could result in a lower pozzolanic reactivity performance of the Borassus ash when used as a cement replacement. Also, it does not meet the fineness criteria outlined in ASTM C618.

From Figure 2 (b), a more refined structure with smaller and more uniform particles was observed as the calcination temperature increased to 600 °C. The increase in calcination temperature likely led to further decomposition of organic components, resulting in a finer Borassus ash structure. The presence of porous structures also indicates a higher surface area, which is beneficial for pozzolanic activity as it allows for better reaction with calcium hydroxide in the cement matrix. ASTM supports the view that finer ash particles with higher surface area can lead to enhanced reactivity in mortar. The improved fineness and porosity demonstrated in Figure 2 (b) suggests that Borassus ash obtained at 600 °C temperature would perform better in cement replacement applications, meeting the criteria of reactivity as specified in ASTM C618.

At high calcination temperature of 700 °C and 800 °C, the Borassus ash particles seem even finer and more angular compared to the previous temperatures, as shown in Figure 2 (c) and (d) respectively. The porous nature is more pronounced, indicating that the Borassus has undergone significant thermal processing. This higher degree of calcination typically improves the Borassus ash's reactivity, making it more suitable as a cement replacement. However, excessively high temperatures can also lead to the sintering of ash particles, reducing their surface area and reactivity (Zhang et al. 2021; Namkung et al., 2016). Similar trend was observed for Rice Husk Ash (RHA), typically calcined at around 500 °C – 700 °C (Ganesan et al., 2008). It was reported that RHA exhibits a high surface area and amorphous silica content at these temperatures, making it a very reactive pozzolan. The trend observed in the Borassus ash, where the ash becomes finer and more porous with increasing temperature, is similar to that of RHA, indicative of good pozzolanic reactivity potential.

Generally, the SEM analysis demonstrates that calcination temperature influences the surface morphology of Borassus ash. Based on the SEM results, the Borassus ash calcined at temperature of 600 °C provides a balance of fineness and porosity, which aligns with the criteria specified in ASTM C618. At this lower temperature, significant fraction of the Borassus particles will be in an amorphous state relative to the crystalline state, which is desirable for better reactivity in cementitious system.

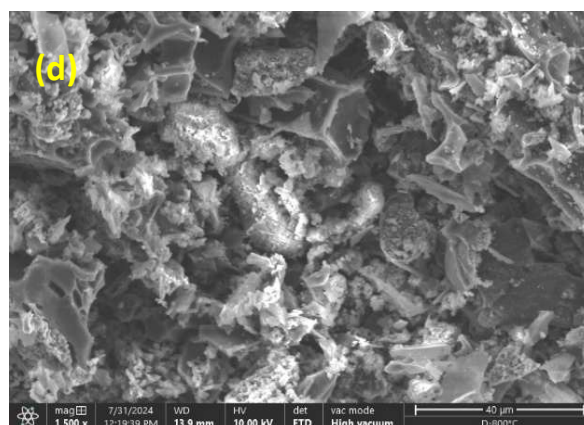
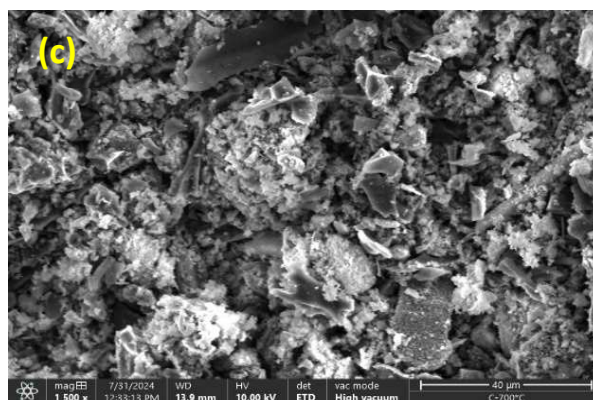
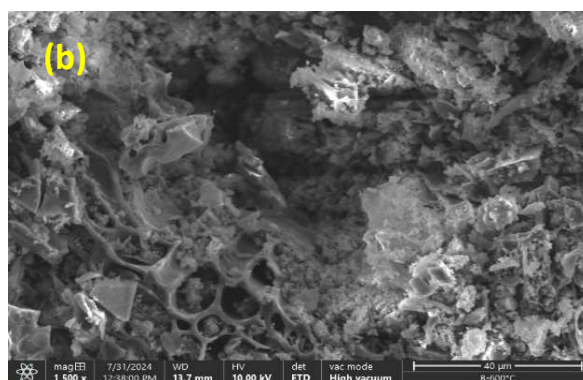
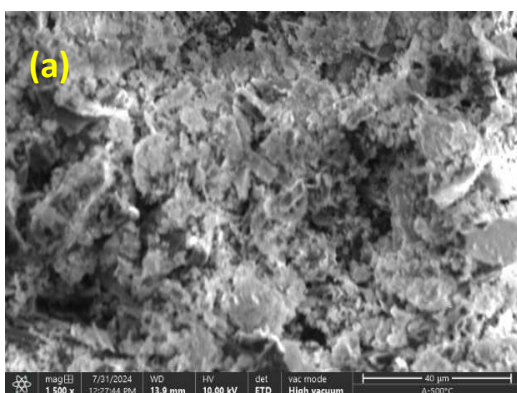


Figure 2: SEM micrograph of Borassus ash at (a) 500 °C (b) 600 °C (c) 700 °C (d) 800 °C

