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Effects of Moulding Compaction on Physical, Mechanical, and Thermal Properties of Hybrid Composite Clay Bricks

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ABSTRACT

The growing demand for affordable, and energy-efficient housing has intensified the need for alternative masonry materials. This study investigates the effect of controlled green compaction pressure on Kona white clay (KWC) and Kona black clay (KBC) blended with rice husk and paper mill sludge. Bricks were fabricated under three conditions: uncompressed laboratory samples, machine-compacted samples at a green pressure of 10 psi (0.069 MPa), and optimized overlay samples developed using response surface methodology. All samples were air-dried, oven-dried, and fired at 1092 °C for KWC and 800 °C for KBC before testing. Porosity decreased consistently with increasing compaction, from 41% to 36% to 25% for KWC and from 48% to 42% to 38% for KBC (laboratory, machine, and overlay samples, respectively). Correspondingly, bulk density increased from 0.90 to 1.02 to 1.10 g/cm³ for KWC and from 0.84 to 0.99 to 1.02 g/cm³ for KBC. Thermal conductivity rose with densification, increasing from 0.40 to 0.51 W/m·K for KWC and from 0.35 to 0.39 W/m·K for KBC, while overlay samples exhibited intermediate values of 0.45 W/m·K (KWC) and 0.36 W/m·K (KBC). Wet compressive strength improved from 1.6 to 2.15 to 4.6 MPa for KWC and from 2.89 to 3.26 to 3.7 MPa for KBC, while dry compressive strength increased from 3.2 to 4.3 to 5.3 MPa for KWC and from 4.9 to 6.5 to 4.6 MPa for KBC. The findings demonstrate a practical pathway for producing durable, lightweight, and thermally efficient bricks for sustainable low-cost housing in Nigeria and similar developing regions.

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Keywords: hybrid composite clay bricks; compaction pressure; porosity and density; compressive strength; thermal conductivity; sustainable construction materials

1.0 INTRODUCTION

The construction industry is under increasing pressure to identify building materials that are both eco-friendly and energy-efficient while also meeting the demand for low-cost housing. This challenge is especially urgent in developing countries, where affordable housing remains a critical need. In developing countries like Nigeria, where economic hardship and the high cost of cement intensify the demand for affordable building materials, adopting a standardized pressure in clay bricks production ensures more predictable brick behavior, reduces breakage during

drying and handling, and enhances production efficiency. The brick industry is very lucrative and this supply gap indicates a window of opportunity for prospective investors and builder to enter the market. The global brick market expanded from USD 585.06 billion in 2024 to USD 612.79 billion in 2025 and is projected to maintain steady growth at a compound annual growth rate (CAGR) of 4.95%, reaching approximately USD 861.45 billion by 2032 [1] This continued expansion is driven by rising construction activities worldwide, sustained infrastructure modernization efforts, and growing demand for innovative and sustainable building materials across a wide range of regions and end-use applications [1]. Existing corporate and commercial bricks markers can also exploit the industrial benefits of the industry. Currently, filling the gap in housing deficit across the developing countries through mass production of bricks for the housing construction is a major concern and the main challenge lies in design and fabrication of affordable and efficient bricks molding machines that will mass produce these bricks and reduced the overwhelming demand in construction industries. According to [2], bricks are best produced commercially with a target strength of 9MPa. This is also closely align with brick strength based on the standard of the Nigerian Building and Road Research Institute (NBRRI) [3]. For compressed earth bricks (CEB), the technical specification is the standard of the Nigerian Building and Road Research Institute (NBRRI) which recommends 3MPa and 6MPa as the minimum wet and dry compressive strength respectively [3]

