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Predictive Modelling of Compressive Strength of Rice Husk Ash Stabilized Clay Burnt Bricks

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ABSTRACT

The demand for sustainable masonry materials and improved burnt brick performance has increased interest in the utilization of agricultural waste in in brick production. This study investigates the predictive modelling of compressive strength of rice husk ash (RHA)-stabilized clay burnt bricks using consistency limit and compaction properties. The natural clay soil used for the brick production was characterized in the laboratory and chemical composition analysis was conducted to assess its suitability for brick production. Rice husk ash was incorporated into the clay at varying proportions of 0, 5, 10, 15, and 20% by weight to evaluate its influence on clay consistency, compaction behavior, and compressive strength when moulded into bricks. Results showed that RHA addition significantly reduced the Atterberg limits, indicating lower plasticity and improved workability. Optimum moisture content increased with RHA content, whereas maximum dry density increased slightly at low replacement levels before decreasing at higher contents due to the lightweight nature of the ash. The compressive strength increased up to 5% RHA, where the highest value was recorded, and decreased with further RHA addition. However, bricks containing up to 15% RHA satisfied the minimum compressive strength requirement of 3.5 MPa specified in NIS 87:2004. The multilinear regression model developed using plasticity index, optimum moisture content, and maximum dry density showed good predictive performance ($R^2 = 0.84$), with close agreement between measured and predicted values within the tested range. The findings suggest that moderate RHA incorporation can therefore improve brick performance while supporting sustainable waste utilization.

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INTRODUCTION

The construction industry is under pressure to reduce its environmental footprint while meeting rising demand for affordable housing, especially in developing countries. Portland cement production is a major source of global CO_2 emissions, which has driven interest in incorporating agricultural wastes such as rice husk ash (RHA) into concrete and masonry products as a partial replacement for cement or other conventional constituents (Iqtidar *et al.*, 2021; Alyami *et al.*, 2024; Kashem *et al.*, 2024; Aslam *et al.*, 2021). RHA is a highly siliceous pozzolanic material obtained by controlled burning of rice husks; its utilization in construction enables both waste valorization and reduction of embodied carbon in building materials (Iqtidar *et al.*, 2021; Kashem *et al.*, 2024).

Extensive research has shown that introducing RHA into concrete and sandcrete blocks can enhance compressive strength and durability when used within an optimal replacement range, while also improving sustainability (Iftikhar *et al.*, 2022; Kashem *et al.*, 2024; Li and Song, 2022; Aslam *et al.*, 2021). Data-driven and soft computing techniques, including artificial neural networks, support vector machines, random forests, boosting algorithms, and gene expression programming, have been widely used to develop predictive models for the compressive strength of RHA-based concrete and blocks, achieving high coefficients of determination (often $R^2 > 0.9$) and low prediction errors (Amin *et al.*, 2023; Iftikhar *et al.*, 2022).

Beyond concrete applications, fired clay bricks incorporating agricultural wastes, including RHA, wheat husk, sawdust, and other biomass residues, have received increasing research attention because of their potential to improve clay thermal performance and enhance sustainability (Ahmad *et al.*, 2025; Blanca *et al.*, 2025; Kazmi *et al.*, 2017). Previous studies on RHA-modified fired bricks reported that moderate RHA incorporation can improve workability and maintain acceptable compressive strength, although excessive replacement may increase porosity and reduce mechanical performance due to weaker particle bonding during firing (Khan *et al.*, 2026; Kazmi *et al.*, 2016). Similar observations have been reported for fired bricks containing other waste additives, where brick performance is strongly influenced by additive content, firing temperature, and raw material characteristics (Kazmi *et al.*, 2016; Blanca *et al.*, 2025).

In the same vein, predictive modelling approaches have increasingly been extended to fired bricks and ceramic-based materials. For instance, Jwaida (2025) developed machine learning models, including random forest, extreme gradient boosting, artificial neural networks, and ridge regression, to predict compressive strength and water absorption of agricultural-waste fired bricks containing RHA and wheat husk, highlighting the importance of manufacturing variables such as soil composition, firing conditions, and additive proportions. Similarly, recent machine-learning studies on agro-waste stabilized bricks have demonstrated that predictive tools can substantially reduce experimental effort while providing reliable estimates of compressive strength from measurable input parameters (Obianyo *et al.*, 2024; Mishra *et al.*, 2025; Mandal and Rajput, 2024; Bouzidi *et al.*, 2024).

