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Enhancement of Mechanical Properties of Unfired Clay Bricks Using Rice Husk Ash and Fibre Reinforcement

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ABSTRACT

This study investigates the production of unfired clay bricks incorporating cement and rice husk ash (RHA) as a binder, with rice husk (RH) serving as fiber reinforcement. The need for eco-friendly building materials is critical, as cement production contributes 7-8% of global CO₂ emissions, and while fired clay bricks are stronger, their high production cost due to significant energy requirements makes them less sustainable. Providing lower-cost building materials can reduce rural-to-urban migration and make housing more affordable for low-income earners. RH fibers were added in varying volumes (0, 5, 10, 15, 20, and 25 vol%) while maintaining a constant RHA and cement content of 10 vol%. The mixed clay bricks were dried for seven days and cured at room temperature (22°C to 28°C) for 21 days, totalling 28 days of curing. Mechanical properties, including compressive strength, flexural strength, and fracture toughness, were evaluated alongside the chemical composition and textural characteristics of the clay and RHA. Particle size distribution (PSD) analysis classified the clay as sandy clay with higher sand content, determined using sieve analysis and the hydrometer method. X-ray fluorescence (XRF) confirmed that the RHA met NIS/ASTM standards, with a minimum of 70% combined SiO₂, Al₂O₃, and Fe₂O₃, qualifying it as a pozzolanic material. Optimal mechanical performance was observed at 5% RH fiber content, with fibers 2-4 mm in length, achieving compressive strength of 7 MPa, flexural strength of 2.1 MPa, and fracture toughness of 2.15 MPa√m, while fiber content beyond 5% resulted in gradual declines, particularly significant after 20%. The study concludes that RH fiber-reinforced composites are suitable for lightweight, durable building materials, promoting environmental sustainability and improved performance.

1 Introduction

Clay is among the earliest raw materials used by humans, particularly in construction and ceramics, due to its moldability and unique characteristics [1-3]. However, its properties vary significantly across regions, influenced by parent

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rocks, diagenetic processes, and weathering, which collectively affect its physical, chemical, mineralogical, and mechanical traits [4-6]. Recent studies have focused on enhancing the sustainability of clay by incorporating waste materials such as rice husk ash (RHA), known for its pozzolanic properties and its potential to reduce the greenhouse effect associated with cement. Global greenhouse gas emissions from cement production alone are estimated at 7-9% [7], while the energy-intensive firing of clay bricks, often reliant on non-renewable resources, further contributes to greenhouse gas emissions.

Although fired clay bricks exhibit superior mechanical strength, their production is associated with high costs and environmental issues, including deforestation and air pollution from kiln operations. Additionally, improper disposal of agricultural waste contributes significantly to environmental pollution [8]. In this context, more research is needed on eco-friendly and renewable building materials. While previous work on RHA has primarily focused on its use in concrete and sandcrete, these applications often involve expensive materials such as sand and granite stone. The high costs of quarrying granite further elevate production expenses. Most studies on composite clay bricks involve fired bricks, whereas this work emphasizes unfired bricks to reduce production costs. Incorporating clay with agricultural waste can lower costs, make housing more accessible to low-income earners, discourage rural-to-urban migration, and promote rural development.

Clay's fine-grained structure makes it ideal for composite production due to its plasticity; however, its application in load-bearing structures is limited by its inherent high compressibility and low strength [9-10]. These limitations can be mitigated by reinforcing clay with materials such as rice husk fibers and RHA, which enhance its strength, durability, and structural integrity. [11] demonstrated that incorporating agricultural waste, including grass, coconut husk, and sugarcane bagasse, improves the thermal insulation and porosity of fired clay bricks. Technological advancements, such as water washing and high-energy magnetic filtration, have further enhanced clay quality, broadening its industrial applications [12]. Clay used in ceramics production typically contains high levels of silica (SiO_2) and alumina (Al_2O_3), which contribute significantly to its plasticity and durability [13, 14]. The quality of clay-based products depends heavily on the properties of the raw materials and their behavior during processing [15].