Several studies have attempted to improve brick production through innovations in machine design, automation, and smart monitoring systems [4]; however, significant gaps remain unaddressed. Researchers have not adequately explored the influence of controlled compaction pressure on the physical and mechanical properties of green bricks, despite the fact that compaction plays a crucial role in determining density, porosity, and overall performance [5,6,7,8]. Existing machine designs rarely integrate material optimization parameters such as molding pressure, moisture content, or waste proportion, creating a disconnect between machine efficiency and brick quality. Furthermore, there is no established benchmark for pressure applied in green stage during production in bricks resulting in inconsistent product strength and durability across different production setups. Addressing these gaps is important because optimized compaction directly affects the uniformity, strength, and long-term durability of bricks, which are essential for safe and cost-effective housing construction. Compaction also supports the thermal performance of hybrid bricks by helping balance strength and insulation which is an important requirement for energy-efficient housing [9] (Lachheb et al,2026). By establishing 10psi (0.069MPa) as a workable compaction pressure for green bricks, producers can achieve improved particle packing, reduced internal voids, and stronger dry compressive strength without compromising the lightweight and thermally efficient nature of the brick. This enables the development of high-quality, eco-friendly bricks that are suitable for mass production and capable of contributing meaningfully to reducing Nigeria's housing deficits. This paper seeks to address the absence of a clearly defined and experimentally justified benchmark compaction pressure for green hybrid clay bricks, a critical gap that previous studies on brick production and machine design have largely overlooked. While existing research has focused on automation, machine efficiency, and general material innovations, it has not adequately linked controlled molding pressure to brick quality, consistency, and mass-production suitability. In particular, no widely accepted pressure standard exists to guide the design of affordable brick molding to ensure predictable physical, mechanical, and thermal performance of bricks in low-cost housing applications.

2.0 Materials and methods

2.1 Materials

In this research, Earthen materials (clay), rice husk(RH), paper mill sludge (PMS) and water were used. The clay samples were collected randomly from sampling points in Kona Garu at a depth of 1.1meters in accordance with the [10], while the paper mill off cuts were collected from Namnai mills and paper

shredding Jalingo. The rice husk was collected at Gadan Bobboji also in Jalingo local government area of Taraba state. Kona Garu is on the northern fringe of what was once a vast Jukun confederacy situated approximately 35km southeast of river Benue, and 10km north of Jalingo city, north eastern Nigeria [11] .It is roughly located between latitude 10°50′ and 8° 90′ North and longitude 11° and 12° East of the meridian and covers a landmass of about 1025sq km with an estimated population of over 30,000 persons [11]. The map of study area is presented on Figure 1 and the clay samples are presented in Figure 2 and 3.

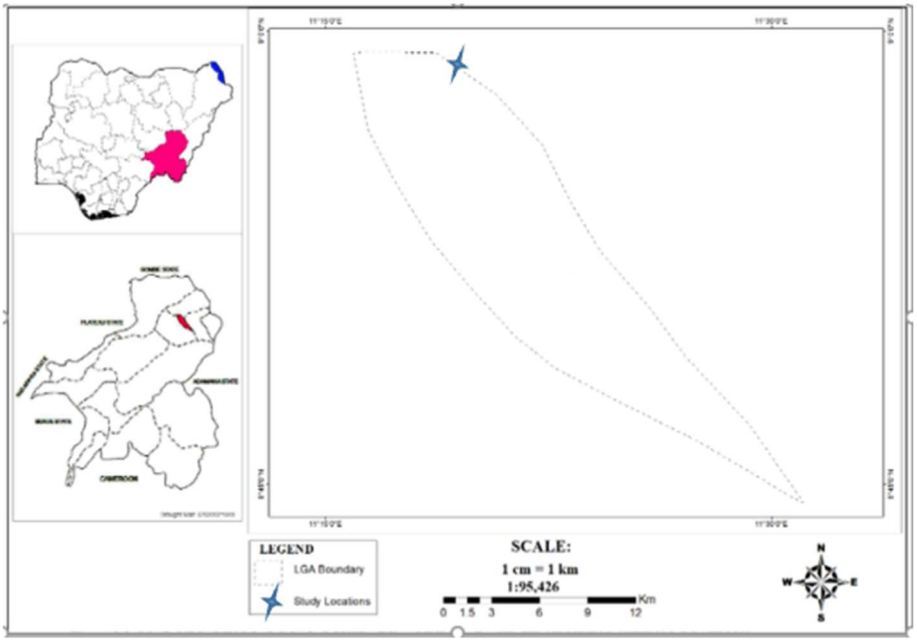


Figure 1: Map of Jalingo Local Government Showing the Study Area



Figure 2: Kona white clay



Figure 3: Kona black Clay

2.2 Experimental procedure (Methods)

The schematic diagram presented in Figure 4 shows the experimental processes carried out in this study:

