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Physicochemical And Mechanical Performance Of Lime-Based Binders Incorporating Rice Husk Ash And Calcined Clay

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Abstract
The environmental concerns linked to ordinary Portland cement have increased the demand for alternative binder systems that utilize locally available resources efficiently and still provide adequate performance. This study investigates the potential of rice husk ash (RHA) and calcined clay (CC) as supplementary pozzolanic materials in lime-based binders. The objective was to comparatively evaluate the influence of these materials on physicochemical properties, reactivity, and mechanical performance and to establish relationships between these parameters. RHA and CC were produced under controlled calcination conditions and characterized using chemical, mineralogical, and surface analyses. Pozzolanic reactivity was assessed through electrical conductivity measurements, while performance was evaluated using water absorption and compressive strength tests. The results showed that both materials satisfied standard chemical requirements for pozzolans; however, their reactivity differed significantly due to variations in structure and surface characteristics. RHA exhibited a predominantly amorphous structure and a high specific surface area, resulting in faster reaction kinetics, greater calcium hydroxide consumption, and slightly higher compressive strength when used in lime-based mortars. In contrast, CC displayed a mixed amorphous–crystalline composition and lower surface area, leading to slower but sustained reactivity. The incorporation of both pozzolans improved compressive strength and reduced water absorption compared to pure lime mortar. After 28 days, blended mortars achieved strengths of approximately 4.2–4.3 MPa, indicating suitability for non-structural applications. The findings demonstrate that binder performance is governed by the combined effects of chemical composition, phase structure, surface properties, and reaction kinetics rather than composition alone. This study provides a systematic comparative assessment of RHA and CC in lime-based systems and highlights the importance of integrating physicochemical characteristics with reactivity measurements to better understand and optimize the performance of sustainable binder materials.
Keywords: *Rice husk ash, calcined clay, lime-based binders, pozzolanic reactivity, compressive strength, electrical conductivity.*

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I. Introduction

The construction industry is a significant contributor to global carbon dioxide (CO_2) emissions, largely due to the extensive use of ordinary Portland cement (OPC). Cement production is energy-intensive and generates substantial CO_2 through fuel combustion and limestone calcination, accounting for approximately 7–8% of global anthropogenic emissions. A major portion of these emissions originates from clinker production, particularly from limestone decarbonation and fossil fuel use [1, 2]. Additionally, the industry's dependence on raw material extraction, transportation, and fuel consumption increases resource demand and overall environmental impact [3].

These challenges have driven the search for alternative binder systems that are resource-efficient and locally available while maintaining adequate performance. Consequently, research in concrete technology has increasingly focused on reducing cement content through the use of supplementary cementitious materials (SCMs). Various agricultural and industrial by-products, including rice husk ash (RHA), fly ash (FA), silica fume (SF), limestone, calcined clays (CC), and natural pozzolans, have been widely investigated as partial cement replacements [4–7]. In parallel, lime–pozzolana binders have gained renewed attention, where pozzolanic materials react with calcium hydroxide to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrates, contributing to the development of stable cementitious matrices [8–10]. However, their broader application is constrained by slow reaction kinetics and low early-age strength.

The availability and long-term reliability of conventional SCMs are becoming increasingly uncertain. Reductions in coal-based power generation and shifts in industrial processes are limiting the supply of materials such as fly ash and slag, while increased transportation distances add cost and logistical challenges. In many regions, these materials must be imported, further restricting their use. Scrivener *et al*. [3] highlight that commonly

used SCMs, including slag, fly ash, and silica fume, are unlikely to meet the growing global demand for cement replacement materials and that agricultural ashes alone cannot fully compensate for this shortfall.

As a result, increasing attention is being directed toward locally available alternative pozzolanic materials, particularly underutilized agricultural and industrial waste ashes [6]. Among these, rice husk ash (RHA) and calcined clays (CC) have shown considerable promise due to their high pozzolanic reactivity. RHA is rich in amorphous silica and exhibits high reactivity when properly processed [11], while calcined clays, especially those derived from kaolinitic sources, contain reactive aluminosilicate phases formed during thermal activation [2]. Both materials have demonstrated effectiveness in improving the performance of blended cement systems [12–16]. In regions such as Kenya, where volcanic pozzolans are limited, clay deposits and agro-industrial residues such as rice husks are abundant but remain largely underutilized, indicating strong potential for their application as locally sourced binder materials.

Despite these developments, most studies have focused on OPC-based systems, with comparatively limited attention given to lime-based binders. Furthermore, RHA and calcined clays have typically been studied independently, with limited direct comparison under similar experimental conditions. In addition, the relationship between physicochemical characteristics, reaction kinetics, and mechanical performance in lime-based systems remains insufficiently explored.

The research gap addressed in this study is the lack of comparative understanding of the influence of rice husk ash and calcined clay on the physicochemical properties, reactivity, and mechanical performance of lime-based binders, as well as the limited integration of these parameters. This study contributes by providing a systematic comparative evaluation of RHA and calcined clay in lime-based systems and by establishing relationships between reaction kinetics (via electrical conductivity), phase composition (XRD), and mechanical performance. Accordingly, the objective of this study is to comparatively evaluate the influence of rice husk ash and calcined clay on the physicochemical characteristics, reactivity, and mechanical properties of lime-based binders. It is hypothesized that both rice husk ash and calcined clay will enhance the pozzolanic reactivity of lime-based binders, with differences in performance arising from their distinct chemical compositions, resulting in variations in strength development, porosity, and water absorption behavior.