Rice husk ash (RHA), a byproduct of rice milling, is rich in silica and exhibits pozzolanic properties, making it an excellent additive for enhancing the structural qualities of clay-based materials [16,17]. Its fine particle size increases reactivity, resulting in stronger and more durable composites, with finer particles demonstrating enhanced pozzolanic activity [17, 18]. Incorporating RHA into clay bricks improves compressive strength, reduces water absorption, and enhances durability [19]. Furthermore, RHA serves as a sustainable alternative to synthetic binders, promoting environmental sustainability. With a silica content ranging from 70% to 97%, RHA is a highly effective pozzolan [20]. A study by [21] explored the use of RHA and lime sludge to stabilize clay soil, achieving significant carbon emission reductions. Their findings revealed that RHA, with silica content ranging from 80% to 96%, improves mechanical properties. Studies on dried rice husk also shows that it contain 70 -85% organic matter, 32.24% cellulose, 21.44% lignin, and 21.34% hemicelluloses [22]. This is known to depend on some factors such as the climatic conditions, and soil types. Mechanical analysis showed a notable increase in compressive strength from 20 KN/m² to 375 KN/m² in specimens produced with 3% RHA, 3% cement, and 1% promoter [23].

The industrial applications of clay are influenced by its mineralogical and chemical composition, crystal structure, and physical characteristics, including color and firing behavior [24-27]. These attributes make clay indispensable for producing ceramics, such as bricks and tiles [28, 29]. Similarly, RHA has diverse industrial applications, including use in refractories, ceramics, cement production, and as a filler in rubber and plastic composites [30]. Research has shown that adding RHA to clay enhances specific properties, such as reduced shrinkage, improved plasticity, and increased crack resistance, making it highly valuable for composite materials [31].

This study focuses on clay from Akerebiata, Ilorin, Nigeria. These clay deposits, situated in northern Ilorin (between longitudes 4°30' - 4°37' and latitudes 8°27' - 8°32'), rest on basement complex rocks. Prior research by Oladimeji and Adepoju [32] examined the socio-economic aspects of traditional pottery in this area, highlighting low investment levels and subsistence-scale production. The primary objective of this study is to investigate the potential of reinforcing clay-cement matrices with rice husk fibers and partially replacing cement with RHA to enhance the mechanical properties of the composites. Specifically, it aims to evaluate how varying rice husk fiber volume fractions influence the compressive strength, water absorption, and durability of the clay-cement composites. Additionally, the research seeks to assess the pozzolanic contribution of RHA as a binder and its impact on the overall performance of these composites, offering valuable insights into the feasibility of utilizing agricultural waste materials for sustainable construction.

2 Experimental Methodology

2.1 2.1 Materials

Clay soil was sampled from the Akerebiata area in Ilorin, Nigeria, longitudes 4°30'–4°37' and latitudes 8°27'–8°32'. The clay was extracted from a depth of approximately 10 meters to ensure the collection of a representative sample. After excavation, the clay was sun-dried, crushed, and ground into a fine powder using a mortar and pestle (Figure 1). The powdered clay was then sieved through a fine mesh sieve to obtain uniform particle size. Rice husk, sourced from a rice milling site in Gambari, Ilorin, was used for fibre reinforcement, while the mould used for sample preparation was locally fabricated.

2.2 Methods

2.2.1 Calcinations of the rice husk ash (RHA)

The rice husk (RH) was first air-dried to facilitate combustion. A traditional forge (figure 2), fuelled by coal with forced air circulation was used for the calcinations process, with temperature varying between 700°C to 810°C. The rice husk was placed into a metal vessel and positioned on the burning coal using long tongs. After combustion, the material was allowed to cool. The calcined rice husk was then ground and sieved into a fine powder as shown in figure 3. According to research, finer particles, achieved through extended grinding, significantly improve the properties of cement-based composites [29].



