



ORIGINAL RESEARCH ARTICLE

PHYSICO-MECHANICAL CHARACTERIZATION OF HYBRID COMPOSITE GASKET DEVELOPED USING SUGARCANE BAGASSE ASH, SODA-LIME WASTE GLASS POWDER, AND EPOXY RESIN

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ABSTRACT

The environmental and health risks posed by conventional gasket materials such as asbestos and synthetic rubbers have created a pressing need to develop sustainable alternatives for mechanical sealing applications. This study investigated the potential of hybrid composite gaskets composed of sugarcane bagasse ash, soda-lime waste glass powder, and epoxy resin as an environmentally friendly alternative. Five different compositions were formulated using the hand lay-up method and evaluated for mechanical and thermal properties such as density, porosity, hardness, tensile strength, thermal endurance, Scanning Electron Microscopy (SEM), and X-ray Fluorescence (XRF) analysis. The results showed that Sample C1 (10% bagasse ash, 30% glass powder, 60% epoxy) demonstrated optimal performance, recording the highest tensile strength of 30.91 N/mm² and a thermal resistance of 170°C. These values exceed the typical performance range of NBR (Nitrile Butadiene Rubber) gaskets, which generally show a tensile strength of 17 N/mm² and a thermal resistance range of 120°C. All samples exhibited low porosity (0.01%–0.04%), supporting effective sealing capability, although still higher than the NBR control gasket (0.008%). XRF analysis revealed that SiO₂ was the dominant oxide in both fillers, contributing to thermal stability, hardness, and wear resistance, while Al₂O₃ and CaO enhanced structural rigidity. SEM examination of the optimal sample (Sample C1) revealed that its superior performance was primarily due to regions of uniform filler dispersion and strong interfacial bonding. While high-resolution imaging at 6,000x and 7,000x identified localized micro-voids and filler pull-out, these were isolated instances that did not compromise the structural integrity of the composite. The high tensile strength indicates that the well-bonded regions in the optimal 30:10 (Glass:Ash) ratio effectively dominated the load-transfer mechanism. The presence of micro-voids, visible only at high magnifications, provided the physical basis for the 0.04% porosity without significantly impairing the primary mechanical and thermal performance of the sample.

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1.0 Introduction

Industrial gaskets play a critical role in ensuring the integrity of mechanical assemblies by preventing fluid leakage, maintaining pressure boundaries, and resisting chemical or thermal degradation (Durlon, 2025). Conventional gasket materials such as asbestos and nitrile butadiene rubber (NBR) have long been favored due to their sealing ability and chemical resistance (Mohammed et al., 2015; Redon et al., 2023). However, asbestos presents significant health risks due to its fibrous and carcinogenic nature (Norshirwaan et al., 2017), while synthetic rubber production is heavily dependent on non-renewable petroleum resources, leading to environmental pollution and long-term waste accumulation (Ajayi et al., 2024).

Nigeria produces over 89.63 million tons of crude oil annually, which is nearly equaled by the amount of waste it generates each year Arogundade, S. (2018). Furthermore, with an anticipated 72.46 million tonnes of waste generated annually, Nigeria will account for about 25% of all waste produced in Africa (World Bank, 2025). The increasing environmental issue highlights the need for creating sustainable composite materials for engineering uses, focusing on both decreasing reliance on non-renewable resources and reducing ecological impact. One promising area of application is in the production of gasket materials, which are widely used in the automotive, aerospace, and industrial sectors. Since typical gasket components such as asbestos and synthetic fibers have been linked to adverse health and environmental effects (Mohammed *et al.*, 2015), the search for alternative, eco-friendly and sustainable gasket materials that do not compromise performance has gained significant momentum.

Several studies have investigated the development of reinforced composites using natural fibers, industrial waste, and synthetic materials to enhance mechanical and thermal performance. Composites reinforced with sawdust and recycled glass (Birniwa *et al.*, 2021), bamboo and glass fibers (Raghavendra *et al.*, 2010), and other agro-based fibers have demonstrated improved tensile, flexural, and compressive properties when subjected to appropriate chemical treatments and optimized filler ratios. Traditional fabrication methods such as hand lay-up are widely used due to their simplicity and low tooling requirements. However, they often result in inadequate fiber volume fractions, poor fiber–resin bonding, and higher void content, limiting mechanical performance (Agwa *et al.*, 2022). In contrast, vacuum-assisted resin infusion and RTM techniques offer superior control over fiber distribution, reduced void content, and significantly enhanced flexural strength, modulus, and strain characteristics, with increases of 45.7%, 17.4%, and 35.6%, respectively, compared to hand lay-up samples (Balasubramanian *et al.*, 2018).