II. Materials And Methods

Materials

Rice husks (RH) were randomly collected from two rice milling facilities at Nyangweso Market, Homa Bay, Kenya. Raw clay samples were obtained from two locations, Orembe and Namba Karabok in Homa Bay, where brick-making activities are prevalent. At each site, three samples were collected from a depth of approximately 0.9 m (3 ft) and then mechanically combined to form representative composite samples and stored in labeled polythene bags. Commercial hydrated lime (HL), conforming to KS EAS 18-1:2017 [17], was supplied by Laboklin Chimique Company Limited (Nairobi, Kenya) and used as the primary calcium source. The lime had a specific gravity of approximately 2.73. Standard river sand with a maximum particle size of 4.75 mm was used as fine aggregate. The sand had a specific gravity of 2.64 and a fineness modulus of 2.83. Deionized water was used for all experimental procedures.

Methods

Sample preparation

Rice husks were cleaned by sieving, air separation, and washing to remove coarse particles, light impurities, and dust. The cleaned husks were sun-dried for two days and subsequently oven-dried at 110 °C for 24 h. The clay was manually cleared of debris and oven-dried at 110 °C for 24 h. After drying, the clay was crushed using a jaw crusher to obtain particles smaller than 2 mm, followed by grinding in a planetary ball mill (Retsch PM100) for 15 min at 200 rpm. The ground material was then sieved through a 90 µm mesh to remove coarse particles and obtain a uniform feedstock prior to calcination. The sand was washed with deionized water to remove fines and impurities, oven-dried at 105 ± 5 °C to constant mass, and sieved to exclude particles larger than 5 mm.

Calcination of the pozzolans

The dried rice husk (RH) was converted to ash by calcination in a muffle furnace under an air atmosphere at 600 °C for 2 h, using a controlled heating rate of approximately 10 °C/min. After calcination, the material was allowed to cool gradually inside the furnace to room temperature (approximately 24 h). The resulting rice husk ash (RHA) was then ground under dry conditions using an HFM 100 grinder for 30 min to achieve a particle size passing a 75 µm sieve and subsequently stored in airtight containers. Similarly, the milled clay was calcined at 600 °C for 2 h under the same furnace conditions, with a heating rate of approximately 10 °C/min. The calcined material was cooled inside the furnace to ambient temperature and then ground for approximately 30 min. The resulting calcined clay (CC) was sieved through a 75 µm mesh, with more than 90% of the material passing the sieve.

The calcination temperature of 600 °C was selected based on both technical and practical considerations. Dehydroxylation of kaolinite, which results in the formation of reactive metakaolin, typically occurs within the temperature range of 500–600 °C, with temperatures around 600 °C being sufficient to produce an amorphous aluminosilicate phase with significant pozzolanic reactivity [18]. A calcination duration of 2 h was adopted in line with previous studies, which have shown that this period is adequate to achieve substantial dehydroxylation and transformation of clay minerals without inducing excessive particle coarsening. In addition, operating at 600 °C represents a lower thermal requirement compared to clinker production in OPC systems, making it a practically viable processing condition.

Physical, Chemical, and Mineralogical Analysis

The particle size distribution of the pozzolanic materials was determined using a sieve analyzer equipped with a range of standard mesh sizes. The specific surface area was measured using the Brunauer–Emmett–Teller (BET) method with a Gemini 2375 V5.0 nitrogen adsorption analyzer. The chemical composition of the pozzolans and hydrated lime was analyzed using an Epsilon 3XLE X-ray fluorescence (XRF) spectrometer (Malvern Panalytical, Almelo, Netherlands). The mineralogical composition, including crystalline phases, was identified by X-ray diffraction (XRD) using a Bruker AXS diffractometer (Karlsruhe, Germany). For the loss on ignition (LOI) test, approximately 1 g of sample was first dried at 110 °C for 1 h and weighed. The sample was then heated to 1000 °C for 1 h, cooled in a desiccator, and reweighed. The LOI was calculated as the percentage mass loss during heating [19]. This test was performed on calcined materials to evaluate the remaining volatile content after thermal treatment.

Evaluation of Pozzolanic Activity

The pozzolanic activity of the materials was evaluated using the electrical conductivity method, following John [19] and Musyimi *et al*. [2]. Distilled water (200 mL) was heated to 38 ± 1 °C in a 250 mL beaker, and 0.8 g of calcium hydroxide ($Ca(OH)_2$) was dissolved to obtain a saturated solution. The initial electrical conductivity of the calcium hydroxide solution, $EC_{o,}$ was measured using a conductivity meter and monitored until stabilization. Subsequently, 5 g of finely ground pozzolana was added to the solution and stirred for two minutes. Electrical conductivity measurements, EC_t, were recorded at 30-minute intervals over a period of 4 h. A control test consisting of a $Ca(OH)_2$ solution without pozzolana was also conducted under identical conditions to account for any natural variation in conductivity over time. In addition, a parallel test using pozzolana and distilled water (without $Ca(OH)_2$) was performed to determine the intrinsic conductivity contribution of the pozzolana, EC_P. This value was used to correct the measured conductivity values. The corrected electrical conductivity was calculated using equation 1:

$$EC_{corrected} = EC_t - EC_p \qquad \text{Eq. 1.}$$

The pozzolanic activity was then expressed as the loss in conductivity relative to the initial conductivity of the $Ca(OH)_2$ solution as shown in Equation 2:

$$EC_{loss} = EC_o - EC_{corrected} \qquad \text{Eq. 2.}$$

Each test was conducted in triplicate, and the average values were used to plot the graph reported.

Mix proportions

Mix proportions are summarized in Table 1, with all quantities expressed relative to the total binder content, which includes both lime and the pozzolanic material.