Most previous predictive studies on brick materials have predominantly relied on complex machine-learning algorithms, which despite their predictive capability often require large datasets and advanced computational expertise and may lack transparency in explaining the influence of individual variables on material performance (Obianyo *et al.*, 2024; Mishra *et al.*, 2025). Multilinear regression presents a particularly attractive approach because it provides a transparent, interpretable, and cost-effective means of quantifying the combined influence of key soil properties on strength development. By incorporating consistency limit parameters, such as plasticity index, alongside compaction characteristics, including maximum dry density and optimum moisture content, the model enables direct engineering interpretation while minimizing the need for extensive experimental testing. Also, the effectiveness of multilinear regression in establishing reliable predictive relationships has been demonstrated in studies involving RHA-modified concrete, stabilized soils and other cementitious materials, where it has provided robust performance while maintaining simplicity and ease of implementation (Obianyo *et al.*, 2020; Ranathunga *et al.*, 2022; Raji *et al.*, 2024; Ganasem *et al.*, 2023).

The present study therefore aims to develop a multilinear regression model for predicting the compressive strength of rice husk ash stabilized clay burnt bricks using consistency limit and compaction parameters as predictor variables. Building on the demonstrated efficacy of regression-based and soft-computing approaches in RHA-modified concretes, sandcrete blocks and soils (Obianyo *et al.*, 2020; Aslam *et al.*, 2021), the proposed work seeks to bridge the gap between soil stabilization and fired-brick technology, contributing an empirically grounded tool for optimizing sustainable brick production.

MATERIALS AND METHOD

Materials

The primary materials used in this study were natural clay soil and rice husk ash (RHA). The clay soil sample was obtained from a depth of 1 to 1.5m at Joseph Sarwuan Tarka University, Markurdi (JOSTUM), (Latitude: 7º43´55.8714´´N, Longitude: 8º32´20.9306´´E), using disturbed sampling technique. The sample was air-dried before use. The RHA was sourced from Makurdi Rice Mill, located at Wurukum, Makurdi, Benue State, Nigeria, where large quantities of rice husks are routinely processed and disposed of by combustion. The ash was sieved to remove unburnt particles and coarse impurities to ensure uniformity before mixing with the clay soil.

Sample Preparation and Stabilization

The clay soil was mixed with rice husk ash at varying proportions (0, 5, 10, 15 and 20%) to evaluate the effect of the additive on the properties of burnt bricks. The mixtures were prepared by thoroughly blending the predetermined percentages of RHA with the clay to obtain homogeneous mixtures. Water was then added to each mixture to achieve proper molding consistency. The prepared mixtures were molded into standard brick specimens (215 mm × 102.5 mm × 65 mm) and allowed to air-dry for 7 days. The bricks were manually molded and compacted to achieve uniform specimen geometry and consistency prior to drying. Since the brick moulding was carried out using conventional manual compaction rather than a controlled mechanical press, the compaction energy applied during molding was not quantified. As such the maximum dry density (MDD) obtained from the Standard Proctor test was used as an indicative compaction-related predictor variable rather than a direct measure of molded brick density.

Furthermore, after drying, the bricks were fired in a kiln at approximately 1050 °C to achieve the required strength and durability for testing. The firing process was conducted under kiln conditions in order to maintain a relatively uniform heating throughout the firing chamber. Detailed control of firing parameters such as heating ramp rate, atmosphere, and spatial temperature uniformity was not monitored and therefore represents an operational condition of the experimental programme.

Laboratory Testing

Laboratory tests were carried out on the natural clay and the stabilized mixtures to determine their index, compaction, and compressive strength. Index properties including natural moisture content, specific gravity, particle size distribution, and Atterberg limits were determined using standard procedures outlined in BS 1377 (1990). Standard Proctor Compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the soil mixtures. Chemical composition analysis (X-ray fluorescence – XRF) was also performed on the clay soil and rice husk ash to determine their oxide contents.

