

Effect of Rice Husk and Sugarcane Bagasse Pore Formers on the Mechanical Properties of Kaolin Ceramic

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ABSTRACT

The increasing focus on environmental sustainability has generated significant interest in the use of agricultural wastes particularly monocot-based materials rich in silica (SiO_2) as pore-forming agents in ceramic development. Their low cost, ease of handling, and commercial availability make them promising candidates for producing porous ceramics with tailored pore structures. Despite the abundance and economic potential of kaolin clay in Nigeria, its applications remain underutilized. This study investigates the effect of rice husk (RH) and sugarcane bagasse (SCB) as sustainable pore-forming agents on the mechanical properties of Gwarzo kaolin. Porous ceramic samples were fabricated using the pore-forming technique (PFT), incorporating locally sourced kaolin with varying weight percentages (3%, 6%, and 9%) of RH and SCB. After firing, the sacrificial pore-formers were eliminated to generate porosity. Mechanical properties specifically compressive strength, tensile strength, and hardness were evaluated. For RH-incorporated samples, compressive strengths of 5.33 MPa, 3.16 MPa, and 1.96 MPa were recorded for 3%, 6%, and 9% compositions, respectively. In contrast, SCB-based samples exhibited compressive strengths of 3.35 MPa, 1.17 MPa, and 0.58 MPa at corresponding compositions. Similarly, tensile strengths for RH samples were 0.83 MPa, 0.53 MPa, and 0.26 MPa, outperforming SCB samples which recorded 0.55 MPa, 0.25 MPa, and 0 MPa. Hardness values for RH samples were 64.5 HV, 57.3 HV, and 48.7 HV, compared to 56.6 HV, 45.5 HV, and 0 HV for SCB samples. The results indicate that rice husk is a more effective pore-forming agent than sugarcane bagasse in enhancing the mechanical performance of kaolin-based porous ceramics.

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INTRODUCTION

Rice husk (RH), the protective outer layer of rice grains, decomposes at a relatively low temperature, as compared with the high-temperature sintering of kaolin. Decomposition of RH yields rice husk ash (RHA), a rich source of reactive silica. Given their proven potential as pore formers in various studies (Ali *et al.*, 2017; Wei *et al.*, 2018; Liu *et al.*, 2019), RH and RHA are widely recognized as leading agricultural waste materials for creating porous ceramics.

Sugarcane bagasse (SCB) is the dry, fibrous residue left after sugarcane juice extraction. Approximately 3 tonnes of wet bagasse are generated from every 10 tonnes of sugarcane processed. Bagasse is primarily composed of cellulose, with its content varying by sugarcane type and harvesting method. A newer variety, "Energy Cane," has gained attention for its high fiber yield, despite lower sucrose content (Haghdan *et al.*, 2016).

Porous ceramic systems with engineered pore structures have been extensively

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employed in diverse industrial settings, leveraging their superior thermal shock resistance, chemical inertness, and mechanical properties to facilitate applications including filtration, biomedical implants, and catalytic processes (Ketov *et al.*, 2021; Dey *et al.*, 2021; Li *et al.*, 2020; Yoon *et al.*, 2007; Wang *et al.*, 2021; Ohji *et al.*, 2012). Porous ceramic membranes exhibit exceptional thermal and chemical stability, making them ideal for separation applications such as microfiltration and ultrafiltration, with significant relevance to industries like chemicals, food processing, and textiles (Ali *et al.*, 2018; Saini *et al.*, 2019; Aissat *et al.*, 2019; Abdullayev *et al.*, 2019). Typically, these membranes consist of a porous ceramic support that offers both mechanical strength and permeability. Alumina is widely utilized as a coating on ceramic substrates owing to its stability, filtration efficacy, and ability to optimize economic viability by reducing the quantity of costly materials required (Zou *et al.*, 2024).

The expense of commercial ceramic membranes is largely due to the cost of traditional raw materials and the energy-intensive sintering process. Alongside alumina, other popular materials like zirconia, titania, and silica are often employed (Souza *et al.*, 2021), necessitating elevated sintering temperatures (1500–1800 °C) (Dhuban *et al.*, 2019; Yang *et al.*, 2020), that lead to substantial energy consumption. Using natural raw materials like kaolin and clay offers a cost-effective and sustainable option, as they're abundant, affordable, and have good plasticity, which can also lower sintering temperatures (Lima *et al.*, 2024; Kamoun *et al.*, 2020).