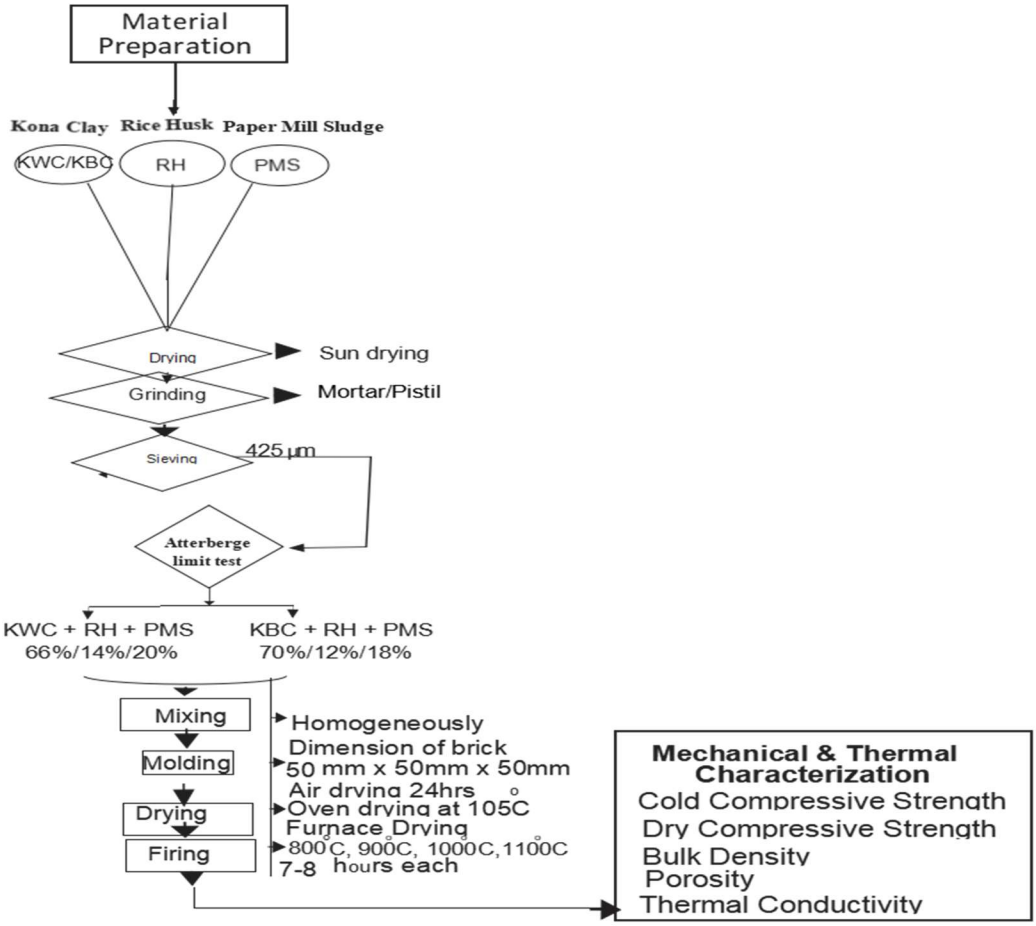


Figure 4: Experimental flow chart process for the development and characterization of the lightweight hybrid bricks