Sugarcane bagasse, an abundant agricultural residue, has been extensively studied for its potential as a reinforcing material in polymer matrices Ridhwan Jumaidin *et al.* (2022). Chemical treatments, including alkali, acid, and esterification processes, have been shown to improve its thermal stability, crystallinity, and interfacial bonding with resins, thereby enhancing tensile and flexural strength (Loh *et al.*, 2013; Phiri *et al.*, 2025). Similarly, waste glass powder, when ground to micro or nanoscale, has been effectively utilized as a reinforcement agent due to its high silica content, hardness, and chemical inertness (Mosaberpanah *et al.*, 2018; Zheng *et al.*, 2024). Hybrid reinforcement strategies that combine natural fibers with glass particles have yielded composites with balanced strength, thermal resistance, and stiffness (Nazari *et al.*, 2025).

In the development of gaskets, both natural and synthetic fibers, elastomers, and thermosetting resins have been utilized to produce non-asbestos sealing materials that offer enhanced safety and performance. Selecting the appropriate resin matrix, like epoxy, is essential for ensuring chemical resistance, structural integrity, and adhesion under thermal and mechanical stresses (Junma Seal, 2023). Previous studies have shown that epoxy-based composites reinforced with agro-waste fillers have exhibited improved hardness and tensile strength at optimized filler levels (Adewale *et al.*, 2008). Similarly, rice husk ash in composite brake pads has shown enhanced thermal resistance compared to conventional materials (Nandiyanto *et al.*, 2022).

In sealing applications, banana fiber-reinforced composites have demonstrated considerable improvement in pressure retention, although brittleness and moisture absorption remained issues (Sivaranjana *et al.*, 2021). Other researchers have noted that filler particle size and distribution significantly affect composite performance, with finer particles improving mechanical bonding and thermal resistance (Pavlyuchkova *et al.*, 2024). Additionally, glass-based fillers are known to enhance wear resistance, making them valuable in components subjected to friction and mechanical stress (Suresha *et al.*, 2006).

Although these studies confirm the potential of agro-waste and inorganic fillers in engineering composites, few have explored hybrid combinations of different waste materials and their influence on multiple performance metrics of gaskets. This study addresses this gap by combining bagasse ash and waste glass powder with epoxy resin to develop hybrid composite gaskets using the hand lay-up method. The research explores how different proportions of the two waste fillers affect the physical, mechanical, and thermal properties of the resulting gasket materials. Furthermore, performance is compared to a commercial NBR gasket to assess suitability for industrial applications.

The objective of this study is to produce hybrid composite gasket samples using bagasse ash, waste glass, and epoxy resin; investigate their physical, mechanical, and thermal properties; conduct SEM and XRF analyses to understand their microstructure and elemental composition; and compare their performance with that of a standard NBR gasket.

2. Materials and Method

2.1 Materials

Sugarcane bagasse was collected from Sabo Market, Sagamu, Ogun State, Nigeria. After washing and sun-drying for five days, it was incinerated in a furnace to obtain sugarcane bagasse ash (SBA). The ash was further sieved to achieve a fine particulate size of less than 75 μ m. Soda-lime waste glass powder (WGP) was commercially sourced in a pre-processed fine powder form with a particle size of less than 150 μ m. A commercial epoxy resin served as the binder, and a standard NBR gasket was used as a benchmark.



Plate I: Scale, epoxy, and hardner

2.2 Method

2.2.1 Preparation of test samples

The composite gaskets were fabricated using the hand lay-up method. This method was selected because of its simplicity, low cost, and suitability for laboratory-scale material development, especially where sophisticated equipment such as vacuum-assisted resin infusion or resin transfer molding is not readily available. Although advanced techniques are known to produce composites with lower void content and improved mechanical performance, the hand lay-up method remains appropriate for preliminary material development and comparative studies. In this study, process control was carefully maintained through thorough mixing and proper curing to minimize void formation and ensure acceptable mechanical performance.

Sugarcane bagasse ash and soda-lime waste glass powder were prepared in accordance with procedures commonly reported in the literature for composite filler preparation, including drying, grinding, and sieving to achieve fine and relatively uniform particle sizes. The fillers were weighed using a digital balance based on weight fraction formulation. The epoxy resin content was kept constant at 60 wt% for all samples, while the proportions of bagasse ash and waste glass powder were varied between 10 wt% and 30 wt% to study the influence of filler composition on the physical and mechanical properties of the composites. The dry fillers were first blended manually using a spatula to achieve an initial uniform distribution. Epoxy resin was then added gradually and mixed thoroughly using continuous manual stirring until a homogeneous paste was obtained. Manual mechanical mixing was adopted to ensure even wetting of the fillers by the resin and to reduce particle agglomeration.

The resulting composite paste was poured into pre-lubricated molds and cured at room temperature for 24 hours, after which they were demolded and allowed to stabilize before testing.