Incorporating solid waste materials as pore-forming agents or structuring additives in ceramic processing offers a clever approach to valorizing potentially polluting by-products, thereby reducing environmental impact (Li *et al.*, 2020; Xavier *et al.*, 2022; Hubadillah *et al.*, 2020). Using locally sourced and abundant materials like rice husk, sugarcane bagasse, and kaolinitic clays from Gwarzo is crucial for creating affordable and eco-friendly technological solutions. Building on existing research that uses rice husk and sugarcane bagasse in ceramics (Dele-Afolabi *et al.*, 2018; Dele-Afolabi *et al.*, 2022), our study

pioneers the combination of raw rice husk and sugarcane bagasse with Gwarzo's local kaolinitic clays to examine the mechanical properties of porous ceramic substrates.

MATERIALS AND METHODS

Materials

The materials used in this study include Kaolin clay sourced from Gwarzo Local Government, Kano State, Nigeria; Rice husk (RH) obtained from a rice mill in Hadejia, Jigawa State, Nigeria; Bentonite clay procured from Maiduguri, Borno State, Nigeria; and Sugarcane bagasse (SCB) acquired from Hadejia market, Jigawa State, Nigeria.

METHODS

Preparation/Characterization of Kaolin, RH, SCB, and Porous ceramic pellets

These entail preparation of kaolin powder as mentioned by Zewdie *et al.* (2021) and Shitu (2025), X-Ray Fluorescence (XRF) analysis of the as-prepared kaolin powder in accordance with ISO 12677:2011, X-Ray Diffraction (XRD) analysis of the powder in accordance with ISO 18325:2016, Preparation of RH and SCB as described by Dele-Afolabi *et al.* (2018), Thermogravimetric analysis (TGA/DTG) to find the heating schedule of the pore formers as mention elsewhere (Shitu, 2025), and preparation of porous ceramics as detailed by Dele-Afolabi *et al.* (2021). The resulting sintered RH and SCB pellets were subjected to mechanical characterizations viz:

Test for Compressive Strength

Compressive strength testing was conducted in accordance with ASTM C39. The procedure involved the following steps:

Sample Preparation

The diameter and thickness of each ceramic disc sample were measured to calculate its cross-sectional area using the formula $A = \pi \frac{d^2}{4}$

The samples were then cleaned to remove any debris or contaminants that could affect the testing process.

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Testing Machine Setup

A Techquipment Universal Testing Machine (SM1000) was used for the compressive strength testing. The machine was calibrated and checked for proper functioning before each test. The hydraulic press was inspected, and the load cell was calibrated. The machine was set to "Compression Test" mode on the control panel.

Testing Procedure

Each ceramic disc sample was carefully positioned between the two compression platens of the testing machine, ensuring that it was centered to avoid uneven loading. The disc was aligned parallel to the machine's vertical axis to prevent tilting during the test. A spacer or base was used, if necessary, to ensure proper alignment and positioning. A loading rate of 0.5 mm/min to 2 mm/min was selected, which is suitable for brittle materials like ceramics. The machine was activated to apply compressive force gradually, and the force reading and displacement were observed on the machine's display. The test was continued until the sample failed, typically resulting in a crack or rupture. The maximum force applied at failure was recorded as the compressive strength of the ceramic disc. The various compressive strengths were plotted against weights of the pore formers as shown in Figure 1 below

Test for Tensile Strength

The tensile strength of the ceramic samples was evaluated using the diametrical compression test, also known as the Brazilian test, in accordance with ASTM C1161-18. The testing procedure involved the following steps:

Sample Preparation

The ceramic disc samples were prepared to ensure a uniform shape and surface, typically a cylindrical disc.

Testing Procedure

The disc sample was positioned in the testing machine so that the load would be applied across its diameter. A compressive load was applied along the diameter of the disc using a set

of loading plates. The load increased steadily until the disc fractured, typically along a plane perpendicular to the applied force. The maximum load at fracture was recorded.