Compressive strength tests was performed on the bricks after firing to evaluate their performance. The compressive strength test was carried out using compression testing machine, and the results were compared with the requirements of Nigerian standards for burnt bricks. For each RHA replacement level, three (3) brick specimens were tested, and the reported compressive strength values represent the average response of the tested specimens.

Development of Predictive Model

A multilinear regression analysis was carried out using Microsoft Excel Package to develop a predictive model for estimating the compressive strength of the RHA stabilized clay burnt bricks. The model was developed from soil consistency limit and compaction parameters, including plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD), as independent variables with compressive strength as response factor. The selection of these variables was based on their engineering relevance to clay workability, compaction behaviour, and density–strength relationships in fired burnt bricks. Model performance was evaluated using the coefficient of determination (R^2) and comparison between measured and predicted compressive strength values. To maintain model simplicity and interpretability for engineering application, multilinear regression was adopted as the primary predictive framework. On a noted, given the relatively limited experimental dataset associated with the investigated RHA addition levels, the multilinear regression model was intended as an exploratory predictive framework for identifying relationships between consistency limit and compaction characteristics and compressive strength, rather than a universally generalizable model. Model performance was assessed primarily through goodness-of-fit between measured and predicted values within the investigated range of mixtures.

RESULTS AND DISCUSSION

Index and Engineering Properties of Natural Clay Soil

The natural moisture content of the clay is high at 38.56%, while its specific gravity of 2.1 is somewhat low, implying some porosity or lighter mineral content (Table 1). Atterberg limits show a Liquid Limit (LL) of 51.65% and a Plastic Limit (PL) of 27%, giving a Plasticity Index (PI) of 24.65%, which indicates a fairly plastic clay with moderate shrink-swell potential, supported by a Linear Shrinkage (LS) of 3.57%. Compaction tests revealed an Optimum Moisture Content (OMC) of 13.19% and a Maximum Dry Density (MDD) of 1.59 g/cm^3, suggesting that the soil requires moisture adjustment for proper densification during brick molding. Water absorption tests on bricks made from this clay gave a value of 12.31%, reflecting the fine texture and porosity, while the Compressive Strength of 3.87 N/mm^2 indicates moderate load-bearing capacity for fired bricks. Based on the Atterberg limits and particle size distribution, the soil is classified under the USCS as CH, representing an inorganic clay of high plasticity, and under the AASHTO system as A-7-6, consistent with high plasticity clayey soils that may require stabilization for engineering applications. These properties suggest that the clay is suitable for brick making, although care must be taken with moisture content and firing to optimize strength and reduce water absorption.

Table 1: Showing Results for Index and Engineering Properties of Natural Clay Soil

Properties	Values
Natural Moisture Content (%)	38.56
Specific Gravity	2.10
Liquid Limit (%)	51.65
Plastic Limit (%)	27
Plasticity Index (%)	24.65
Linear Shrinkage (%)	3.57
Optimum Moisture Content (%)	13.19
Maximum Dry Density (g/cm^3)	1.59
Water Absorption (%)	12.31
Compressive Strength (N/mm^2)	3.87

Oxide Composition of Clay Soil

The clay's chemistry in Table 2 is dominated by SiO_2 (58.6%) and Al_2O_3 (27.24%), indicating it's largely an alumino-silicate clay. The Fe_2O_3 (9.71%) content is relatively high, which tends to give the clay a reddish hue and can affect its firing behavior and strength. Fluxing oxides like CaO (4.37%), MgO (2.39%), K_2O (1.26%), TiO_2 (1.8%), Na_2O (0.83%), and trace MnO (0.08%) help lower the melting point during firing and influence the densification and color of the final brick. The Loss on Ignition (LOI) of 6.8% suggests there's a decent amount of volatile material (like bound water or organic matter) that will burn off when heated.