2) Fourier-Transform Infrared Spectroscopy

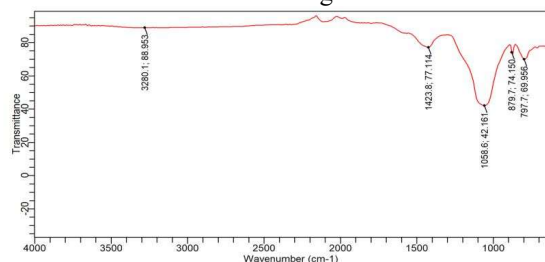
Fourier-Transform Infrared Spectroscopy (FTIR) spectra presented in Figure 3 (a- d) reveals significant insights into the structural changes and functional groups of Borassus ash subjected to calcination temperatures of 500, 600, 700, and 800 °C. At 500 °C, the spectrum shows characteristic peaks at 797.65 cm⁻¹, 879.65 cm⁻¹, 1058.56 cm⁻¹, 1423.84 cm⁻¹, and 3280.06 cm⁻¹, as shown in Figure 4 (a). The peak at 797.65 cm⁻¹ is attributed to Si-O-Si bending vibrations, indicative of the silicate framework within the ash. The peak at 879.65 cm⁻¹ corresponds to C-O bending, suggesting the presence of carbonate groups. The prominent peak at 1058.56 cm⁻¹ is typically associated with Si-O stretching, while the peak at 1423.84 cm⁻¹ may represent C=O stretching, indicative of carbonates or organic matter. The broad peak at 3280.06 cm⁻¹ is attributed to O-H stretching vibrations, which could be due to hydroxyl groups from absorbed moisture or structural water. The moderate intensity of these peaks indicates a stable structure with a balanced composition of silicate and carbonate groups, potentially enhancing the pozzolanic reactivity of the ash when mixed with cement.

At 600°C (Figure 3b), the FTIR spectrum reveals shifts in the wavenumber peaks, with notable peaks at 790.19 cm⁻¹, 1043.65 cm⁻¹, 1416.38 cm⁻¹, 1796.57 cm⁻¹, and 2653.86 cm⁻¹. The Si-O-Si bending vibration remains consistent at 790.19 cm⁻¹, as shown in Figure 3 (b). However, the C-O bending vibration shifts slightly to 1043.65 cm⁻¹, indicating a possible reduction in carbonate content. The Si-O stretching vibration, observed at 1416.38 cm⁻¹, suggests an increase in silicate content. The emergence of a peak at 1796.57 cm⁻¹, representing C=O stretching, could imply a higher concentration of carbonates or organic residues. Additionally,

the O-H stretching vibration is observed at 2653.86 cm⁻¹, indicating the presence of structural water. The increased intensity of the silicate-related peaks at 600°C suggests an enhancement in the ash's pozzolanic reactivity compared to the sample at 500°C.

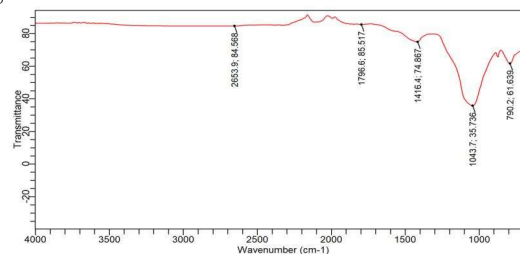
Further analysis at 700 °C and 800°C in Figures 3 (c) and (d) show continued presence of Si-O-Si bending vibrations at 790.19 cm⁻¹ and 782.74 cm⁻¹, consistent across all samples. The C-O bending vibrations are observed at 1036.19 cm⁻¹ and 1028.75 cm⁻¹, reflecting a similar trend to that in the 600 °C sample. Si-O stretching vibrations at 1416.38 cm⁻¹ and 1401.48 cm⁻¹ remain prominent, further indicating the persistence of silicate structures. New peaks at 2325.88 cm⁻¹ and 2117.13 cm⁻¹ suggest the formation of additional phases at these higher temperatures, potentially related to CO₂ from decarbonation processes. The O-H stretching vibrations, observed at 2653.86 cm⁻¹ and 2325.86 cm⁻¹, indicate that despite the high temperatures, some hydroxyl groups remain. The mixed trend in peak intensities at 700 °C and 800 °C suggests that while the material becomes more crystalline, certain active sites necessary for pozzolanic reactions might be reduced.

Finally, the presence of Si-O-Si and Si-O stretching vibrations across all samples suggests that Borassus ash has a substantial silica content, similar to other pozzolanic materials like fly ash (Jain & Singh, 2018). Additionally, the presence of carbonate groups (C-O and C=O vibrations) indicates some similarity to ashes like palm oil fuel ash, which also contain residual organic content, as highlighted by Abdullah et al. (2019).



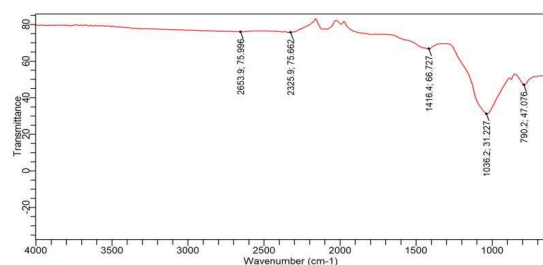
Peak Number	Wavenumber (cm ⁻¹)	Intensity
1	797.65030	69.95632
2	879.65173	74.14982
3	1058.56395	42.16083
4	1423.84305	77.11409
5	3280.05730	88.95329

(a)