Table 1: Mix proportions of mortar constituents by mass

Mix ID	Lime	CC	RHA	Sand	Water
L-C	1.0	-	-	3.0	0.50
L-RHA	0.5	-	0.5	3.0	0.50
L-CC	0.5	0.5	-	3.0	0.50

Mortar mixtures were prepared using hydrated lime as the primary binder, with rice husk ash (RHA) and calcined clay (CC) used as pozzolanic additives. In the blended systems, the pozzolanic materials partially replaced lime, while a reference mix containing only hydrated lime was included for comparison. All mixtures were proportioned with a binder-to-sand ratio of 1:3 by mass. For the blended mortars, 50% of the lime was replaced by either RHA or CC, resulting in a binder composition of 1:1 (lime:pozzolan) by mass. This replacement level was selected to provide sufficient reactive silica and alumina from the pozzolans while retaining adequate

calcium hydroxide to sustain the pozzolanic reaction. A constant water-to-binder ratio of 0.50 was maintained for all mixes to ensure comparable workability and performance.

Mortar preparation

Mortar prisms were prepared in accordance with KS EAS 2168-1:2020 [20], with minor modifications. Hydrated lime and the pozzolanic materials were first dry-blended in the proportions presented in Table 1 to ensure binder homogeneity. The mortar mix consisted of 1350 g of graded sand and 450 g of a pozzolan–lime blend at a 1:1 mass ratio. Mixing was carried out using an automatic mortar mixer for 90 s to obtain a uniform consistency. The fresh mortar was placed into greased three-part molds (40 × 40 × 160 mm) and compacted in layers using 20 strokes of a steel tamping rod per layer. After casting, the specimens were kept in their molds under high humidity conditions (95 ± 5% RH, 20 ± 2 °C) for 48 h. The prisms were then demolded and cured under laboratory conditions at 60 ± 5% relative humidity and 20 ± 2 °C, following ASTM C109 procedures [21]. Air curing was adopted to allow both carbonation of lime and pozzolanic reactions to occur under conditions representative of practical applications. All specimens were cured for 28 days prior to testing. Early-age strength measurements (3 and 7 days) were not conducted due to the relatively slow reaction kinetics of lime-based systems [22].

Water absorption

This test was carried out according to BS 1881-122:2011 [23]. Initially, three mortar samples were dried in a ventilated oven at 60 ± 5°C until they reached a constant weight. After drying, they were cooled in a desiccator, and the dry weight of each sample was recorded as m_1. The samples were then gently submerged in a sealed container of water for 48 hours. To ensure any trapped air escaped, the specimens were tilted at approximately 45° during immersion. Once completely submerged, they were placed vertically to begin the test. After the 48-hour period, the samples were taken out, lightly wiped with a damp cloth, and their saturated weight was recorded as m_2. The water absorption of the concrete samples was then calculated as a percentage using Equation 3.

$$W = \frac{m2-m1}{m1} \text{ x } 100 \qquad \text{Eq 3}$$

Compressive Strength Determination

The compressive strength of the mortar was measured following KS EAS 148-1:2017 [24], with minor modifications. After curing, tests were carried out using a compressive strength machine (SSC-546, Instron, Norwood, USA). Each mortar prism was positioned lengthwise so that its end face extended about 10 mm beyond the platens or auxiliary plates and was aligned centrally within ±0.5 mm. The load was applied gradually at a rate of 2400 ± 200 N/s until the specimen fractured. Each test was performed in triplicate, and the resulting compressive strength values were calculated and reported in megapascals (MPa).

III. Results And Discussion

Chemical Composition of RHA, CC, and Lime

Table 2 displays the chemical composition of CC, RHA, HL, and LOI in percent by mass of each sample.

Table 2: Oxide chemical composition and loss on ignition (LOI) of CC, RHA, and HL (wt%). Values are presented as mean ± standard deviation.

Test Sample	CC	RHA	HL
SiO_2	78.90 ± 0.01	95.02 ± 0.005	—
Al_2O_3	12.35 ± 0.005	0.50 ± 0.005	0.21±0.01
Fe_2O_3	3.68 ± 0.005	0.25 ± 0.005	—
CaO	0.57 ± 0.005	0.86 ± 0.005	88.45±0.02
MgO	1.72 ± 0.005	—	1.24±0.02
K_2O	0.73 ± 0.05	1.09 ± 0.005	—
Na_2O	1.25 ± 0.01	0.25 ± 0.005	—
LOI	10.67 ± 0.577	5.66 ± 0.577	27.14±0.02
SiO_2 + Al_2O_3 + Fe_2O_3	94.94 ± 0.012	95.78 ± 0.008	—

The pozzolanic materials analyzed exhibited combined SiO_2, Al_2O_3, and Fe_2O_3 contents exceeding 70%, satisfying the compositional requirements of KS EAS 18-1:2017 [17] and ASTM C618:1999 [25]. While this confirms compliance with standard chemical criteria, it does not, on its own, establish pozzolanic reactivity, which

is also governed by factors such as amorphous phase content, fineness, and dissolution behavior, as examined in subsequent sections.

A notable distinction between the two materials lies in their oxide composition. RHA is predominantly silica-rich, whereas calcined clay contains comparatively lower silica but a significantly higher alumina content (12.35%). The high silica content of RHA is attributed to the accumulation of orthosilicic acid in rice plants during growth [26], consistent with findings reported in earlier studies [19, 27]. Variations in oxide composition are expected due to differences in raw material sources and processing conditions [28]. This compositional difference suggests that RHA is more likely to favor the formation of silica-rich reaction products, while calcined clay may promote the development of additional aluminosilicate phases, thereby influencing reaction pathways and strength development differently.