Tensile Strength Calculation

The tensile strength was calculated using the following equation:

$$\sigma_{\text{tensile}} = \frac{2P}{\pi dt}$$

where σ_{tensile} is the tensile strength, P is the applied load, d is the diameter of the sample, and t is the thickness of the sample. The varied tensile strengths were plotted against weights of the pore formers as depicted in Figure 2.

Test for Hardness

The Vickers hardness of the ceramic disc samples was evaluated according to ASTM E92. The testing procedure involved the following steps:

Sample Preparation

The ceramic disc samples were selected and ensured to be clean and free of surface contaminants, cracks, or defects that could affect the test results.

Vickers Hardness Tester Setup

A Vickers Hardness Tester (MV1-PC) was used for the hardness testing. The machine was calibrated before testing, and the correct indenter and load were selected based on the material and expected hardness range of the ceramic sample. The tester was checked to ensure that the indenter was clean and free from wear or contamination.

Testing Procedure

The ceramic disc sample was carefully placed on the testing platform and aligned properly to ensure that the indenter would be applied perpendicularly to the surface. The desired load was selected based on the expected hardness of the sample, and the Vickers Hardness Tester was activated to apply the load. The indenter was pressed into the surface of the ceramic disc for a predefined duration (typically

10-15 seconds), and the load was applied gradually to prevent sudden impact or vibrations. After the load was removed, the diagonal lengths of the indentation were measured using an optical system integrated into the Vickers Hardness Tester. The Vickers Hardness (HV) was calculated using the formula:

$HV = 1.854 \times F/d^2$, where F is the applied load (in kgf) and d is the average length of the diagonal of the indentation (in mm). The hardness value was typically displayed directly on the Vickers Hardness Tester. Figure 3 depicted the plots of the various hardness values versus weights of the pore formers.

RESULTS AND DISCUSSION

X-Ray Fluorescence (XRF) of the Kaolin

The Gwarzo kaolin is primarily composed of silica (53.9%) and alumina (37.94%) with minor impurities, consistent with the theoretical composition of kaolinite. This compositional similarity indicates that the Gwarzo kaolin conforms to the characteristic mineralogical

profile of kaolinite and is comparable to other kaolin clays globally.

X-Ray Diffraction of the Kaolin

The XRD pattern of the kaolin sample confirms the presence of kaolinite, quartz, and silica, with a prominent peak at 26.8° (2θ) corresponding to the crystallographic plane of kaolinite.

Thermal Analysis of RH and SCB

The thermal behavior of RH and SCB pore formers was investigated using TGA and DTG, revealing similar trends with initial weight loss due to water removal and subsequent decomposition of hemicellulose, cellulose, and lignin at higher temperatures. The decomposition temperatures varied between RH (320-600°C with an endothermic peak at 400°C) and SCB (endothermic peak at 410°C), informing the development of a heating schedule for porous kaolin samples.

COMPRESSIVE, TENSILE STRENGTH AND HARDNESS OF THE SAMPLES

Compressive Strength Analysis.