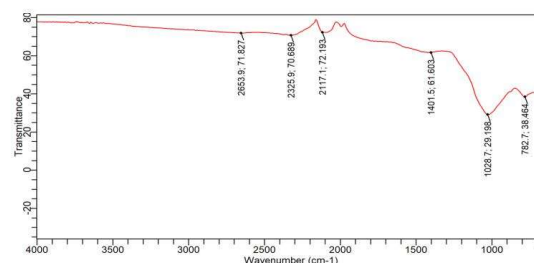
Peak Number	Wavenumber (cm ⁻¹)	Intensity
1	790.19562	61.63912
2	1043.65459	35.73631
3	1416.38838	74.86677
4	1796.57684	85.51749
5	2653.86454	84.56826

(b)



Peak Number	Wavenumber (cm ⁻¹)	Intensity
1	790.19562	47.07590
2	1036.19992	31.22658
3	1416.38838	66.72680
4	2325.85881	75.66164
5	2653.86454	75.99614

(c)



Peak Number	Wavenumber (cm ⁻¹)	Intensity
1	782.74095	38.46368
2	1028.74524	29.19775
3	1401.47903	61.60313
4	2117.12789	72.19267
5	2325.85881	70.68897

(d)

Figure 3: FTIR analysis of Borassus ash at (a) 500 °C (b) 600 °C (c) 700 °C (d) 800 °C

3.1.3 X-ray Diffraction (XRD)

Figure 4 presents the X-ray diffraction patterns for the Borassus ash, illustrating the mineralogical evolution as the calcination temperature increases from 500 to 800 °C. The evolution patterns show significant changes in crystalline phase transformation and structural reorganisation as the calcination temperature changes. This behaviour is primarily governed by thermally induced mineral decomposition, biogenic silica phase transformation, and possible secondary interactions between silica and alkali or alkaline-earth oxides, naturally present in biomass ash.

The XRD pattern for Borassus ash calcined at 500 °C reveals different, distinct, and identifiable diffraction peaks at characteristic 2θ positions, predominantly corresponding to cristobalite and lime (CaO). The diffraction peaks associated with the cristobalite are observed at 2θ values of approximately 22, 28.4, and 35.5 °, demonstrating the presence of crystalline biogenic silica. The characteristic reflections associated with CaO were observed at 32.3 and 37 °, confirming the formation of lime during thermal decomposition. The appearance of CaO in the XRD pattern is attributed to the presence of calcium carbonate and calcium oxalate in Borassus plant tissue, which decompose into CaO and CO₂ during calcination.

The appearance of cristobalite confirms the crystallisation of biogenic silica, originally present in the Borassus biomass. Plant materials typically store silica in amorphous phytolith structures composed of hydrated silica (SiO₂·nH₂O) (Yang et al., 2021). When subjected to elevated temperature, the amorphous silica undergoes dehydration and structural rearrangement of the SiO₄ network, leading to the formation of crystalline silica polymorphs such as cristobalite and quartz (Magdziarz et al., 2017). However, the moderate peak intensity observed at 500 °C suggests the presence of a significant amount of silica in an amorphous state, which is desirable in pozzolanic reactivity in cementitious systems.

At an increased calcination temperature of 600 °C, sharper and more intense diffraction peaks were observed, especially peaks associated with cristobalite. The increased peak intensity and narrower peak widths indicate improved crystallinity and a more ordered silica framework. This suggests the thermal activation of the transformation of amorphous silica into a more stable crystalline polymorph, such as cristobalite, via reorganisation of the SiO₄ tetrahedral network at a relatively moderate temperature (Vassilev et al., 2017). Furthermore, the presence of mineralising agents from alkali and alkaline earth elements, such as potassium (K), calcium (Ca), and magnesium (Mg) lower the silica crystallisation activation energy, enhancing the formation of cristobalite at moderate temperatures (Yang et al., 2021). Studies on thermally treated silica-containing biomass ashes, including rice husk ash (Amin et al., 2019; Xu et al., 2016; Nair et al., 2008), sugarcane bagasse ash (Cordeiro et al., 2008; Karim et al., 2016; Lim et al., 2015) and palm oil fuel ash (Tangchirapat and Jaturapitakkul, 2010; Balaji et al., 2022) have reported similar crystallization behavior.

Further increase of the calcination temperature to 700 °C and 800 °C, leads to the observed reduction in the intensity of the cristobalite peaks and the development of a more complex diffraction pattern. This reduction can be attributed to the secondary mineral reactions between silica and alkali or alkali-earth oxides to form complex silicate phases. The mineralogical evolution observed in this study has important implications for the potential utilization of Borassus ash as a supplementary cementitious material. Pozzolanic reactivity of biomass ashes is primarily governed by the proportion of amorphous silica relative to the degree of crystallinity.

Highly amorphous silica is generally more reactive in cementitious systems due to its highly disordered structure that rapidly dissolves in alkaline environments and reacts with calcium hydroxide during hydration to form secondary

calcium silicate hydrate (C-S-H) gel (Hari et al., 2024; Prado et al., 2019). In contrast, highly crystalline phases such as cristobalite are relatively inert and significantly affect the pozzolanic reactivity performance due to their stable lattice structure. Based on the XRD observations, the calcination temperature of 600 °C appears to promote sufficient mineral decomposition while maintaining a balance between crystalline and amorphous phases, which is advantageous for cementitious applications.

Overall, the XRD analysis demonstrates that calcination temperature plays a critical role in controlling the mineralogical composition, crystallinity, and potential reactivity of Borassus ash. Understanding these thermally induced phase transformations is essential for optimising calcination temperature to obtain Borassus ash with desired properties.