The oxide composition of the clay further indicates that it is not purely kaolinitic. The presence of MgO, Na_2O, and K_2O points to contributions from secondary mineral phases such as illite, feldspars, or other aluminosilicates commonly found in natural clays. Consequently, only a portion of the material is expected to transform into highly reactive phases upon calcination. The remaining components may act as inert or partially reactive phases, affecting the overall reactivity and performance of the calcined clay.

Hydrated lime differs fundamentally from RHA and calcined clay in that it serves as the primary calcium source rather than a pozzolanic material. Its high CaO content, in line with EN 459-1 requirements [29], ensures the availability of calcium hydroxide necessary for reaction with the siliceous and aluminous phases of the pozzolans. Strength development in these systems is therefore controlled by the interaction between lime and the reactive components of the pozzolanic materials. In addition to pozzolanic reactions, carbonation of calcium hydroxide contributes to matrix densification through the formation of calcium carbonate, enhancing stiffness and overall performance, as reported in previous studies [30–31].

From a reactivity standpoint, the high silica content of RHA indicates a greater potential for rapid calcium hydroxide consumption, particularly at early stages, whereas the higher alumina content of calcined clay is expected to support slower but more sustained reactions. These differences are reflected in the electrical conductivity trends and mechanical performance discussed in later sections.

The MgO content in all samples remained below 5%, reducing the risk of deleterious expansion, while the total alkali content ($Na_2O + K_2O$) was below 1.5%, minimizing the likelihood of alkali-related deterioration [32]. The LOI values, which indicate the presence of residual volatile components, were within acceptable limits for both RHA and calcined clay in accordance with ASTM C618 [25] and BS EN 450 [33]. The relatively high LOI observed for hydrated lime is consistent with the release of CO_2 during the decomposition of carbonate phases and subsequent hydration processes. These characteristics suggest that the performance of the materials is primarily governed by their pozzolanic behavior rather than adverse chemical effects.

Mineralogical Composition of RHA, Calcined Clay, and Lime

XRD was used to determine the mineralogical composition of the CC, RHA, and lime samples. The results are shown in Figures 1-3.