Table 2: Showing Oxide Composition of Clay Soil

Oxide	SiO_2	Al_2O_3	FeO_3	K_2O	MgO	TiO_2	CaO_2	Na_2O	MnO	P_2O_5	LOI
% Composition	58.6	27.24	9.71	1.26	2.39	1.8	4.37	0.83	0.08	0.04	6.8

Oxide Composition of Rice Husk Ash (RHA)

The chemical composition of Rice Husk Ash (RHA) in Table 3 shows a very high SiO_2 content (75.04%), indicating it is strongly siliceous, which is typical of RHA. The minor oxides, including Al_2O_3 (1.70%), Fe_2O_3 (1.68%), CaO (3.17%), MgO (1.18%), K_2O (6.25%), Na_2O (9.76%), and SO_3 (1.32%), are present in small amounts and act as fluxes that can influence pozzolanic activity and firing behavior. The Loss on Ignition (LOI = 8.39%) reflects residual carbon and volatile matter remaining from incomplete combustion, which is typical for RHA.

Table 3: Showing Oxide Composition of RHA

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
% Composition	75.04	1.70	1.68	3.17	1.18	6.25	9.76	1.32	8.39

Atterberg Limit

The Atterberg limit results show that the addition of rice husk ash (RHA) progressively reduced the consistency limits of the clay soil (Figure 1). The liquid limit (LL) decreased from 51.65% at 0% RHA to 32.6% at 20% RHA, while the plastic limit (PL) reduced from 27% to 17.5% over the same range of RHA content. Similarly, the plasticity index (PI) decreased from 24.65% in the natural soil to 15.1% at 20% RHA. This consistent reduction in LL, PL, and PI with increasing RHA content suggests that the ash modifies the soil's consistency characteristics by reducing its plasticity. The decrease in plasticity may be attributed to the non-plastic nature of RHA and its high silica content, which dilutes the clay fraction responsible for plastic behavior. Additionally, the ash particles likely occupy the spaces between clay particles, resulting in reduced water adsorption and lower plasticity. Consequently, the treated soil becomes less cohesive and more workable, which is beneficial for brick production as it reduces excessive shrinkage and cracking during drying and firing. The results indicate that the incorporation of RHA improves the workability of the clay by lowering its plasticity characteristics.

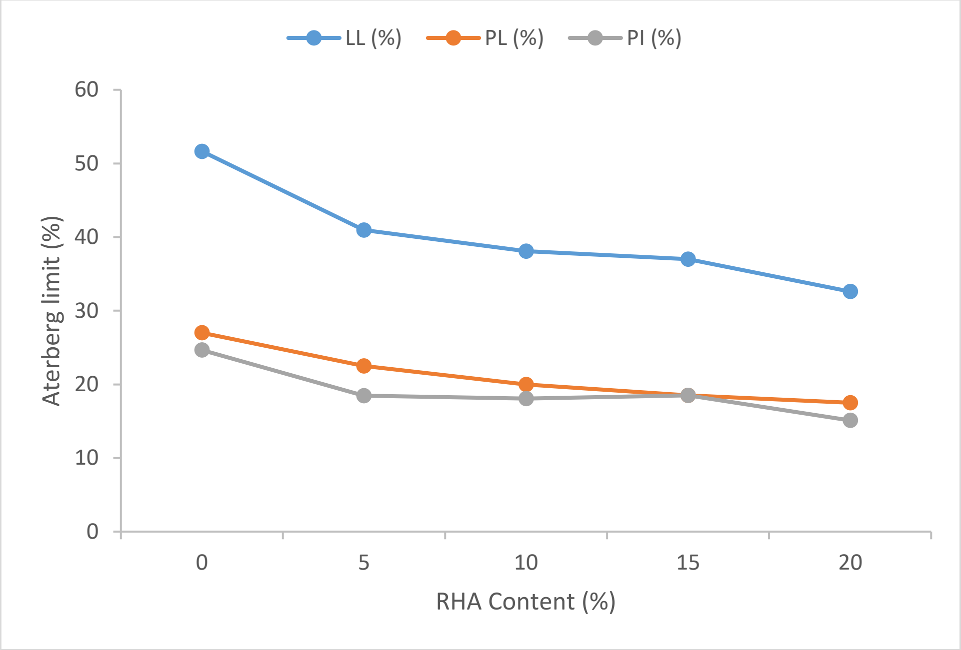

Figure 1: Liquid Limit, Plastic Limit and Plastic Index at Varying RHA Percentages