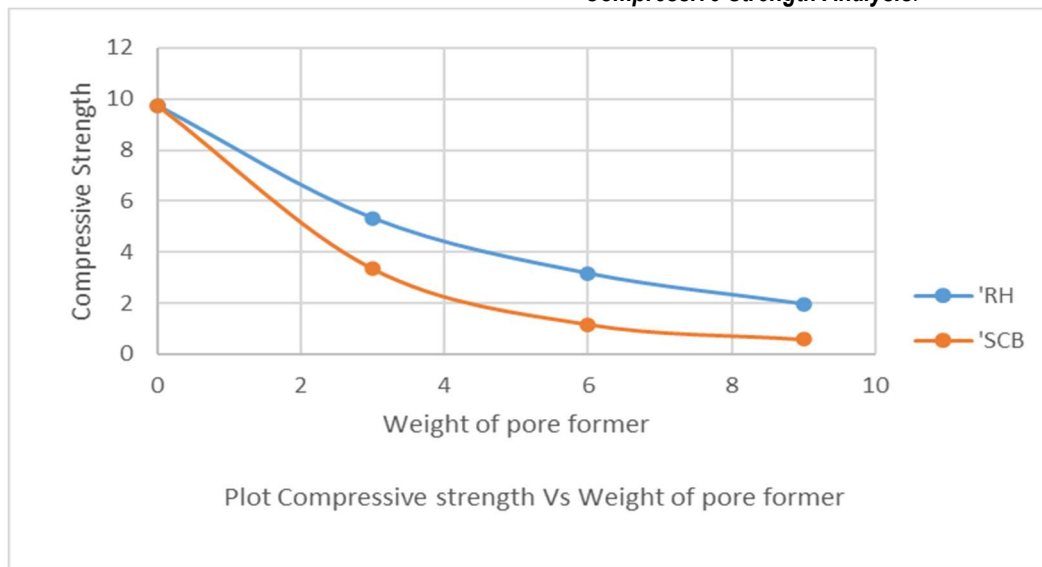


Figure 1: Graph of compressive strength against weight of pore former

Reference to Figure 1 above, the compressive strength of porous ceramic samples

was significantly influenced by the type and content of pore formers, namely RH and SCB. For

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RH samples, the compressive strength decreased from 5.33 MPa to 1.96 MPa as the RH content increased from 3% to 9%, exhibiting an inverse relationship between porosity and compressive strength. Similarly, SCB samples showed a decrease in compressive strength from 3.35 MPa to 0.58 MPa with increasing SCB content. Notably, RH samples exhibited higher compressive strength values compared to SCB samples across all weight percentages, with a more gradual decline in strength as RH content increased. In contrast, SCB samples showed a more pronounced decline, particularly at higher concentrations. These results suggest that RH may contribute to more evenly distributed and

smaller pores, which have a less severe impact on mechanical properties, whereas SCB may result in larger, more irregular pores, leading to a greater reduction in compressive strength. This observation is consistent with the expected relationship between porosity and mechanical strength, as reported by Liu *et al.* (2016). The difference in compressive strength between RH and SCB samples can be attributed to the distinct pore structures and distributions induced by each pore former.

Tensile Strength Analysis

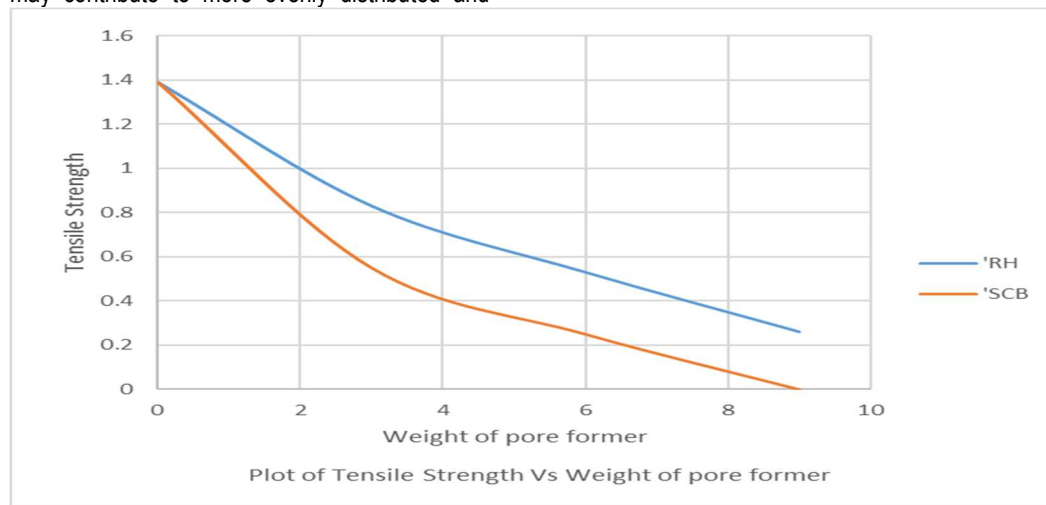


Figure 2: Graph of Tensile strength against weight of pore former

Considering, Figure 2, above, the tensile strength of the ceramic samples was found to be low, consistent with the brittle nature of ceramics. Both sets of samples, with RH and SCB as pore formers, exhibited a progressive decrease in tensile strength with increasing pore former content. This trend is attributed to the introduction of stress concentration points due to increased porosity, which weakens the ceramic matrix, as reported by Dele-Afolabi *et al.* (2017). Notably, RH samples showed a more gradual reduction in tensile strength, retaining some structural integrity even at 9% RH content. In contrast, SCB samples experienced a more significant drop in tensile strength, becoming non-functional (0 kPa) at 9%

SCB content. This variation may be due to differences in pore characteristics, with RH potentially producing finer or more evenly distributed pores, whereas SCB may create larger or more interconnected pores that severely weaken the ceramic.