Fig. 1- (A) Drying process of the clay sample, (B) grinded and sieve clay sand



Fig. 2- shows the calcinations process of rice husk ash.



Fig. 3- Calcined and sieved rice husk ash (RHA)

2.2.2 Fabrication of rice husk ash/ rice husk reinforced ceramic composites

The finely sieved clay was used as the matrix phase, with rice husk (RH) incorporated as fibre reinforcement in varying volume percentage (0 to 25%) at 5% intervals. The volumetric measurement of the materials ranging was done using a measuring cup, with one cup representing 5 vol% each. The binder consisted of a combination of rice husk ash (RHA) and cement, with 20 vol% of the cement partially replaced by RHA, while the total binder content was kept constant at 10% across all formulations (Table 1). This partial replacement of cement with RHA was based on its proven pozzolanic properties, which have been shown in previous studies to improve the compressive strength of cementitious composites, while reducing the environmental footprint associated with cement production [18, 20].

The mixture of clay, cement, RHA, and RH was produced according to the design proportion on Table 1 and thoroughly mixed in dry form first on a clean slab using a trowel, after which water was gradually added to achieve the desired consistency mortar. The Water content used varies as the fiber content increases and the clay content reduces at each interval. The mixture was then poured into wooden moulds, designed with dimensions of 200 mm × 30 mm × 20 mm for flexural strength tests, and 60 mm × 60 mm for compressive strength tests. The mould dimension was chosen based on the mechanical test machine standard used for the analysis, which is Testometric FS 50 AT. The rice husk ash and cement acted as the primary binders, contributing to the cohesion and workability of the mixture. According to previous studies, finer particles, such as those from RHA, improve mortar workability and strength by filling voids and enhancing particle packing [33]. Once the mixture was set into the moulds, it was gently removed from the mould after setting for two hours and then left to cure for 28 days to allow for proper hydration and development of mechanical properties (Figure 4).

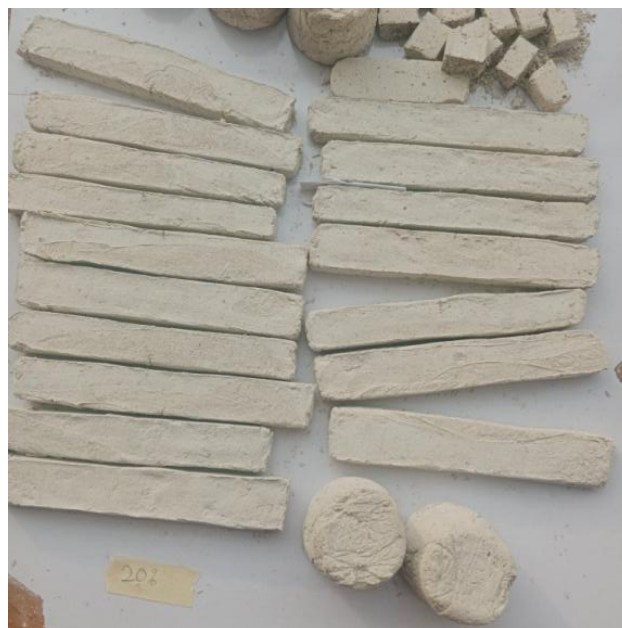


Fig. 4 - Fabricated composite samples after curing

Table 1: Design Proportion of the Composites Sample.