Compaction Characteristics
The Optimum Moisture Content (OMC) increases steadily across the entire range of RHA contents. It starts from 13.19% at 0% RHA and rises sharply to 19.87%at 5% RHA (Figure 2). It then reduces slightly to 10% RHA (19.24%) and increases more significantly at 15% and 20% RHA. In contrast, from Figure 3, the Maximum Dry Density (MDD) starts from 1.59 g/cm^3 and increases modestly to 1.61 g/cm3 at 5% RHA before starting a steady decline as the RHA content increases, it then drops to 1.29 g/cm3 at 20% RHA. These observations are consistent with findings by Agbede (2011) and Janbuala *et al.* (2013), who reported that adding small amount of RHA to clay may slightly improve particle packing, but higher proportions always result in reduced dry density and increased OMC due to the ash’s lightweight and high-porosity characteristics.

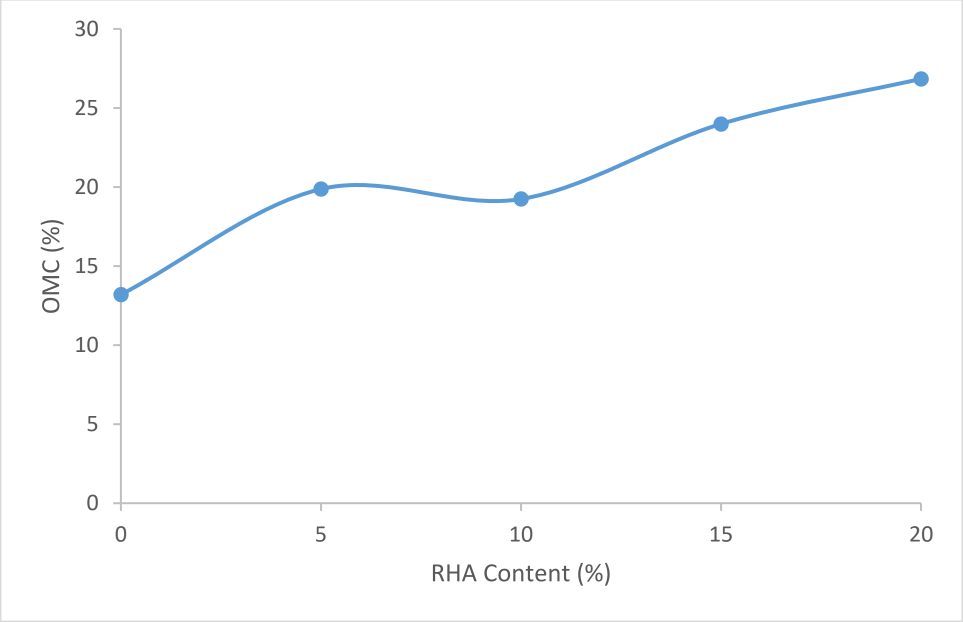

Figure 2: Optimum Moisture Content at Varying RHA Percentages

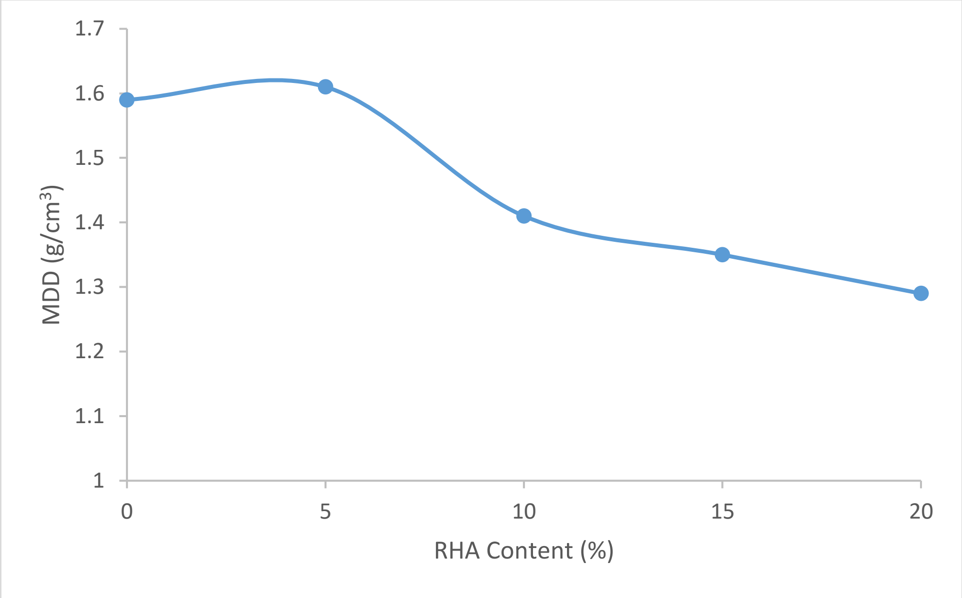

Figure 3: Maximum Dry Density at Varying RHA Percentages

Compressive Strength

The compressive strength results in Figure 4 indicate that the inclusion of rice husk ash (RHA) significantly influenced the mechanical performance of the burnt clay bricks. The control sample (0% RHA) recorded a compressive strength of 3.87 MPa, representing the inherent strength of the natural burnt clay brick. Upon the addition of 5% RHA, the compressive strength increased markedly to 7.02 MPa, which is the highest value obtained in this study. This improvement may be attributed to the high silica content of RHA, which enhances particle bonding and improves the internal structure of the brick. The fine particles of RHA also act as a filler material that reduces voids and promotes better densification during brick formation and firing. However, when the RHA content was increased beyond this level, the compressive strength gradually decreased to 5.83 MPa at 10%, 3.77 MPa at 15%, and 2.72 MPa at 20% RHA. The reduction at higher RHA contents is likely due to excessive ash replacing the clay fraction responsible for cohesion, which results in increased porosity and weaker particle bonding within the brick matrix. In terms of standard requirements, the NIS 87:2004 – Standard for Burnt Bricks specifies a minimum compressive strength of about 3.5 MPa for burnt clay bricks used in construction. Based on this requirement, the bricks containing 0%, 5%, 10%, and 15% RHA meet the minimum strength requirement, although the 15% RHA sample (3.77 MPa) is only slightly above the threshold. In contrast, the 20% RHA brick (2.72 MPa) falls below the specified limit and therefore does not conform to the standard for structural application. The results therefore suggest that the incorporation of RHA can enhance the strength of burnt bricks when used in moderate quantities, with 5% RHA identified as the optimum content for achieving maximum compressive strength while still satisfying the requirements of the Nigerian standard.