The relationship between pore former content and tensile strength indicates that increasing porosity reduces tensile strength, but the extent of reduction varies with the type of pore former. While RH samples remain functional even at higher pore former contents, SCB samples become unsuitable for applications requiring mechanical strength beyond a critical threshold of 9% pore former content. These findings suggest

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that RH may be a more suitable pore former for applications requiring a balance of porosity and strength.

Hardness Analysis

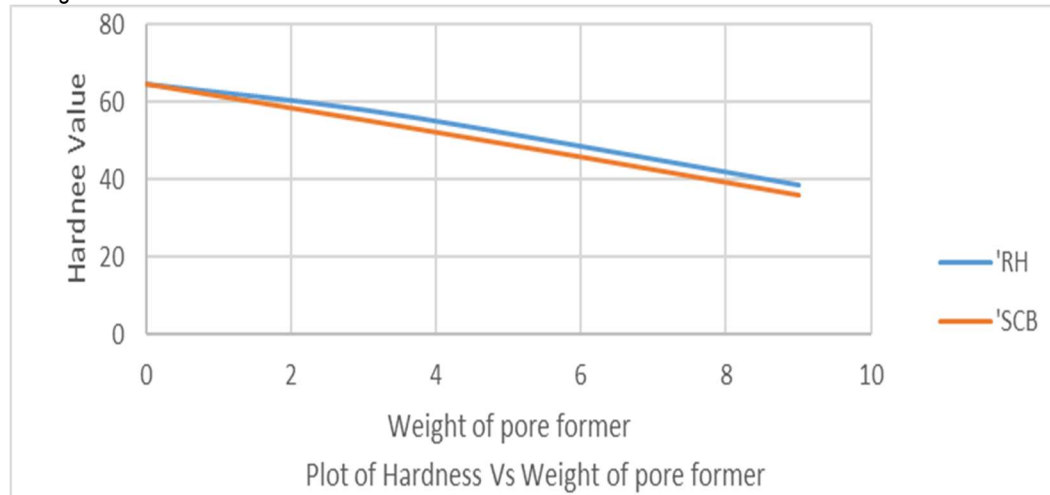


Figure 3: Graph of Hardness against weight of pore former

With respect to Figure 3 above, the hardness of the porous ceramic samples decreased with increasing pore former content, regardless of whether RH or SCB was used. For RH samples, the hardness values decreased from 58.2 HV to 38.6 HV as the RH content increased from 3% to 9%. Similarly, SCB samples exhibited a decrease in hardness from 55.6 HV to 36.1 HV with increasing SCB content. These findings are consistent with the expected relationship between porosity and hardness, where higher porosity leads to reduced material density and lower hardness, as reported by Ali *et al.* (2017).

Notably, RH samples exhibited slightly higher hardness values compared to SCB samples at the same weight percentages, suggesting that RH may be more effective in maintaining the structural integrity and hardness of the ceramic. The observed differences in hardness can be attributed to the nature of the pore formers, with RH potentially producing smaller, more evenly distributed pores, whereas SCB may introduce larger or more irregular pores, leading to a greater reduction in hardness. Overall, both RH and SCB decrease the hardness of the kaolin-based ceramics, but RH has a slightly

less detrimental effect, likely due to differences in pore size and distribution.

CONCLUSION

The incorporation of RH and SCB as pore formers in kaolin-based ceramics leads to a decline in compressive strength, tensile strength, and hardness with increasing content. However, RH exhibits a more favorable effect on preserving mechanical properties compared to SCB, likely due to the formation of smaller and more uniformly distributed pores. In contrast, SCB tends to create larger and more irregular pores, resulting in a more pronounced degradation of mechanical properties. These findings suggest that RH may be a more suitable pore former for applications requiring a balance of porosity and mechanical strength.

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