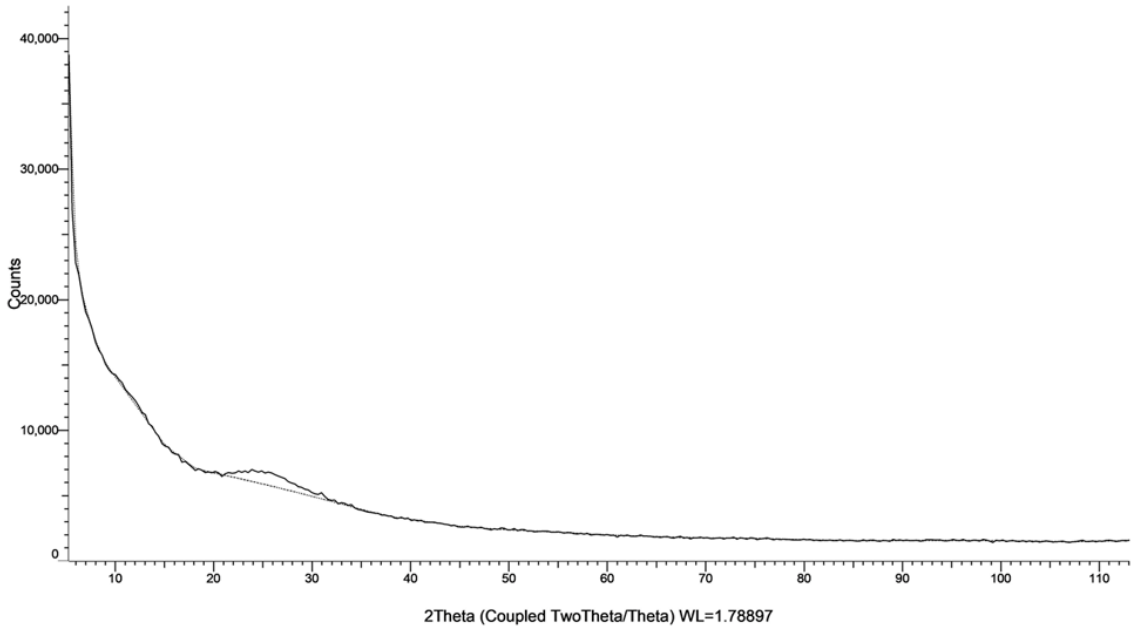

Figure 1: XRD diffractogram of RHA

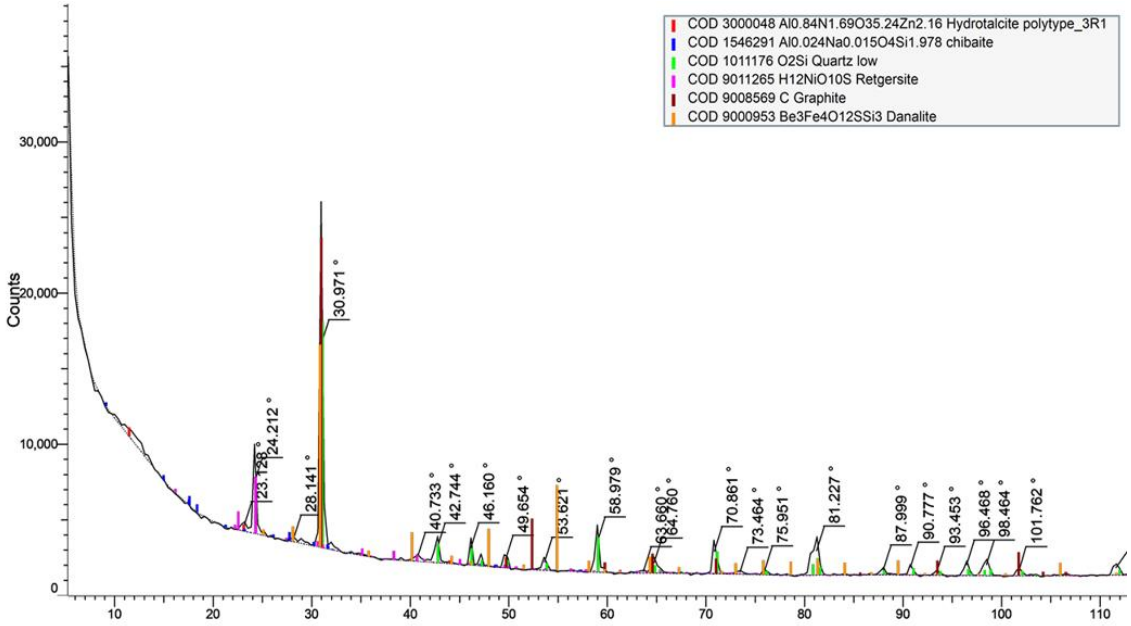

Figure 2: XRD diffractogram of clay calcined

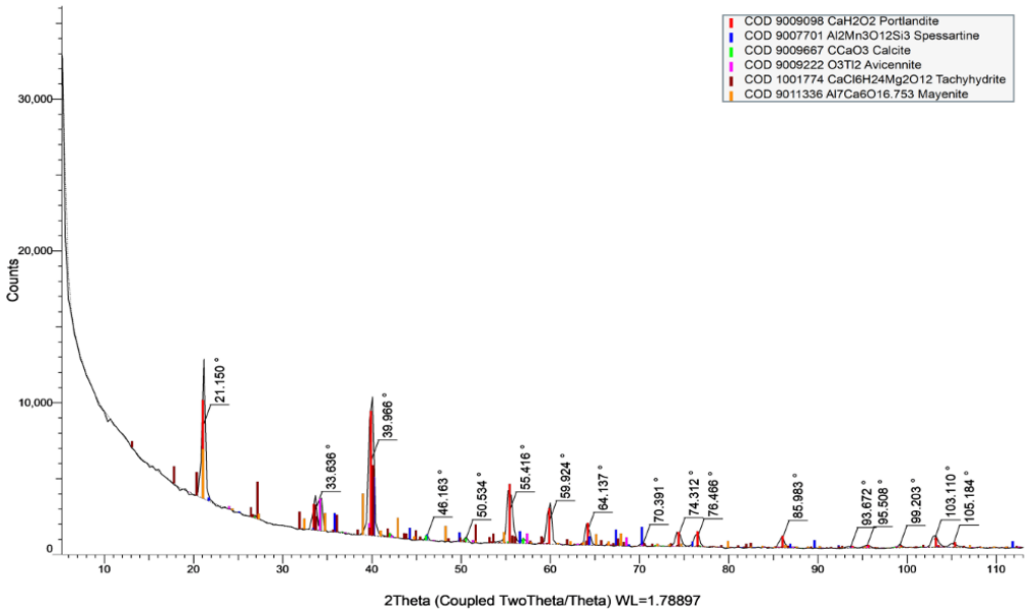

Figure 3: XRD diffractogram of pure hydrated lime

The XRD patterns (Fig. 1) show that RHA is predominantly amorphous, as indicated by the broad diffuse hump between 20° and 30° (2θ) and the absence of sharp crystalline peaks. When interpreted alongside the XRF results, which show a very high silica content (95.02%), this confirms that the silica in RHA is largely present in an amorphous form. This is a critical observation, as amorphous silica is significantly more reactive than its crystalline counterparts. Therefore, the combination of high silica content (XRF) and amorphous structure (XRD) suggests that RHA has a strong potential for rapid pozzolanic reaction, particularly at early stages. Similar amorphous characteristics have been reported by Adamu *et al*. [34] and Endale *et al*. [35], although minor crystalline phases such as quartz are sometimes observed.

In contrast, the calcined clay exhibits a mixed amorphous–crystalline structure. The XRF results indicate substantial amounts of both silica and alumina (Table 2), suggesting potential for aluminosilicate reactivity. However, the XRD patterns reveal that this composition is only partially transformed into an amorphous reactive phase, as evidenced by the presence of a broad hump around $2\theta \approx 19.8°$ alongside distinct crystalline peaks such as quartz. The disappearance of kaolinite and illite peaks confirms that thermal activation has occurred, leading to the formation of amorphous metakaolin-like phases, consistent with Canda *et al*. [36]. However, the persistence of crystalline phases implies that not all components contribute equally to reactivity.

This distinction between chemical composition (XRF) and phase assemblage (XRD) is critical. While calcined clay contains sufficient silica and alumina to meet pozzolanic compositional criteria, the XRD results indicate that only a fraction of these oxides exists in a reactive amorphous state. The remaining crystalline phases, particularly quartz, are largely inert and may act as fillers rather than reactive components. This explains why, despite having adequate oxide composition, calcined clay is expected to exhibit a slower or less extensive reaction compared to RHA. These observations provide a mechanistic basis for interpreting subsequent results, particularly electrical conductivity measurements and strength development, where differences in reactivity between the two pozzolans are anticipated.