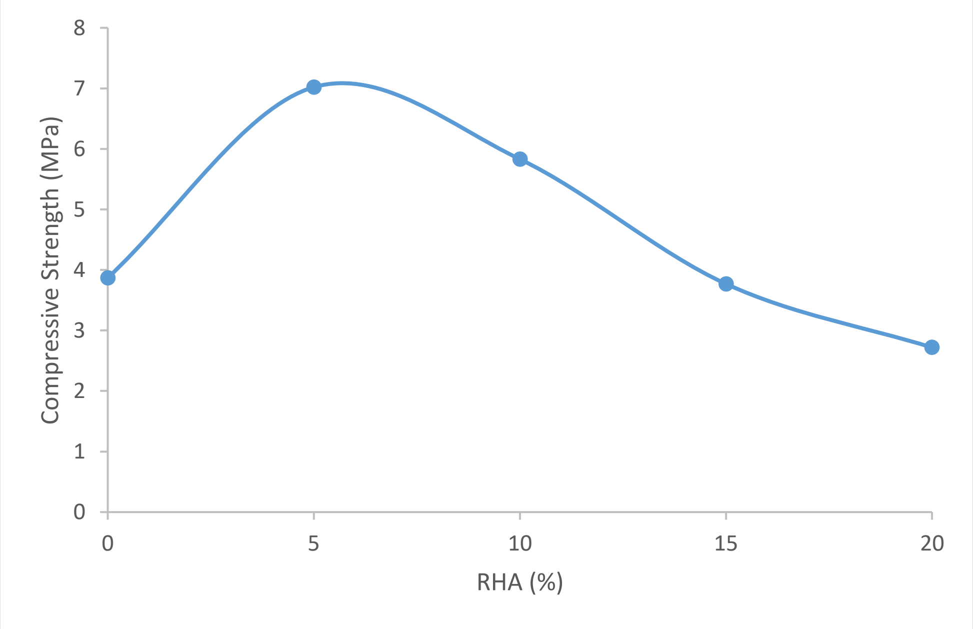

Figure 4: Compressive Strength at Varying RHA Percentages

Multilinear Regression Model Analysis

The multilinear regression analysis developed to predict the compressive strength of rice husk ash stabilized clay burnt bricks from consistency limit and compaction properties produced the model with a sum of squares (SS) of 14.30, a mean square (MS) of 2.77, and a coefficient of determination (R^2) of 0.84 (Table 4). The R^2 value indicates that approximately 84% of the variation in compressive strength is explained by the combined effects of the plasticity index (PI), optimum moisture content (OMC), and maximum dry density (MDD). This relatively high coefficient of determination suggests that the developed regression model has good predictive capability and that the selected soil index properties significantly influence the compressive strength of the rice husk ash stabilized burnt bricks. The remaining 16% of unexplained variation may be attributed to other factors not included in the model, such as firing temperature, particle size distribution, or the microstructural characteristics of the rice husk ash.

The regression coefficients further reveal the nature of the relationship between the independent variables and compressive strength. The negative coefficient of PI (-0.796) indicates that an increase in plasticity index leads to a reduction in compressive strength, suggesting that highly plastic clays may produce weaker burnt bricks due to increased shrinkage and the development of microcracks during drying and firing. Similarly, the negative coefficient of OMC (-0.283) implies that higher moisture requirements during compaction tend to reduce the resulting compressive strength, possibly due to increased pore spaces after drying. Conversely, the positive coefficient of MDD (14.549) shows that compressive strength increases significantly with increasing maximum dry density, highlighting the importance of proper compaction in improving the structural integrity of the bricks. The constant term (4.641) represents the baseline compressive strength when the predictor variables are held constant. Overall, the model demonstrates that density-related properties exert a stronger positive influence on compressive strength, while higher plasticity and moisture demand tend to adversely affect the strength of rice husk ash stabilized clay burnt bricks.

Table 4: Multilinear Regression Model

Model	SS	MS	R^2
Compressive strength (MPa) $= -0.796(PI) - 0.283(OMC) + 14.549(MDD) + 4.641$	14.30	2.77	0.84

Measured vs Predicted Compressive Strength

The comparison between the measured and predicted compressive strength values in Figure 5 indicates that the developed regression model provides a reasonably good prediction of the compressive strength of rice husk ash stabilized clay burnt bricks. Although slight deviations exist between the predicted and experimental results, the overall trend of strength variation is well captured by the model. The differences observed in some cases may be attributed to experimental variability, material heterogeneity, or factors not incorporated in the regression model such as firing conditions and microstructural changes. Nevertheless, the close agreement between the measured and predicted values confirms the reliability of the developed model for estimating compressive strength from the selected soil properties.