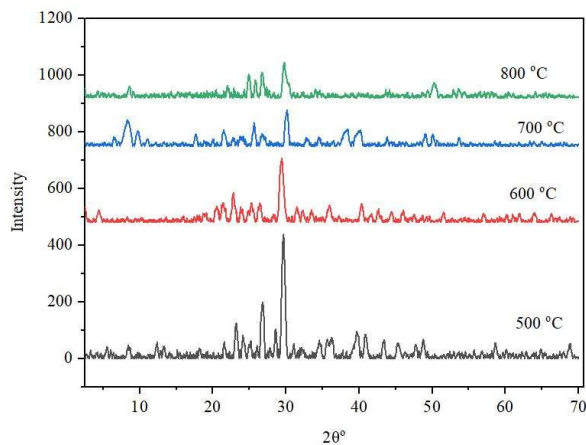


Figure 4: XRD evaluation of Borassus ash at (a) 500 °C (b) 600 °C (c) 700 °C (d) 800 °C

3.1.4 X-ray Fluorescence

The chemical analysis presented in Table 5 confirms that Borassus ash contains key components essential for pozzolanic activity, including Silicon dioxide (SiO_2) at 76.80 %, Aluminum Oxide (Al_2O_3) at 3.74 %, and Iron Oxide (Fe_2O_3) at 1.56 %. Together, these oxides constitute a combined total of 82.10 %, which aligns with the ASTM C618 and IS 3812-1 standards, which stipulates a minimum of 70 % for pozzolanic materials. The composition of cement indicates that the CaO percentage is higher than the SiO_2 , providing a hint that excess $\text{Ca}(\text{OH})_2$ will be formed in the presence of water. This excess $\text{Ca}(\text{OH})_2$ can be exploited to react with the reactive silica in Borassus ash for strength enhancement. The XRF results of Borassus ash indicates that it is indeed a pozzolanic material and holds significant potential as a viable partial replacement for cement in construction applications.

Table 5: XRF analysis of Cement and Borassus ash calcined at Different Temperatures

Oxide Composition	Cement	Borassus Ash			
		500 °C	600 °C	700 °C	800 °C
SiO_2	27.37	76.94	76.80	74.87	68.23
Fe_2O_3		1.46	1.56	1.45	0.3
Al_2O_3		1.11	3.58	3.74	3.54
MgO		1.98	3.13	3.48	3.17
K_2O	0.70	3.13	3.48	3.17	2.90
CaO	0.44	1.83	1.92	1.73	2.92
$\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$	61.01	10.05	10.13	10.00	6.85
		81.98	82.1	79.86	70.05

3.2 Physical and Mechanical Properties

Based on the morphological and chemical analysis, Borassus ash obtained at a calcination temperature of 600 °C provides a good balance of fineness and porosity, better intensity of the silicate-related peaks, good proportion of amorphous silica relative to the degree of crystallinity, and the highest percentage of $\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$, suggesting good potential for pozzolanic reactivity performance. This Borassus ash was used as a partial replacement of cement in a mortar mix. The physical and mechanical properties of mortar mixes containing Borassus ash at different proportions are evaluated.

3.2.1 Setting Time

The setting time measures the physical transition of cement paste from an initial set (plastic/workable state) to a final set (rigid/hardened state) upon the addition of water. Table 6 presents the results of the initial and final setting time of mortar mixes containing 0%, 10%, and 20% of Borassus ash. As observed, increasing the proportion of Borassus ash in mortar results in a longer initial and final setting time, as the mortar paste offers less resistance to penetration. Incorporation of Borassus ash at 10 and 20 % increased the initial setting time by 12.3 and 23.1 %, and the final setting time by 7.1 and 10.3 %, respectively. This extended setting time is advantageous as it provides additional time for mixing, transporting, placing, and finishing the mortar, which is particularly beneficial in hot weather or large-scale construction projects where delays may occur. Additionally, the result shows that incorporating 10% and 20% Borassus ash increases the water requirement by 3g and 7g, respectively. This suggests that the ash influences the hydration process, likely contributing to the slower setting time. The increased water demand may be attributed to the ash's fine texture and porous surface, which absorbs some of the water, necessitating additional water to maintain the

desired workability. This higher water absorption confirms the fineness and porosity observed in the SEM image.

Table 6: Initial and final setting time of the mortar mixes

Borassus ash replacement (%)	Cement (g)	Borassus (g)	Water (g)	Initial setting time (min)	Final setting time (min)
0	400.0	0.0	120	138	338
5	380.0	20.0	120	140	340
10	360.0	40.0	123	155	362
15	340.0	60.0	125	165	368
20	320.0	80.0	127	170	373

3.2.2 Density

Figure 5 shows the effect of Borassus ash as a partial replacement for cement on the hardened density of mortar at ages of 7 and 28 days. It can be seen from the results that the mortar density increased as the Borassus ash proportions increased up to 15%. The increase in the density of mortar ranged from 2 – 7 % for mortar with 5 – 15% of Borassus ash ratios compared to the control (0% Borassus ash). Beyond the 15% replacement of cement with Borassus ash, the density declined by 0.4 % for 20 % of Borassus ash ratios compared to the 15 % Borassus ash, though still higher than the control density by 7 %. The result trends are similar for both 7 and 28 ages. The control sample (0% ash) exhibited a slight density increase from 2040 kg/m³ to 2056 kg/m³ after 28 days. Borassus ash replacements of 5%, 10%, 15%, and 20% generally resulted in increased densities, with the 15 % replacement showing the highest density of 2218 kg/m³ at 28 days. The 20 % replacement recorded a slight decline in density with a value of 2208 kg/m³ at 28 days, suggesting the optimum replacement to be 15 % to achieve the highest density. While higher ash content can enhance density, the benefits may plateau beyond a certain level. Overall, the findings indicate that Borassus ash can effectively increase mortar density, with 15% replacement appearing optimal for a balance between early and long-term curing periods.