The hydrated lime pattern is dominated by sharp portlandite peaks, confirming its highly crystalline nature and role as a calcium source rather than a reactive pozzolan. Minor calcite peaks indicate partial carbonation due to exposure to atmospheric CO_2. When considered together with the XRF data showing high CaO content, this confirms that lime primarily supplies calcium hydroxide required for reaction with the amorphous phases of the pozzolans. The absence of an amorphous halo further indicates that lime itself does not contribute to pozzolanic reactivity but instead governs the availability of calcium for reaction. The dominance of sharp portlandite reflections and the absence of a broad amorphous halo suggest that little to no secondary reaction occurs in the pure lime sample. This aligns with the typically slow strength development observed in lime-based systems [37-39].

Physical Characterization of RHA, Calcined Clay, and Hydrated Lime

Table 3 illustrates the specific gravity and SSA values of hydrated lime, RHA, and calcined clay, respectively.

Table 3: Physical properties of hydrated lime, CC, and RHA

Property	Lime	CC	RHA
Specific gravity	2.7	2.6	2.2
BET surface area (m^2/g)	-	10.7	72.1

The physical properties presented in Table 3 highlight clear differences between RHA and calcined clay (CC), which directly influence their reactivity and performance in lime-based binders. Although the specific gravity values of lime and CC are relatively similar, the notably lower value for RHA reflects its more porous and less dense structure. At an equivalent mass replacement, this implies that RHA introduces a larger solid volume into the mixture, potentially affecting particle packing and water demand. This behavior is consistent with the highly porous silica framework commonly reported for RHA [40].

A more pronounced distinction is observed in the BET surface area, where RHA exhibits a value nearly seven times higher than that of CC. This parameter is critical because it governs the availability of reactive sites for pozzolanic reactions. The high surface area of RHA enhances dissolution and facilitates rapid calcium hydroxide consumption, leading to faster reaction kinetics, particularly at early stages. This observation aligns with previous studies, which attribute the high reactivity of RHA to its porous structure and increased availability of amorphous silica [40-41].

In comparison, the lower surface area of CC suggests reduced accessibility of reactive sites and consequently slower reaction kinetics. However, its reactivity is also influenced by the presence of thermally activated aluminosilicate phases formed during calcination. As a result, while RHA is expected to drive rapid early-stage reactions, CC is more likely to contribute progressively through sustained pozzolanic activity. This distinction is important for interpreting subsequent results, particularly electrical conductivity and strength development, where differences in reaction rates between the two materials become evident.

Variations in surface area relative to values reported in the literature [42-44] can be attributed to differences in processing conditions, such as calcination temperature, grinding intensity, and particle size distribution. Nevertheless, the relatively high surface area obtained for RHA in this study indicates effective processing, which is essential for enhancing its reactivity. The results suggest that RHA and CC exhibit distinct reactivity profiles in lime-based systems, with RHA favoring rapid early reactions due to its higher surface area, while CC contributes more gradually. These differences provide a framework for understanding the physicochemical and mechanical behavior discussed in subsequent sections.

Pozzolanic Activity Test Results

To identify the best treatment conditions, the electrical conductivity drop of saturated calcium hydroxide when RHA and clay calcined at different temperatures and periods were added was monitored. Figure 6 displays the conductivity loss with respect to time.

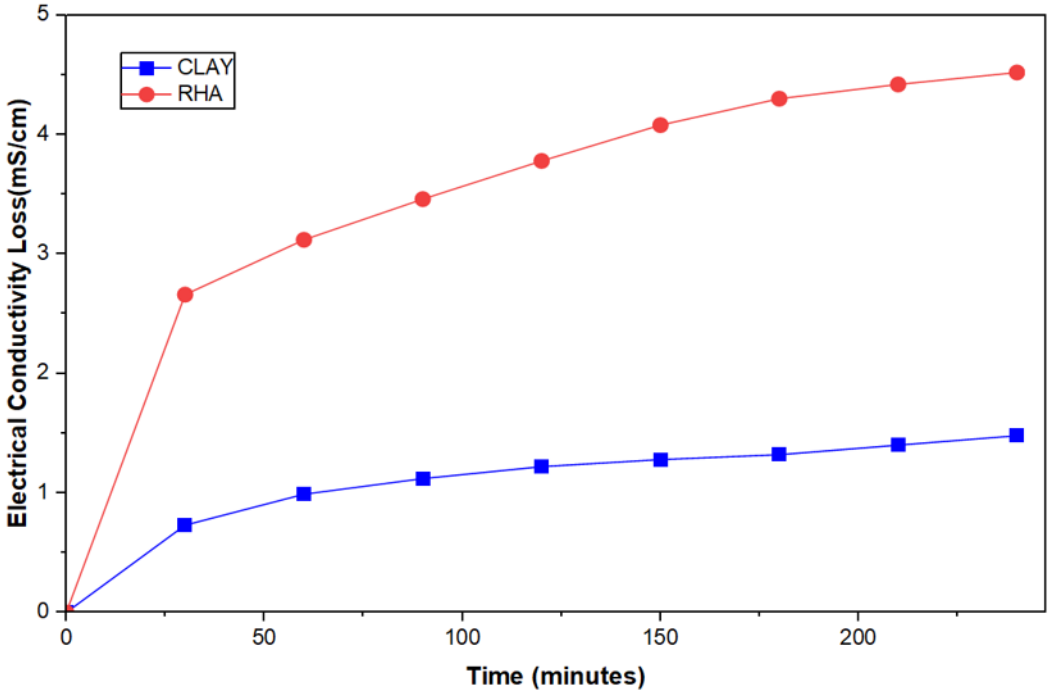

Figure 4: Pozzolanic Activity of Calcined Clays & RHA Samples Calcined for 2 h at 600 °C

Figure 4 illustrates the evolution of electrical conductivity in the lime–RHA and lime–CC systems, which reflects the depletion of ionic species associated with pozzolanic reactions [20]. Similar trends have been reported by Luxán *et al*. [45], John [19], and Assumptor *et al*. [27]. Although both systems show a progressive decrease in conductivity over time, the rate and magnitude of this reduction differ, indicating variations in reactivity.