Samples No	Cement/RHA (Vol. %)	Clay (Vol. %)	RH Fiber (Vol. %)	Total (Vol. %)
1	10	90	0	100
2	10	85	5	100
3	10	80	10	100
4	10	75	15	100
5	10	70	20	100
6	10	65	25	100

2.2.3 Physical and Chemical Characterization of the clay and rice husk ash

The particle size distribution (PSD) of the clay was analyzed using the hydrometer method to assess the impact of particle size on the mechanical properties of the material. Hydrometer testing, suitable for finer particles, was used to predict the porosity and compaction behavior of the clay for the composites samples. The PSD analysis employed both sieve analysis and hydrometer method. Mechanical shaker was used for the sieve analysis after proper drying, after which 50g of clay particles that passed through 0.075mm sieve was now used for the hydrometer method, following the method outlined by Gavlack, Horneck, and Miller [34]. This involves the separation of particles through sieving and sedimentation in a soil-water suspension with a 5% sodium hexametaphosphate (HMP) dispersing solution. Stokes' law governed the sedimentation process, and periodic measurements of the suspension's density were taken to characterize the particle size.

For chemical analysis, the clay and RHA samples were examined using X-ray fluorescence (XRF) at Rolab Laboratory, Ibadan. Samples were first dried, crushed, and ground into fine powders before being subjected to XRF analysis. The test identified the concentrations of major oxides, such as silica (SiO₂) and alumina (Al₂O₃), as well as trace elements. Understanding the chemical composition was critical for evaluation of the clay and the pozzolanic activity of the RHA, which plays a significant role in enhancing the strength, and overall performance of the ceramic composites.

2.2.4 Mechanical Characterization of composite samples

The compressive strength of the clay-RHA-RH composites was assessed to evaluate their load-bearing capacity. Cylindrical samples (60 mm in diameter and 60 mm in height) were prepared and cured for 28 days. Testing was conducted using a Testometric FS 50 AT machine (5000 kN capacity) at the University of Ilorin's Mechanical Engineering Department, adhering to ASTM C39 standards. A total of 30 samples (5 for each percentage level) were tested, with compressive strength (σ) calculated using Equation (1):

$$\sigma = F/A \quad (1)$$

where F is the average maximum load, and A is the cross-sectional area of the sample. This test offered insights into the structural stability and durability of the composites.

The flexural strength of the composites was evaluated using a three-point bending test, following ASTM C293 standards. Beam-shaped samples were subjected to a central load with support at two points. The test assessed the material's resistance to bending, critical for applications under flexural stresses. A total of 24 samples (4 per percentage level) were tested, and the flexural strength (σ_f) was calculated using Equation (2):

$$(\sigma_f) = \frac{3FL}{2BH^2} \quad (2)$$

Where F is the average maximum load, L is the span length (160 mm), B is the width (30 mm), and H is the thickness (20 mm). Results were plotted against the volume percentage of reinforcement.

The fracture toughness (KIC) of the composites was determined through single-edge notch beam (SENB) testing. Notched specimens (notch length: 6 mm) were subjected to a three-point bending load until failure. Fracture toughness was calculated using Equation (3), with $f\left(\frac{a}{w}\right)$ as the compliance function and “a” as the crack length, following ASTM E399-90

guidelines. This test provided essential data on the material's crack resistance, critical for assessing long-term durability in structural applications.[35].

$$K_{IC} = f\left(\frac{a}{w}\right) \sigma_f \sqrt{\pi a} \quad (3)$$

$$f\left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{\frac{1}{2}}}{2\left(1+2\frac{a}{w}\right)\left(1-\frac{a}{w}\right)^{\frac{3}{2}} \times [1.99 - \left(\frac{a}{w}\right)\left(1-\frac{a}{w}\right)(2.15 - 3.93\frac{a}{w} + 2.7\frac{a^2}{w^2})]} \quad (4)$$

3 Results and Discussion

3.1 Particle Size Distribution (PSD)

The particle size distribution (PSD) of the clay sample using sieve analysis and Soil hydrometer ASTM 152H indicates a composition predominantly of fine sand, as shown in Table 2. The absence of gravel suggests a fine-textured material, which is beneficial for composite applications, enhancing workability and bonding [36]. This is made possible as it improved packing by filling up voids spaces which can initiate cracking. With a clay content of 19.00% and a silt content of 15.00%, derived from hydrometer readings at 6 hours for clay and 40 seconds for silt, these findings highlight the material's suitability for high plasticity and binding capacity. The presence of 66.00% fine sand will enhance drainage and reduces shrinkage during drying providing a favourable balance between strength and workability. The dirty white colour indicates potential organic matter or iron oxides, influencing the aesthetic and mechanical behaviour of the final composite. The implications of this PSD analysis are significant for the formulation of clay-RHA-RH composites. Understanding of the PSD allows for better control over the mixing process and the resulting material properties, optimizing them for specific structural applications.