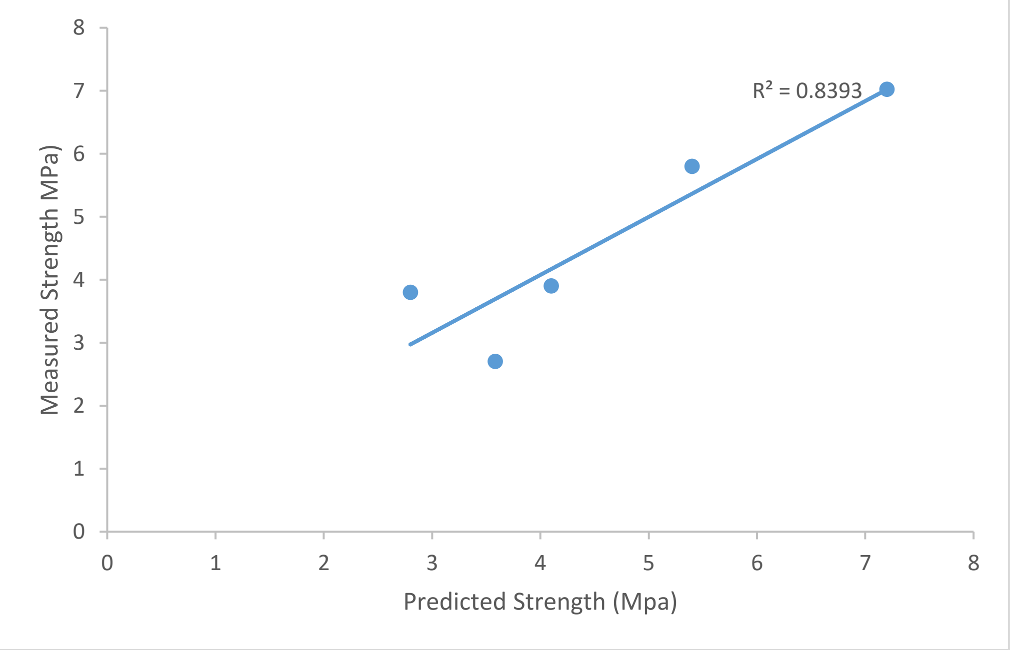

Figure 5: Measured vs Predicted Compressive Strength Values

CONCLUSION

This study investigated the predictive modelling of compressive strength of rice husk ash (RHA) stabilized clay burnt bricks using from consistency limit and compaction properties and the following highlight the conclusions and key findings.

i. The natural clay soil exhibited high plasticity, classified as CH under the USCS and A-7-6 under AASHTO, indicating suitability for brick production but requiring stabilization for enhanced engineering performance.

ii. Oxide analysis showed dominance of SiO_2 and Al_2O_3 in the clay, confirming its aluminosilicate nature favorable for fired bricks. Rice husk ash (RHA) contained high silica content (75.04%), indicating strong pozzolanic and stabilizing potential.

iii. Incorporation of RHA significantly reduced the Atterberg limits of the clay improving workability.

iv. Compaction tests showed optimum moisture content increased with RHA addition, while maximum dry density slightly rose at 5% RHA (1.61 g/cm³) before decreasing at higher contents due to the lightweight, porous nature of the ash.

v. Compressive strength improved with moderate RHA addition, reaching a maximum of 7.02 MPa at 5% RHA compared to 3.87 MPa for the control. Higher RHA contents (10–20%) led to reduced strength due to increased porosity and lower cohesion.

vi. According to NIS 87:2004, bricks containing up to 15% RHA met the minimum compressive strength requirement of 3.5 MPa, while 20% RHA bricks were unsuitable for structural applications.

vii. The developed multilinear regression model effectively predicted compressive strength, with $R^2 = 0.84$. Analysis indicated that plasticity index and optimum moisture content negatively influence strength, whereas maximum dry density has a strong positive effect.

viii. The study demonstrates that moderate RHA incorporation (~5%) enhances compressive strength and workability of clay bricks while promoting sustainable reuse of agricultural waste.

A limitation of this study is that water absorption, fired density, and porosity were not evaluated for the RHA-stabilized brick blends, although these parameters may influence pore development, durability, and compressive strength behavior in fired bricks. Detailed firing characteristics such as heating ramp rate and temperature uniformity, as well as quantified brick forming pressure were not explicitly monitored during production. Potential multicollinearity among predictor variables, particularly between optimum moisture content and maximum dry density, was not explicitly assessed using statistical indicators such as variance inflation factors or condition indices. Future studies should incorporate these parameters alongside replicate testing and advanced statistical validation to further improve the robustness and generalizability of predictive models for RHA-stabilized burnt bricks.

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