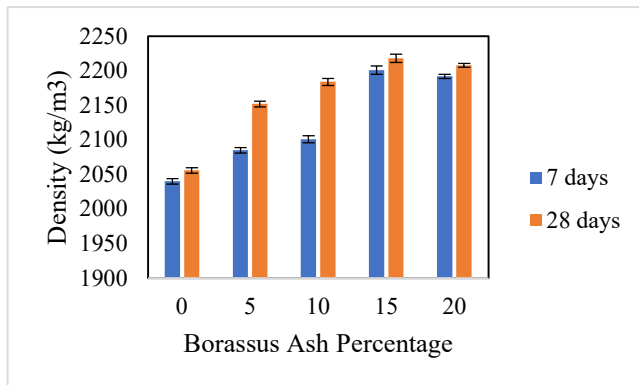


Figure 5: Density of mortar containing Borassus ash

3.2.3 Compressive Strength

Figure 6 shows the compressive strength results for the mortar with Borassus ash as a partial cement replacement. From the results, it can be observed that the compressive strength generally rises as the curing age increases from 7 to 28 days. This could be attributed to the continued hydration process leading to the production of more hydration product (C-S-H), which is responsible for strength development. The results revealed distinct trends over the 7 and 28 day curing periods. The mortar incorporating Borassus ash showed enhanced compressive strength at both ages. The rise in compressive strength ranged from 0.1 to 33 % for mortar with 5 – 15 % Borassus ash compared with the control at 28 days. As observed, the compressive strength of mortar with 5 % Borassus ash is comparable to or greater than that of the control at 7 and 28 days, surpassing it by 0.1 %. An increment of the Borassus ash content to 10 % resulted in increased compressive strength by 13 %. Further increment of the Borassus ash to 15 % still raises the compressive strength by 33 % with respect to the control mix at 28 days. Beyond the 15 %, there was a drop in the compressive strength by 5.2 % at 20 % incorporation of Borassus ash. The increase in compressive strength over time (7 and 28 days) can be attributed to the presence of significant fraction of amorphous silica (SiO₂) in Borassus ash, which reacts with calcium hydroxide (Ca(OH)₂), a byproduct of cement hydration, to produce additional Calcium Silicate Hydrate (C-S-H), an essential component for the development of strength (Kareem et al., 2023). In addition, the fine Borassus ash particles fill microscopic voids present in the mortar, creating a denser and less permeable structure (Guo et al., 2025). The synergetic influence of the chemical reaction and the filler effect of fine ash particles, often leads to improved compressive strength, reduced porosity, and enhanced long-term durability in cementitious composites (Gabrijel et al., 2021; Ottosen et al., 2016). The lack of sufficient CH to react with increased SiO₂ from Borassus ash, resulting in pronounced porosity and a drop in mortar density, can be linked to the lower compressive strength at higher Borassus ash replacement levels (Silva et al., 2021; Kareem et al., 2023).

This compressive strength trend observed in Borassus ash is consistent with earlier well-studied findings on mortar mixes containing agricultural biomass ashes such as bamboo leaf ash, corn leaf ash, and rice husk ash, which have been investigated as supplementary cementitious materials. Replacing cement with rice husk ash at 5 – 10 % in pervious concrete mortar mix resulted in higher compressive strength than the control, which is attributed to the high content of silica in the rice husk ash that promotes the formation of additional calcium-silicate-hydrate (C-S-H), thereby enhancing the hydration process and yielding more C-S-H hydrates and ettringite in the cement mortar (Khankhaje et al., 2025). A similar trend has been reported for concrete mixes containing corn leaf ash, where increasing the corn leaf ash content to 7.5% enhances the compressive strength due to the better cement hydration reaction that supports better aggregate binding ability (Aswin et al., 2021). Likewise, Onikeku et al. (2019) reported 10 % replacement

level of bamboo leaf ash provides the optimum compressive strength.

It is noteworthy to state that the targeted 28 days mean compressive strength value of 8 N/mm² was achieved by the control mortar and mortar containing Borassus ash, while mortar incorporating 15 % Borassus ash replacement level exhibited the optimum compressive strength of 14.9 N/mm².

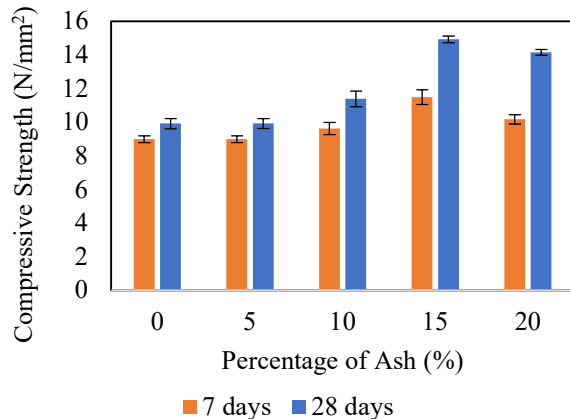


Figure 6: Compressive Strength of mortar containing Borassus ash

4.0 Conclusions

From the study, the following conclusions were drawn

- i. Calcination of Borassus at 600 °C temperature gave the better surface morphology, balance of fineness and porosity, increased intensity of the silicate-related peaks, sufficient mineral decomposition while maintaining a balance between crystalline and amorphous phases, demonstrating potential to perform better in cement replacement applications, meeting the criteria of reactivity as specified in ASTM C618.
- ii. Borassus ash calcined at 600 °C temperature gave the highest SiO₂, Al₂O₃, and Fe₂O₃ combination of 82.1 %, which aligns with the ASTM C618 and IS 3812-1 standards requiring a minimum of 70% for pozzolanic materials.
- iii. Compared to the control mortar, mortar mixes containing Borassus ash at 10 and 20 % increased the initial setting time by 12.3 and 23.1 %, and the final setting time by 7.1 and 10.3 %, respectively;
- iv. Generally, the replacement of cement with Borassus ash at 5%, 10%, 15%, and 20% resulted in increased densities, with the 15 % replacement showing the highest density of 2218 kg/m³ at 28 days. The 20 % replacement recorded a slight decline in density with a value of 2208 kg/m³ at 28 days; and
- v. The optimum compressive strength of 14.93 N/mm² was obtained with mortar containing 15 % of Borassus ash, which is 33 % above the control strength. Beyond the 15 %, there was a