Table 2- Particle Size Distribution

Sample	Percentage
Sand	66.00
Fine(silt and clay)	34.00
Clay	19.00
Silt	15.00
Colour	Dirty white

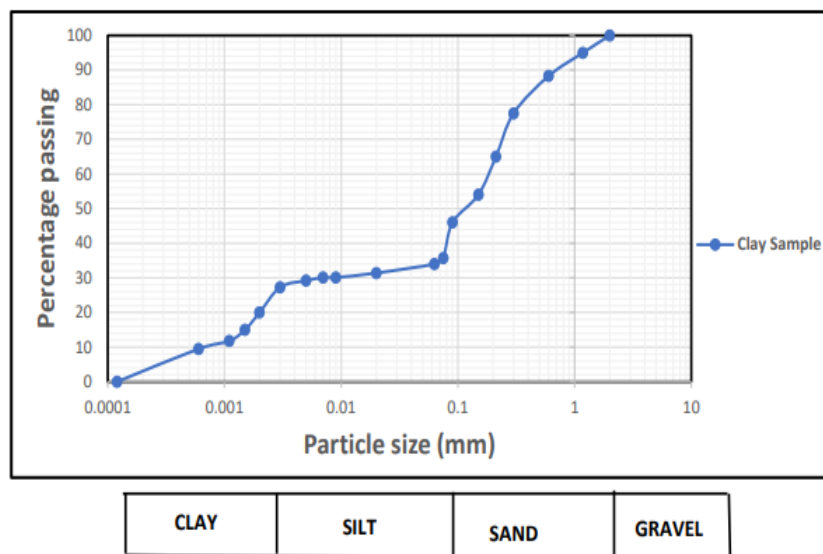


Fig. 5 – particle size distribution curve of the clay sample studied

3.2 Major oxide and Trace Elements Concentration of Soil Samples

The chemical analysis presented in Table 3 reveals that the clay sample contains 63.30% silica (SiO_2), indicating a sandy composition that significantly impacts the clay's plasticity and workability. While increased silica enhances the strength of bricks, it may also reduce moldability, presenting a trade-off in composite formulation. The alumina (Al_2O_3) content is 12.30%, which is beneficial for enhancing plasticity and bonding, ultimately contributing to the overall strength of the bricks. Iron oxide (Fe_2O_3) levels at 2.15% suggest that the bricks will exhibit a reddish-brown colour upon firing, which could be desirable for aesthetic applications.

Additionally, the clay sample contains low levels of alkali earth metals, with calcium oxide (CaO) at 1.40% and magnesium oxide (MgO) at 0.55%. Alkali oxides, including potassium oxide (K_2O) and sodium oxide (Na_2O), present at 0.30% and 3.70%, respectively, act as fluxing agents that lower the melting point during firing, thereby influencing the texture and strength of the final product. The presence of titanium dioxide (TiO_2) at 0.20% contributes to durability and color while helping to control expansion during firing. Lastly, the sample has a low Loss on Ignition (LOI) of 2.02%, indicating minimal volatile material loss during firing, which is advantageous for maintaining the integrity and performance of the ceramic composites.