The selected formulations were chosen to balance filler loading and resin content, ensuring adequate matrix continuity for effective stress transfer while incorporating sufficient waste-derived fillers to improve stiffness, hardness, and thermal resistance. This approach also allowed the identification of an optimal composition that provides improved performance while maintaining good processability. The compositions of the samples are presented in Table I.

Table I: Optimal Design for the Mixture Composition Using Two-Factorial Design

Sample Number	Sugarcane Bagasse Ash (wt.%)	Waste Glass Fiber (wt.%)	Epoxy Resin (wt.%)
C1	10	30	60
C2	15	25	60
C3	20	20	60
C4	25	15	60
C5	30	10	60

2.3 Sample Testing and Characterization

2.3.1 Density

The density of each sample was determined using the water displacement method, in accordance with ASTM D792. The weight of each sample was recorded using a digital balance, and volume was determined via water displacement.

Density was calculated as:

$$\rho = \frac{m}{v} \tag{1}$$

Where ρ is the bulk density (g/cm³), m is the mass of the composite sample (g), and v is the volume of the sample (cm³).

2.3.2 Porosity

Porosity was analyzed to assess void formation and structural compactness. The test was carried out using the water absorption method in accordance with ASTM D570, where the percentage of open pores was determined by measuring weight differences before and after immersion in distilled water.

$$P = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \tag{2}$$

where P is the percentage porosity (%), W_{wet} is the weight of the sample after immersion in water (g), and W_{dry} is the weight of the dry sample before immersion (g).

2.3.3 Hardness

Surface hardness testing was conducted using the GUNT WP 300 Universal Material Tester equipped with a specialized Brinell hardness testing attachment. In accordance with the principles of ASTM E10, a 10 mm hardened steel ball indenter was pressed into the surface of the hard plastic composite. The manual hydraulic pump was used to apply a standardized test load. Following the removal of the load, the diameter of the indentation was measured to calculate the Brinell Hardness Number (BHN).

2.3.4 Tensile strength

The tensile properties of the specimens were evaluated using a GUNT WP 300 Universal Material Tester (GUNT Hamburg, Germany). This manual hydraulic system has a maximum load capacity of 20 kN. The specimens were secured using the unit's wedge-action grips and subjected to a steady tensile load. The breaking load was monitored and recorded via the integrated large-diameter force gauge, while the elongation was measured using the associated dial gauge to determine the ultimate tensile strength.

2.3.5 Heat resistance

Thermal resistance was evaluated in accordance with ASTM D573 by placing the composite gasket samples in a laboratory oven at incremental temperatures. The temperature at which the sample began to degrade or lose shape was recorded as its maximum thermal resistance.

2.3.6 Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) analysis was performed on the best-performing composite sample (Sample C1) using a (FE-SEM) JEOL JSM-7600F field emission scanning electron microscope. The fractured surface of the sample was coated with a thin conductive layer prior to imaging to prevent charging and improve image quality. Both secondary electron (SE) and backscattered electron (BSE) imaging modes were employed to examine the surface morphology, filler distribution, interfacial bonding, and fracture characteristics of the composite.

2.3.7 X-ray fluorescence (XRF)

X-ray fluorescence (XRF) analysis was performed using a PANalytical Axios mAX Wavelength Dispersive X-ray fluorescence (WDXRF) spectrometer (Malvern Panalytical, Netherlands) to determine the elemental and oxide composition of the bagasse ash and waste glass powder. This instrument was equipped with a 4 kW SST-mAX Rhodium (Rh) anode X-ray tube. This technique recognizes elements by measuring the characteristic secondary X-rays that are emitted when stimulated by a primary X-ray source. The peaks identified in the XRF spectra revealed the types and relative amounts of oxides present. This evaluation verified the appropriateness of the fillers as reinforcements in epoxy-based gaskets, while adhering to safety protocols in accordance with the ALARA principle.



Plate 2: Gasket samples produced

3. Results and Discussion

3.1 Density Test

The density of the composite gaskets is illustrated in Figure 3, showing values between 2.09 g/cm³ and 5.04 g/cm³. The highest density was observed in Sample C3 (5.04 g/cm³), exceeding three times that of the NBR control (1.5 g/cm³), which contained equal parts bagasse ash and waste glass powder. This aligns with findings in Solanki, 2023, which suggests that an optimized mix of organic and inorganic components enhances compaction and density. Lower density, as observed in Sample C1, is advantageous in applications where weight reduction is critical. Composites with reduced density often exhibit improved thermal insulation and lightweight properties, making them desirable for use in heat-sensitive environments, as reported by Verma *et al.* (2012). However, mechanical properties must also be considered to ensure overall performance.