2.3 Constituents Sample Preparation and Production

The clay materials were blended for a single bulk sample and the transportation of the samples was made in accordance with ASTM D 4220 (2004) [10]. These materials were mixed, dried and grinded to particle size, finer than 1 mm for hybrid composite fabrication. Other standard and research confirmed the utilization of clay and paper mill sludge for brick making [12]. For this work, Kona white clay (KWC), Kona Black clay (KBC), Rice husk (RH) and paper mill sludge (PMS) were blended. The matrix i.e. KWC & KBC as well as the additives i.e. RH and PMS were blended for final hybrid composite bricks production. Therefore, three distinct production approaches were evaluated to examine the effect of compaction on hybrid composite clay bricks. Building on findings from our previous work, six different mix formulations were initially investigated, from which an optimal overlay composition was identified. Using this optimization results mix, two additional sets of samples were produced: uncompressed laboratory specimens and machine-compacted specimens molded under controlled conditions using identical material proportions. The hybrid composite formulation for Kona White Clay (KWC) consisted of 66% KWC, 20% paper mill sludge (PMS), and 14% rice husk (RH), fired at 1092 °C, while the Kona Black Clay (KBC) composite comprised 70% KBC, 12% RH, and 18% PMS, fired at 800 °C, as determined from the overlay optimization. Using the results of atterberg limit test, for water content limit and following the procedure in the above section, square cubic bricks with dimension 50mm ×50mm×50mm were produced using electro hydraulic compression machine developed in our previous work. The bricks in figure 5c were air dried at room temperature

for 24 hours and the oven dried at 105±5 °C for additional 24 hours to ensure complete removal of the moisture [12]. Further analysis was conducted.



(a) Fermented hybrid brick materials



(b) Green KWC/KBC Clays Produced



(c)Fired hybrid bricks produced

Figure 5. Procedure for KWC and KBC Produced hybrid bricks (a) Fermented hybrid mix (b) Green KWC/KBC Clays (c) Fired KWC/KBC bricks produced at 1092°C and 800°C

2.4 Constituents Sample Characterization

2.4.1 Atterberg limit and shrinkage Test

The Atterberg limits test includes the plasticity index, which is calculated as the difference between the liquid limit and the plastic limit. [13,14]. All Atterberg limits are determined on samples of soil that pass the sieve #40 (425µm) and are prepared for each test using wet or dry methods [13].

2.4.2 Shrinkage and Firing Test

Clay samples were prepared using protocol in section 2.2. The dimensions then taken diagonally initially. Then samples were dried to 110°C and held for one hour(1h) to ensure total water loss. The specimens were fired at 1092°C and 800°C (KWC & KBC based composite) for 7-9 hours respectively and soaked for 1 hour and allowed to cool overnight for another 24 hours. The brick dimensions were measured again and the percentage firing shrinkage was calculated using equation (1)

$$\text{Firing shrinkage} = \frac{L1-L2}{L1} \times 100 \quad (1)$$

Where L_1 = initial length before firing L_2 = Final length after firing

2.4.3 Porosity Test

This test was carried out using the volumetric and displaced water method. Mass of brick sample was taken and recorded as (A), the sample was submerged in water for 24 hours, then removed and surface dried. The sample was weight again and recorded to as (B). Using the table top scale with steel container and plastic cup. The cup was filled to the brim and then the specimen was gently administered in to the cup filled with water until completely submerged. The displaced water was collected, weighted and recorded as (C). The porosity was calculated as depicted in equation 2;

$$\text{pore volume} = saturated\ weigth(\text{B}) - Dry\ weigth\ (\text{A})$$

$$\text{Bulk volume} = saturated\ weigth(\text{B}) - Displaced\ water\ (\text{C})$$

Porosity is given as $p = \frac{Pore\ volume}{Bulk\ volume} \times 100 = \frac{B-A}{B-C} \times 100$ (2)

2.4.4 Compressive strength

The compressive tests were conducted using a STYE-2000 Universal Materials Testing Apparatus manufactured by SCiENTiFiC BàZàR China. This apparatus is equipped with a maximum 2000 kN load cell and is capable of performing compressive tests on materials. The tests were conducted at room temperature, following the ASTM C918/C918M-13 standard test method [15]. The produced brick samples, measuring 50 mm x 50 mm x 50 mm, was subjected to compression at a constant rate of 1 mm per minute until the brick is fragmented. The response of the material to the applied load, in terms of maximum stress were recorded. Three samples from each preparation batch were tested, and the average values recorded as stated in Equation (3). This testing procedure allow the evaluation of the compressive strength of the samples and provide essential data for further analysis.

$$\text{Compressive Strength} = \frac{Force}{Surface\ Area} = \frac{F}{A} \quad (3)$$

Where F is the average compressive force exerted on the samples and A is the area of the brick sample