Table 3- Concentrations of Major Oxides in the Samples

Major Oxides (%)	Clay	RHA	Portland Cement
SiO_2	63.30	66.95	22.07
Al_2O_3	12.30	6.50	5.34
Fe_2O_3	2.15	5.70	2.47
TiO_2	0.20	0.50	-
CaO	1.40	5.50	65.44
K_2O	0.30	5.20	-
Na_2O	3.70	0.17	0.75
MgO	0.55	3.24	3.79
MnO	10.01	0.02	-
P_2O_5	1.05	3.70	-
SO_3	3.02	-	2.87
LOI	2.02	-	
SUM	100	97.48	

3.3 Major oxide and Trace Elements Concentration of RHA

The rice husk ash (RHA) contains 66.95% silica (SiO_2), as indicated in Table 3, establishing it as a valuable material for pozzolanic activity that enhances binding properties in cement. In contrast, Ordinary Portland Cement (OPC) typically contains only 20-25% silica, suggesting that RHA can substantially improve the binding capabilities of cement. Additionally, RHA has an alumina (Al_2O_3) content of 6.50%, which is crucial for early strength development and falls within the standard range for OPC (4-8%). This further underscores RHA's potential as a supplementary cementitious material. The iron oxide (Fe_2O_3) concentration of 5.70% also aligns with the typical OPC range of 2-6%, indicating that RHA could similarly affect the color and strength of the cement.

Calcium oxide (CaO) content in RHA is 5.50%, significantly lower than the 60-65% typically found in OPC. While RHA can facilitate the binding process, its lower calcium content implies that it may not fully replace OPC without the addition of lime or cement. RHA also includes 3.24% magnesium oxide (MgO) and 5.20% potassium oxide (K_2O), which can influence the setting time and durability of the resulting cement. It is noteworthy that MgO levels in OPC are usually limited to 2% to prevent unsoundness, and K_2O is present in lesser amounts. Research by Oyekan and Kamiyo[37] indicates that the combined content of SiO_2 , Al_2O_3 , and Fe_2O_3 in RHA-blended cement reaches 79%, meeting the ASTM C618 pozzolana standard of 70%. Furthermore, a study by Anowai and Afunanya (2017) found that millet husk ash

(MHA) met the minimum requirement for pozzolanas with a combined content of 70.1%[38]. These findings affirm that RHA qualifies as a suitable pozzolana, with a total content of SiO_2 , Al_2O_3 , and Fe_2O_3 of 79.15%, reinforcing its suitability for enhancing the performance of cement-based materials [34].

3.4 Mechanical Analysis

3.4.1 Compressive Strength Analysis

The compressive strength results presented in Figure 5 indicates enhanced compressive strength up to 5% fibre inclusion with a gradual decline in strength from 10% to 15% fibre reinforcement, followed by a sharp decrease from 15% to 20% reinforcement. The optimal formulation identified for structural applications is 5% rice husk (RH) reinforcement, achieving a compressive strength of 7.2 MPa. This value surpasses the minimum requirements set by the Nigerian Industrial Standards (NIS) and ASTM [39] for sandcrete and common building bricks, which are 2.5 N/mm² and 3.5 N/mm², respectively, for load-bearing applications. This optimal composition results in bricks with enhanced compressive strength, making it suitable for sustainable construction. The organic nature of rice husk fibres contributes to the material's porosity, improving its insulating characteristics. While these composite exhibits moderate compressive strength, it is particularly well-suited for applications where insulation is prioritized against load bearing capacity, such as thermal insulation tiles or panels.