drop in the compressive strength by 5.2 % at 20 % incorporation of Borassus ash. The increment can be attributed to the presence of significant fraction of amorphous silica (SiO₂) in Borassus ash, which reacts with calcium hydroxide (Ca(OH)₂), a byproduct of cement hydration, to produce additional Calcium Silicate Hydrate (C-S-H), an essential component for the development of strength.

REFERENCES

- Abdullah, M. M. A. B., Hussin, K., Bnhussain, M., Ismail, K. N., & Ibrahim, W. M. W. (2019). Mechanism and Chemical Reactions of Palm Oil Fuel Ash (POFA) in Calcium Hydroxide Treatment. *Construction and Building Materials*, 215, 447-455.
- Ganesan, K., Rajagopal, K.R., & Thangavel, K. (2008). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Construction and Building Materials*, 22, 1675-1683.
- Jain, M., & Singh, B. (2018). Characterization of Fly Ash for Its Effective Management and Utilization. *Journal of Cleaner Production*, 172, 1625-1634.
- Mansur, A., Adamu, B., & Abdullahi, H. (2021). Effects of hydromethanol hypocotyls extract of Borassus aethiopicum on sperm and gonadal indices of male Wistar rats. *Journal of Medicinal Plants Research*.
- Nguyen, T.H. (2010). Contribution à l'étude de la formulation et du procédé de fabrication d'éléments de construction en béton de chanvre.
- United Nations. (2012). Earth charter [Online]. Retrieved from official website the United Nations: <http://www.un.org/french>.
- Gabrijel, I., Jelčić Rukavina, M., & Štirmer, N. (2021). Influence of wood fly ash on concrete properties through filling effect mechanism. *Materials*, 14(23), 7164. <https://doi.org/10.3390/ma14237164>
- González-Kunz, R. N., Pineda, P., Bras, A., & Morillas, L. (2017). Plant biomass ashes in cement-based building materials: Feasibility as eco-efficient structural mortars and grouts. *Sustainable Cities and Society*, 31, 151–172. <https://doi.org/10.1016/j.scs.2017.03.001>
- Guo, Z., Chen, Z., Yang, X., Zhang, L., Li, C., He, C., & Xu, W. (2025). The influence of rice husk ash incorporation on the properties of cement-based materials. *Materials*, 18(2), 460. <https://doi.org/10.3390/ma18020460>
- He, J., Kawasaki, S., & Achal, V. (2020). The utilization of agricultural waste as agro-cement in concrete: A review. *Sustainability*, 12(17), 6971. <https://doi.org/10.3390/su12176971>
- Ottosen, L. M., Hansen, E. Ø., Jensen, P. E., Kirkelund, G. M., & Golterman, P. (2016). Wood ash used as partly sand and/or cement replacement in mortar. *International Journal of Sustainable Development and Planning*, 11(5), 781–791. <https://doi.org/10.2495/sdp-v11-n5-781-791>
- Arum, R. C., Arum, C., & Alabi, S. A. (2022). The highs and lows of incorporating pozzolans into concrete and

mortar: A review on strength and durability. *Nigerian Journal of Technology*, 41(2), 197–211. <https://doi.org/10.4314/njt.v41i2.1>

Ruano Gutiérrez, E., Ferrández, D., Atanes-Sánchez, E., & Ruano de Pablo, M. (2024). Physico-mechanical characterization of masonry mortars for sustainable construction: Experimental study with four different aggregates. *Sustainability*, 16(14), 6228. <https://doi.org/10.3390/su16146228>

Singh, A. K., Singh, P., Sharma, P., & Sharma, N. (2023). Environmental effects of cement production: A review. *AIP Conference Proceedings*, 2721(1), 070009. <https://doi.org/10.1063/5.0154039>

Firdissa, B., Degefa, S., Mulugeta, E., & Sithole, D. (2025). Optimizing Ethiopian greenhouse gas inventories with customized clinker-specific emission factors in the cement sector. *Discover Applied Sciences*, 7(1). <https://doi.org/10.1007/s42452-025-06608-y>

Zhong, W., & Haigh, J. D. (2013). The greenhouse effect and carbon dioxide. *Weather*, 68(4), 100–105. <https://doi.org/10.1002/wea.2072>

Dey, A., Pani, A. K., & Acharya, P. K. (2023). Properties of mortar using supplementary cementitious materials. *AIP Conference Proceedings*, 2740(1), 060015. <https://doi.org/10.1063/5.0125840>

Fode, T. A., Chande Jande, Y. A., & Kivevele, T. (2023). Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review. *Heliyon*, 9(7), e17924. <https://doi.org/10.1016/j.heliyon.2023.e17924>

Francioso, V., Lemos-Micolta, E. D., Elgaali, H. H., Moro, C., Rojas-Manzano, M. A., & Velay-Lizancos, M. (2024). Valorization of sugarcane bagasse ash as an alternative SCM: Effect of particle size, temperature-crossover effect mitigation & cost analysis. *Sustainability*, 16(21), 9370. <https://doi.org/10.3390/su16219370>