The lime–RHA system exhibited a more rapid decline in conductivity compared to the lime–CC system, indicating faster consumption of calcium hydroxide. This behavior can be explained by the combined physicochemical characteristics derived from previous analyses. XRF results showed that RHA contains a high proportion of silica (Table 2), while XRD confirmed that this silica is predominantly amorphous (Fig. 1). In addition, BET analysis (Table 3) indicated a significantly higher specific surface area for RHA. The combination of high silica content, amorphous structure, and large surface area enhances dissolution and increases the availability of reactive sites, thereby accelerating calcium ion consumption and resulting in a pronounced reduction in conductivity [20]. This observation aligns with previous studies that attribute the high reactivity of RHA to its amorphous silica content and fineness [19, 27].

In contrast, calcined clay contains appreciable amounts of silica and alumina (Table 2), but XRD analysis reveals a mixed amorphous–crystalline structure (Fig. 2), including phases such as quartz. Furthermore, its lower BET surface area (Table 3) limits the accessibility of reactive sites. Consequently, only a portion of the oxides participates effectively in the pozzolanic reaction, leading to slower calcium hydroxide consumption and a more gradual decline in conductivity. This indicates that reactivity is not governed solely by chemical composition but also by phase composition and surface characteristics [44].

Both systems exhibit a sharp initial drop in conductivity within the first 30 minutes, suggesting rapid early-stage reactions, consistent with findings by Walker and Pavía [44] and Figueiredo and Pavía [46]. This stage is likely controlled by the dissolution of readily available amorphous phases. The subsequent divergence in conductivity trends reflects differences in reactivity. The higher surface area of RHA supports sustained exposure of reactive silica and maintains a higher reaction rate. The lower surface area and partial crystallinity of calcined clay result in slower, diffusion-controlled kinetics. These variations in reaction behavior are expected to influence the development of mechanical properties, particularly the rate of strength gain at early and later stages.

Water Absorption

Mortar prisms were subjected to a water absorption test for a period of up to 48 h. The results are as represented in Figure 5.

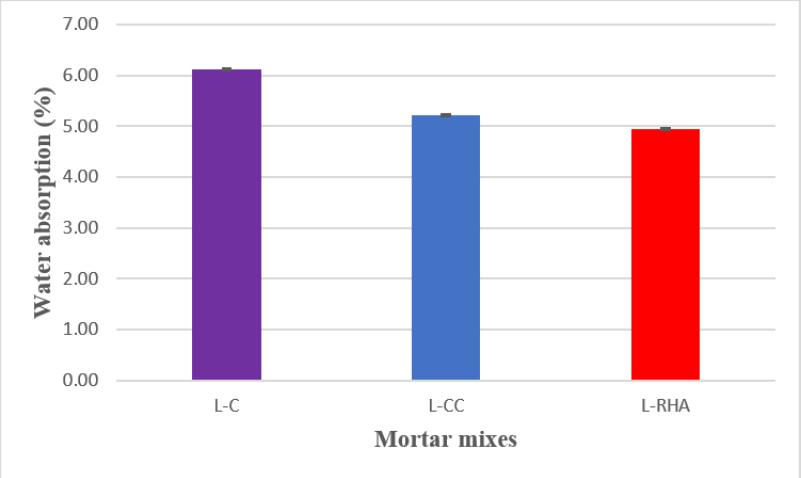

Figure 5: Water absorption of lime-based mortars

Figure 5 presents the water absorption results of the mortars. The pure lime mortar (L-C) recorded the highest water uptake, which is consistent with its inherent material characteristics. As reported by Bartholdy *et al*. [47], this behavior is primarily associated with the porous microstructure and limited hydraulic reactivity of lime-based systems. XRD analysis (Figure 3) further confirms that hydrated lime is predominantly composed of crystalline $Ca(OH)_2$ with minor calcite, indicating the absence of reactive amorphous phases required for effective gel formation and pore refinement. Similar observations have been documented by Janotova and Slížková [48] and Brzyski [49]. During air curing, carbonation leads to the formation of fine pore structures, which facilitate water ingress and may adversely affect durability. Consequently, pure lime mortars tend to exhibit high water absorption, increasing their susceptibility to durability-related issues such as freeze–thaw damage, salt crystallization, and delayed strength development [50].

In contrast, the incorporation of pozzolanic materials significantly reduced water absorption in both L-RHA and L-CC mortars, indicating improved resistance to water penetration. This behavior can be directly linked to the physicochemical characteristics discussed earlier. In the L-RHA system, the high content of amorphous silica promotes rapid pozzolanic reactions, which leads to the formation of dense C–S–H gels that refine the pore structure and reduce capillary connectivity. Although L-CC also shows reduced water absorption, its performance is slightly lower than that of L-RHA. This is attributed to its lower specific surface area, slower reaction kinetics, and the presence of minor crystalline phases, which limit the extent of early-stage pore refinement [44].

The results demonstrate that both RHA and calcined clay can enhance the durability of lime-based mortars by reducing water absorption, with RHA showing greater effectiveness due to its higher amorphous silica content and larger surface area.