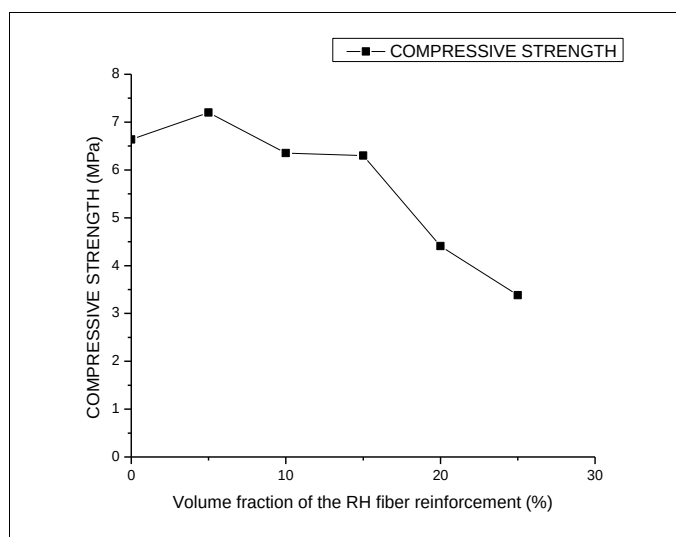


Fig. 6- shows the compressive strength test graph

Table 4 - compressive strength results from similar RHA-based bricks research work

Author (s) and year	Title	Composite Type	Compressive Strength (MPa)
Huq and Farhana, 2018 [20]	Use of rice husk ash as substitute to make clay bricks	Clay/RHA	4.52- 5.56
Alvarado, et.al., 2023[40]	Geopolymer made from kaolin, diatomite, and RHA for ceiling thermal insulation	Geopolymer /RHA	0.10 -10.88
Rabeea W. Bazuhair, 2023 [41]	Laboratory evaluation of the effect of rice husk fiber on soil properties and behaviours	CEBs /0.5-3% RH fiber	2 -2.5
Shanmukh, and B. Saikumar, 2020 [19]	A study on the efficacy of RHA as a full replacement for clay in brick-blocks.	RHA/cement/sand Composite	7.5 – 9.73
Nor Sarwani Mat Saman et. al, 2017 [42]	Development of low thermal conductivity brick using rice husk, corn cob and waste tea in clay brick manufacturing	Clay/RH/Corn cob/waste tea	8.6

3.4.2 Flexural Analysis

The initial flexural strength of the composite at 0% RH fibre reinforcement was 0.9 MPa. A significant increase was observed at 5% reinforcement, rising to 1.93 MPa, which represents over a 100% improvement in strength due to the inclusion of RH fibres. This demonstrates that even a small amount of fibre reinforcement can notably enhance the material's resistance to bending stresses. However, a gradual decline in flexural strength occurs from 10% to 15% fibre reinforcement, with a marked reduction from 20% to 25%, as shown Figure 7.

The composite achieves peak flexural strength at 5% fibre content, indicating its suitability for applications that require moderate bending resistance. Beyond this optimal point, increasing fibre content results in a steady decline in flexural strength, suggesting that excessive fibre can compromise the material's ability to withstand bending stresses. Consequently, while this composite is well-suited for ceramic applications needing a balance of flexibility and lightweight properties, it may not perform effectively in scenarios demanding high bending strength, particularly when the fibre content exceeds 10–15%.

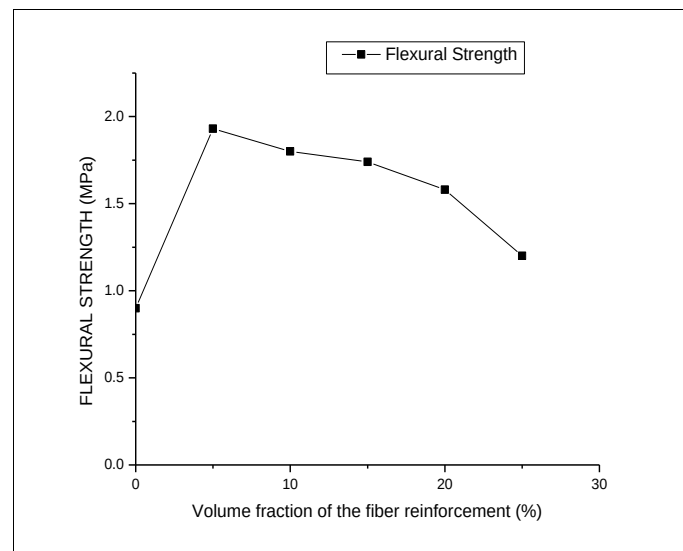


Fig. 7- Flexural strength graph of the composite samples.