Hansted, F. A. S., Mantegazini, D. Z., Ribeiro, T. M., Gonçalves, C. E. C., & Balestieri, J. A. P. (2022). A mini-review on the use of waste in the production of sustainable Portland cement composites. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 41(5), 828–838. <https://doi.org/10.1177/0734242x221135246>

Sequeira, L., Forero, J., Bravo, M., Evangelista, L., & de Brito, J. (2023). Durability of concrete with partial replacement of Portland cement by incorporating reactive magnesium oxide and fly ash. *Materials*, 16(7), 2670. <https://doi.org/10.3390/ma16072670>

Ogbodo, M.C., & Akpabot, A.I. (2021). An assessment of some physical properties of different brands of cement in Nigeria. *IOP Conference Series: Materials Science and Engineering*, 1048.

Yang, X., Lu, D., Zhu, B., Sun, Z., Li, G., Li, J., Liu, Q.S., & Jiang, G. (2021). Phase transformation of silica particles in coal and biomass combustion processes. *Environmental pollution*, 118312.

Magdziarz, A., Gajek, M., Nowak-Woźny, D., & Wilk, M. (2017). Mineral phase transformation of biomass

ashes – Experimental and thermochemical calculations. *Renewable Energy*.

Amin, M.N., Hissan, S., Shahzada, K., Khan, K., & Bibi, T. (2019). Pozzolanic Reactivity and the Influence of Rice Husk Ash on Early-Age Autogenous Shrinkage of Concrete. *Frontiers in Materials*.

Xu, W., Lo, T.Y., Wang, W., Ouyang, D., Wang, P., & Xing, F. (2016). Pozzolanic Reactivity of Silica Fume and Ground Rice Husk Ash as Reactive Silica in a Cementitious System: A Comparative Study. *Materials*, 9.

Nair, D., Fraaij, A., Klaassen, A., & Kentgens, A.P. (2008). A structural investigation relating to the pozzolanic activity of rice husk ashes. *Cement and Concrete Research*, 38, 861–869.

Cordeiro, G.C., Filho, R.D., & Fairbairn, E.M. (2008). Use of Ultra-Fine Sugar Cane Bagasse Ash as Mineral Admixture for Concrete. *Aci Materials Journal*, 105, 487–493.

Tangchirapat, W., & Jaturapitakkul, C. (2010). Strength, drying shrinkage, and water permeability of concrete incorporating ground palm oil fuel ash. *Cement & Concrete Composites*, 32, 767–774.

Lim, N.H., Ismail, M.A., Lee, H., Hussin, M.W., Sam, A.R., & Samadi, M. (2015). The effects of high volume nano palm oil fuel ash on microstructure properties and hydration temperature of mortar. *Construction and Building Materials*, 93, 29–34.

Karim, M.R., Hashim, H., & Razak, H.A. (2016). Assessment of pozzolanic activity of palm oil clinker powder. *Construction and Building Materials*, 127, 335–343.

Balaji, G.R., Vetturayasudharsanan, R., Pavan, P.S., Venkatesh, A., & Pandey, M. (2022). Experimental Investigation on combined effect of eggshell powder and sugarcane bagasse ash as mineral admixture in concrete. *IOP Conference Series: Earth and Environmental Science*, 1125.

Hari, R., Zhuge, Y., & K.M., M. (2024). Performance assessment of pervious concrete incorporated with calcium silicate hydrates (C-S-H) cultivated on rice husk ash substrates – A trend surface analysis interpretation. *Construction and Building Materials*.

Prado, R.J., Tiecher, F., Hasparyk, N.P., & Molin, D.D. (2019). Structural characterization of alkali-silica reaction gel: An x-ray absorption fine structure study. *Cement and Concrete Research*.

Zhang, S., Sun, S., Gao, N., Quan, C., & Wu, C. (2021). Effect of auto thermal biomass gasification on the sintering of simulated ashes. *Applications in Energy and Combustion Science*.

Namkung, H., Xu, L., Kim, C., Yuan, X., Kang, T.J., & Kim, H. (2016). Effect of mineral components on sintering of ash particles at low temperature fouling conditions. *Fuel Processing Technology*, 141, 82–92.

Onikeku, O., Shitote, S.M., Mwero, J.N., & Adedeji, A.A. (2019). Evaluation of Characteristics of Concrete Mixed with Bamboo Leaf Ash. *The Open Construction & Building Technology Journal*.