2.4.5 Bulk density*:*

Predicts the ability of material to withstand heavy load. Bulk density is the weight per unit volume of the clay including the open pore space and it is expressed in grams per cubic meter (g/cm³). For most parts, bulk density varies with the volume concentration of the open and pore space [16] Onyeji (2010) [17] noted that the correlation between bulk density, linear shrinkage and apparent porosity is that, denser clays are less porous and less likely to shrink. Bulk density is calculated using the formula:

$$\text{Bulk Density} = \frac{Mass}{Volume} \quad (4)$$

Where Mass M = mass of dry weight

$$\text{volume V} = lbh$$

Bulk density is an important property consideration as far as transportation is concerned in selecting a material for use as bricks for building.

2.4.6 Thermal conductivity

The thermal conductivity of the produced KWC and KBC hybrid composite bricks were calculated using equation 5

$$K = \frac{Qd}{A\Delta T} = \frac{VIL}{A\Delta T} \quad (5)$$

Where,

K = is the thermal conductivity w/m/k

Q = the Amount of heat transferred (Volt × Current = VI)

A = the surface area of the samples (m^2)

d = the distance between the isothermal samples (m or L)

ΔT= the temperature changes or gradients of the samples

3.0 Results and Discussion

3.1 Impact of Compaction on Porosity, Density, Strength, and Thermal Conductivity

The impact of compaction pressure for KWC & KBC are presented in Table 1 to 4.

Table 1: Porosity (%) of KWC & KBC Samples

Samples	KWC 1092ºC	KBC 800ºC
	Porosity (%)	Porosity (%)
Laboratory made samples (uncompacted)	41	48
Machine samples (compacted)	36	42
Overlay samples (Optimized)	25	38

Table 2: Bulk density (g/cm^2) of KWC & KBC Samples

Samples	KWC 1092ºC	KBC 800ºC
	Bulk density (g/cm^2)	Bulk density (g/cm^2)
Laboratory made samples (uncompacted)	0.9	0.84
Machine samples (compacted)	1.02	0.99
Overlay samples (Optimized)	1.1	1.02

Table 3: Thermal Conductivity (w/m/k) of KWC & KBC Samples

Samples	KWC 1092ºC	KBC 800ºC
	Thermal Conductivity (w/m/k)	Thermal Conductivity (w/m/k)
Laboratory made samples (uncompacted)	0.4	0.35
Machine samples (compacted)	0.51	0.39
Overlay samples (Optimized)	0.45	0.36

Table 4: Wet and dry Compressive Strength of KWC at 1092ºC and KBC at 800ºC

Samples	KWC 1092ºC	KBC 800ºC	KWC 1092ºC	KBC 800ºC
	Wet Compressive Strength KWC	Wet Compressive Strength KBC	Dry Compressive Strength KWC	Dry Compressive Strength KBC
Laboratory made samples (uncompacted)	1.6	2.89	3.2	4.9
Machine samples (compacted)	2.15	3.26	4.3	6.5
Overlay samples (Optimized)	4.6	3.7	5.3	4.6

The porosity results Table 1 clearly show a strong influence of processing condition on the internal structure of both KWC and KBC samples. For KWC fired at 1092 °C, the lab-produced samples exhibited a high porosity of 41%**,** which reduced to 36% in the machine-compacted samples and further decreased to 25% in the overlay samples. A similar trend was observed for KBC fired at 800 °C, where porosity decreased from 48% in the lab samples to 42**%** in the machine samples and 38% in the overlay samples. This progressive reduction in porosity from lab to machine to overlay samples indicates improved particle packing and pore elimination under overlay and

compaction conditions. Despite all samples being prepared using the same mixing method, the differences highlight that compaction and processing conditions play a dominant role in controlling pore structure. Overall, KBC samples consistently showed higher porosity than KWC, suggesting material-dependent sintering and packing behavior.