3.4.3 Fracture Toughness Analysis of the composite samples

The control sample with 0% fibre content exhibits a fracture toughness of approximately $2.05 \text{ MPa}\cdot\text{m}^{1/2}$, while the optimal sample with 5% fibre reinforcement shows an increase to $2.2 \text{ MPa}\cdot\text{m}^{1/2}$. This slight improvement indicates that a minimal amount of RH fibre enhances the material's resistance to crack propagation, likely due to the fibres bridging cracks and redistributing stress. Crack propagation and fiber bridging influence the mechanical behaviour of the composite brick. Crack propagation which is the growth and extension of crack under stress can be initiated at the interface between the RH and clay starting informs of microcracks, which increases with continuous loading but impeded by the presence of fiber. The impediment of the propagation of cracks by the RH fiber which span across the crack, bridges the interface to resist fracture. The fiber pulled out or stretches to transfer stress, absorbs energy, and form a ductile component within the brittle matrix to enhance the material toughness thereby reducing rate of failure. However, from 10% to 20% fibre reinforcement, a gradual decline in fracture toughness is observed, as shown in Figure 8. Increased fibre content beyond 5% leads to a reduction in the material's ability to resist fracture, particularly noticeable after 20% reinforcement. This decline can be attributed to the potential for fibre agglomeration, which disrupts the uniform stress distribution within the matrix, leading to localized weaknesses. Additionally, excessive fibre content may increase porosity and decrease the overall cohesiveness of the composite, making it more susceptible to failure under stress. Thus, while this material is suitable for ceramic applications that require moderate toughness, its performance may diminish in high-stress environments where higher fracture resistance is essential.

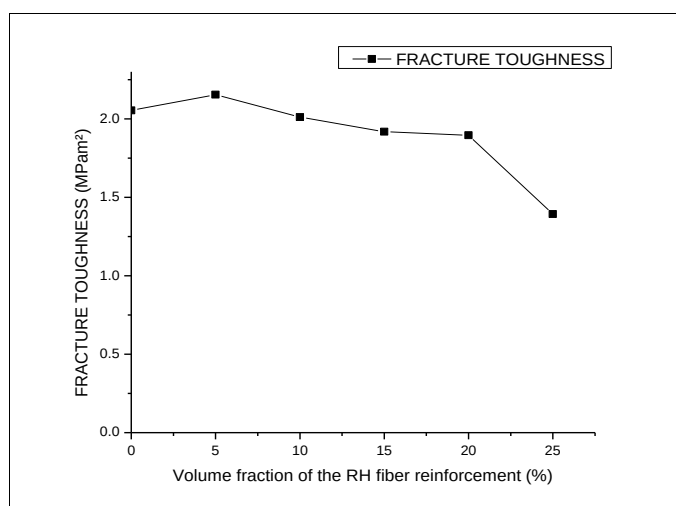


Fig. 8- Fracture Toughness graph of the RH fiber reinforced composite samples

4 Conclusion

This study investigated the engineering properties of clay composites reinforced with rice husk ash (RHA) and rice husk (RH) fibers, demonstrating significant improvements in mechanical performance. The optimal formulation, incorporating 10% Cement/RHA and 5% RH, yielded compressive strengths of 7.2 MPa, surpassing the minimum requirements for load-bearing bricks. Flexural and fracture toughness analyses revealed that low fiber content enhances resistance to bending and crack propagation, while higher fiber concentrations diminish these properties. The findings indicate that the incorporation of agricultural waste materials like RHA and RH not only enhances the structural integrity of clay bricks but also promotes sustainable practices in construction. These composites show promise for applications in thermal insulation and as lightweight, durable building materials, contributing to both environmental sustainability and improved material performance. Further research could explore the long-term durability and performance of these composites under varying environmental conditions.

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