Compressive Strength

The compressive strength results for the mortar mixes used in this study are illustrated in Figure 6.

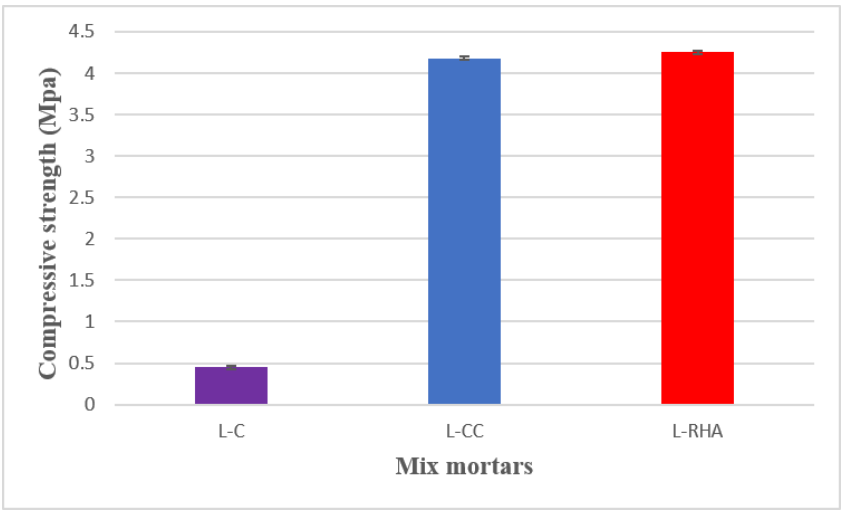

Figure 6: Compressive strength of lime-based mortars

Figure 6 presents the compressive strength of the mortars after 28 days of curing. The incorporation of pozzolanic materials resulted in a substantial increase in strength, with both L-RHA and L-CC mortars exhibiting significantly higher values than the pure lime mortar (L-C). The low strength of L-C is consistent with its physicochemical characteristics. XRD analysis shows that hydrated lime is predominantly crystalline $Ca(OH)_2$ with minor calcite. This indicates a lack of reactive amorphous phases necessary for hydraulic reactions. As a result, strength development in pure lime systems depends mainly on carbonation, a slow process governed by CO_2 diffusion and moisture availability, which limits early- and mid-term strength gain [51].

The enhanced strength observed in L-RHA and L-CC mortars is attributed to pozzolanic reactions between lime and the reactive silica and aluminosilicates present in RHA and calcined clay. These reactions lead to the formation of C–S–H and C–A–S–H gels, which contribute to matrix densification and reduced porosity [48-49]. This densification is consistent with the reduced water absorption observed in Figure 5, confirming improved pore structure refinement in the blended systems.

L-RHA exhibited slightly higher compressive strength than L-CC, which can be linked to its higher content of amorphous silica and greater specific surface area (Table 3, Fig. 1). These characteristics enhance dissolution and accelerate reaction kinetics. This was reflected in the electrical conductivity results, where the lime–RHA system showed faster calcium hydroxide consumption. This rapid formation of C–S–H results in a denser microstructure and improved strength. In comparison, L-CC showed slightly lower strength due to its mixed amorphous–crystalline composition and lower surface area. The presence of crystalline phases such as quartz, identified by XRD, reduces the fraction of reactive material, leading to slower reaction kinetics and delayed gel formation [52].

Despite this, the comparable strength levels of L-RHA and L-CC indicate that both materials are effective pozzolans. While RHA promotes faster strength development due to its highly amorphous structure and high surface area, calcined clay contributes through sustained reactions facilitated by its combined silica and alumina content. These results demonstrate that compressive strength development is governed by the combined influence of chemical composition, phase structure, surface characteristics, and reaction kinetics.

At 28 days, both lime–RHA and lime–CC mortars achieved compressive strengths in the range of 4.2–4.3 MPa, which are suitable for non-structural and low-strength construction applications. These include masonry mortars for low-rise construction, plastering and rendering, floor screeds, and repair works, where moderate strength and durability are required. The findings further demonstrate that the use of locally available pozzolanic materials can effectively enhance the performance of lime-based binders.

IV. Conclusion

- Both rice husk ash and calcined clay satisfied standard chemical requirements for pozzolanic materials; however, reactivity is governed by structural characteristics and surface properties rather than composition alone.
- Rice husk ash, with its predominantly amorphous structure and high specific surface area, exhibits faster reaction kinetics and achieves slightly higher compressive strength in lime-based mortars.
- Calcined clay, containing both amorphous and crystalline phases and having a lower surface area, shows slower reaction kinetics but maintains more gradual and sustained reactivity over time.
- The incorporation of pozzolanic materials enhances compressive strength and reduces water absorption compared to pure lime systems.
- The mortars achieved compressive strengths of approximately 4.2–4.3 MPa, indicating suitability for non-structural applications.
- The study establishes a relationship between chemical composition, mineralogical characteristics, surface properties, and electrical conductivity behavior, demonstrating their combined influence on binder performance.
- No direct microstructural analysis was conducted; the proposed mechanisms are inferred from literature, a single processing condition, and results limited to 28 days.
- Long-term durability and environmental performance were not evaluated.
- Future work should include microstructural characterization, durability assessment, and optimization of mix design and processing conditions.
- Future research should incorporate uncalcined (raw) clay as a reference material to better isolate and quantify the influence of calcination on reactivity, phase evolution, and overall performance in lime-based systems.

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Data availability

The datasets generated and/or analyzed during the current study are publicly available in the Zenodo repository at https://doi.org/10.5281/zenodo.19411246.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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