The bulk density results in Table 2 are consistent with the porosity trends and further confirm the effect of compaction and overlay processing. For KWC, the lab samples recorded the lowest bulk density of 0.90 g/cm³**,** which increased to 1.02 g/cm³ in the machine-compacted samples and reached 1.10 g/cm³ in the overlay samples. Similarly, KBC lab samples showed a bulk density of 0.84 g/cm³, increasing to 0.99 g/cm³ for machine samples and 1.02 g/cm³ for overlay samples. The inverse relationship between porosity and bulk density is evident, as samples with lower porosity exhibited higher densities. The overlay samples demonstrated the highest degree of densification for both materials, while machine compaction significantly improved density compared to laboratory preparation alone.

Thermal conductivity values in Table 3 reflect the combined influence of porosity and bulk density. For KWC, the laboratory samples showed the lowest thermal conductivity of 0.40 W/m·K, which increased to 0.51 W/m·K in the machine-compacted samples, while the overlay samples recorded an intermediate value of 0.45 W/m·K**.** In the case of KBC, thermal conductivity followed a similar pattern, increasing from 0.35 W/m·K in laboratory samples to 0.39 W/m·K in machine samples and 0.36 W/m·K in overlay samples. The lower thermal conductivity of the laboratory samples can be attributed to their higher porosity, as air-filled pores reduce heat transfer. Conversely, the higher conductivity observed in machine-compacted samples is associated with increased density and improved solid-to-solid contact, facilitating heat flow. KWC samples generally exhibited slightly higher thermal conductivity than KBC, consistent with their higher bulk densities.

The wet and dry compressive strength results in Table 4 further demonstrate the superiority of overlay and machine-compacted samples over laboratory produced samples. For KWC at 1092 °C, wet compressive strength increased from 1.6 MPa in laboratory samples to 2.15 MPa in machine samples and significantly to 4.6 MPa in overlay samples. The corresponding dry compressive strengths were 3.2 MPa**,** 4.3 MPa, and 5.3 MPa, respectively. For KBC at 800 °C, wet compressive strength values increased from 2.89 MPa in lab samples to 3.26 MPa in machine samples and 3.7 MPa in overlay samples, while dry compressive strength values were 4.9 MPa**,** 6.5 MPa, and 4.6 MPa, respectively. In all cases, dry strength exceeded wet strength, indicating some degree of moisture sensitivity. However, overlay and machine-compacted samples retained significantly higher strength under both conditions, which correlates well with their lower porosity and higher density.

In general, the findings demonstrate that although all samples were prepared using the same mixing method, the final physico-mechanical properties are strongly governed by the processing and compaction conditions. Overlay samples consistently exhibited the lowest porosity (25–38%), highest bulk density (1.02–1.10 g/cm³), and superior compressive strength (up to 5.3 MPa dry), indicating optimal microstructural development. Machine-compacted samples showed marked improvement over lab-produced samples confirming the importance of compaction in achieving enhanced performance. Laboratory samples, while having lower strength and density, exhibited lower thermal conductivity (0.35-0.40 W/m·K), which may be advantageous for insulation applications. Overall, overlay results provides the best balance of mechanical integrity and densification, while machine compaction offers a practical approach to approaching overlay-level performance in real-world applications.

4. Conclusion

This study has demonstrated that controlled green compaction plays a decisive role in determining the physical, mechanical, and thermal performance of hybrid composite clay bricks produced from locally available materials. The results show that applying a compaction pressure of 10 psi (0.069 MPa) significantly reduces porosity and increases bulk density through improved particle rearrangement and packing, leading to enhanced inter-particle bonding. Consequently, both wet and dry compressive strengths improved markedly compared to uncompressed laboratory samples, meeting and exceeding relevant Nigerian Building and Road Research Institute (NBRRI) requirements for compressed earth bricks. While increased compaction led to higher thermal conductivity due to reduced air-filled voids, the optimized samples achieved a balanced performance, maintaining acceptable thermal insulation alongside superior mechanical strength. The findings confirm that excessive porosity reduction is not necessary to achieve optimal strength and that controlled, moderate compaction provides the most favorable combination of properties. By establishing 10 psi as a practical and effective benchmark compaction pressure for green hybrid clay bricks, this research bridges a critical gap between brick molding machine design and material performance. The study provides a clear technical basis for the development of affordable, efficient bricks and supports the mass production of durable, lightweight, and thermally efficient bricks, thereby contributing to sustainable construction practices and addressing housing deficits in Nigeria and other developing countries.

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