- Aswin, M., Maranatha, E.S., & Nola, L.D. (2021). Effect of use of corn leaf ash on concrete compressive strength. *IOP Conference Series: Materials Science and Engineering*, 1122.
- Khankhaje, E., Jang, H., Kim, J., & Rafieizonooz, M. (2025). Utilizing Rice Husk Ash as Cement Replacement in Pervious Concrete: A Review. *Developments in the Built Environment*.
- Henin, V., & Uglione, P. (2022). Environmental integration tool approach: Self-determined commitment and the adoption of pro-environmental behaviors. *Frontiers in psychology*, 13, 903103. <https://doi.org/10.3389/fpsyg.2022.903103>
- Morin, J. F., Allan, J., & Jinnah, S. (2024). The survival of the weakest: the echo of the Rio Summit principles in environmental treaties. *Environmental Politics*, 33(3), 486–507. <https://doi.org/10.1080/09644016.2023.2236505>
- IPCC. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*. <https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-9/>
- Kumar, S., Roy, S., & Das, P. (2024). Integrating energy efficiency in residential buildings: A user-centric web interface approach. *Current World Environment*, 19(3), 1223–1234. <https://www.cwejournal.org/vol19no3/integrating-energy-efficiency-in-residential-buildings-a-user-centric-web-interface-approach>
- Li, C., Wang, J., & Liu, Y. (2025). Carbon footprint of the construction sector is projected to double by 2050. *Communications Earth & Environment*, 6, Article 284. <https://www.nature.com/articles/s43247-025-02840-x>
- Koffi, S., & Konin, A. (2024). Influence of the addition of palm (*Borassus aethiopum* Mart.) fibers on the durability of compressed earth blocks. *Advances in Materials*, 13(3), 37–45. <https://doi.org/10.11648/j.am.20241303.11>
- Thomas, B. S., Yang, J., Mo, K. H., Abdalla, J. A., Hawileh, R. A., & Ariyachandra, E. (2021). Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. *Journal of Building Engineering*, 40, 102332. <https://doi.org/10.1016/j.jobbe.2021.102332>
- Saki, T., Konan, K. H., & Kouassi, K. P. (2020). Nutritional and antinutritional profile of *Borassus aethiopum* Mart. fruit pulp from Côte d'Ivoire. *International Journal of Pharmacy and Pharmaceutical Sciences*, 12(11), 35–41.
- Mandelot-Matetelot, J. F., Le-Majeur, V., & Mogire, J. (2025). Performance analysis of Ronier fibers (*Borassus aethiopum*) with silica fume on concrete properties. *Engineering, Technology & Applied Science Research*, 15(1), 18590–18602. <https://doi.org/10.48084/etasr.9591>
- Villar-Cociña, E., Morales, E.V., Santos, S.F., Savastano, H., & Frias, M. (2011). Pozzolanic behavior of bamboo leaf ash: Characterization and determination of the kinetic parameters. *Cement & Concrete Composites*, 33, 68–73.
- Frías, M., Savastano, H., Villar, E., Sánchez de Rojas, M., & Santos, S.F. (2012). Characterization and properties of blended cement matrices containing activated bamboo leaf wastes. *Cement & Concrete Composites*, 34, 1019–1023.
- Cordeiro, G.C., & Sales, C.P. (2016). Influence of calcining temperature on the pozzolanic characteristics of elephant grass ash. *Cement & Concrete Composites*, 73, 98–104.
- Cordeiro, G.C., & Sales, C.P. (2015). Pozzolanic activity of elephant grass ash and its influence on the mechanical properties of concrete. *Cement & Concrete Composites*, 55, 331–336.
- Kanning, R.C., Portella, K.F., Bragança, M.D., Bonato, M.M., & Santos, J.C. (2014). Banana leaves ashes as pozzolan for concrete and mortar of Portland cement. *Construction and Building Materials*, 54, 460–465.
- Binici, H., Yucegok, F., Aksogan, O., & Kaplan, H. (2008). Effect of Corncob, Wheat Straw, and Plane Leaf Ashes as Mineral Admixtures on Concrete Durability. *Journal of Materials in Civil Engineering*, 20, 478–483.
- Shakouri, M., Exstrom, C.L., Ramanathan, S., & Suraneni, P. (2020). Hydration, strength, and durability of cementitious materials incorporating untreated corn cob ash. *Construction and Building Materials*, 243, 118171.
- Adesanya, D.A., & Raheem, A.A. (2009). A study of the workability and compressive strength characteristics of corn cob ash blended cement concrete. *Construction and Building Materials*, 23, 311–317.
- Roselló, J., Soriano, L., Santamarina, M.P., Akasaki, J.L., Monzó, J.M., & Payá, J. (2017). Rice straw ash: A potential pozzolanic supplementary material for cementing systems. *Industrial Crops and Products*, 103, 39–50.
- Al-Akhras, N., & Abu-Alfoul, B.A. (2002). Effect of wheat straw ash on mechanical properties of autoclaved mortar. *Cement and Concrete Research*, 32, 859–863.
- Biricik, H., Aköz, F., Türker, F., & Berktaş, I. (2000). Resistance to magnesium sulfate and sodium sulfate attack of mortars containing wheat straw ash. *Cement and Concrete Research*, 30, 1189–1197.
- Pinheiro, S.M.D.M., Font, A., Soriano, L., Tashima, M. M., Monzó, J., Borrachero, M. V., & Payá, J. (2018). Olive-stone biomass ash (OBA): an alternative alkaline source for the blast furnace slag activation, *Construction Building Materials*. 178, 327–338.
- Pandey, A. & Kumar, B. (2019). Effects of rice straw ash and micro silica on mechanical properties of pavement quality concrete, *Journal of Building Engineering*. 26, 1–12.
- Ikubanni, P., Oki, M., Adeleke, A.A., Adediran, A.A., & Adesina, O.S. (2020). Influence of temperature on the chemical compositions and microstructural changes of ash formed from palm kernel shell. *Results in Engineering*.

British Standards Institution. (2013). *Testing concrete. Methods for mixing and sampling fresh concrete in the laboratory* (BS 1881-125:2013). London, UK

British Standards Institution. (2019). *Testing hardened concrete. Density of hardened concrete* (BS EN 12390-7:2019). London, UK

British Standards Institution. (2019). *Testing hardened concrete. Compressive strength of test specimens* (BS EN 12390-3:2019). London, UK

ASTM International. (2023). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (ASTM C618-23). West Conshohocken, PA

Bureau of Indian Standards. (2013). *Pulverized fuel ash – Specification: Part 1 for use as pozzolana in cement, cement mortar and concrete* (IS 3812-1:2013). New Delhi, India