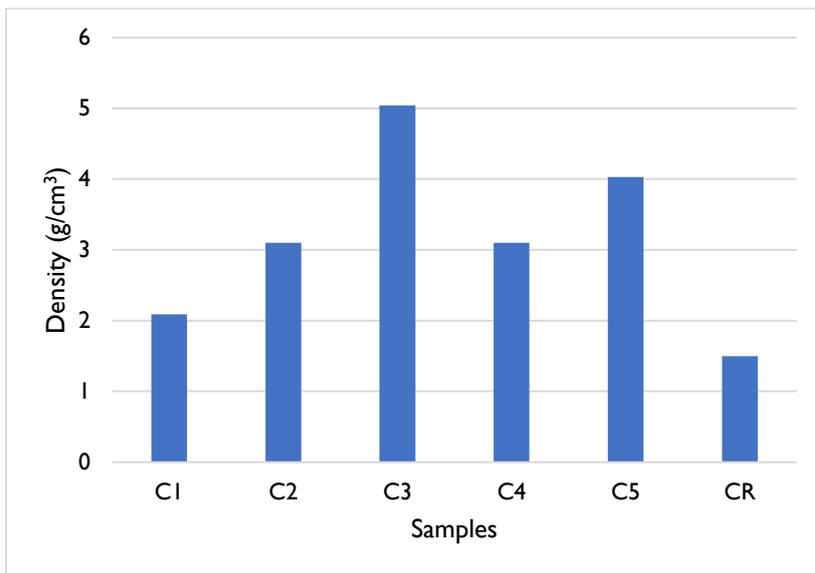


Figure 1: Density of various composite samples

3.2 Porosity Test

The porosity values shown in Figure 2 are low for all samples, ranging between 0.01% and 0.04%. This indicates good filler–matrix bonding and minimal void formation. Sample C1 recorded the highest porosity (0.04%), which may be due to its lower bagasse ash content (10%) and higher waste glass content (30%). The reduced presence of bagasse ash, which contains finer and more irregular particles, limited effective pore filling during fabrication, resulting in slightly higher void formation. As the bagasse ash content increased from C1 to C5, a general reduction in porosity was observed, indicating improved packing efficiency and reduced air entrapment within the composite matrix.

Samples C3 and C5 recorded the lowest porosity values 0.01%, suggesting that higher bagasse ash contents (20% and 30%, respectively) enhanced matrix compaction by filling micro-voids between particles. This behavior is consistent with findings reported by Kumar *et al.* (2021), who observed that fine ash fillers improve particle packing and reduce void content in epoxy-based composites. Samples C2 and C4 showed intermediate porosity values 0.03%. The slight increase in porosity observed in Sample C4, despite its higher bagasse ash content compared to C3, can be attributed to localized particle agglomeration and non-uniform dispersion. At this specific filler ratio, the increased viscosity of the epoxy-filler mix may have trapped air during the hand lay-up process before curing was complete. This is consistent with Mohanty *et al.* (2006), who noted that excessive natural filler can lead to agglomeration-induced voids even when finer particles are present. Although all composite samples exhibited higher porosity than the NBR control gasket (0.008%), the values remained within acceptable limits for sealing applications.

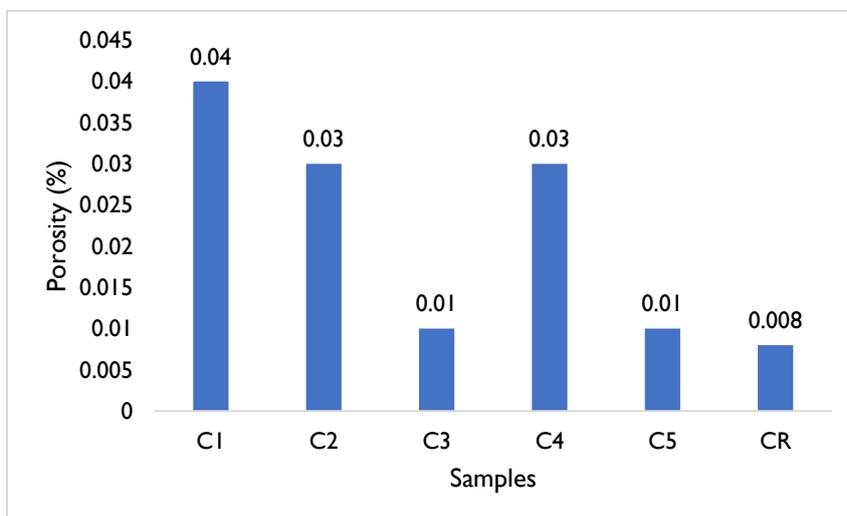


Figure 2: Shows the porosity of various composite samples

3.3 Hardness Test

The hardness expressed as Brinell Hardness Number (BHN), are in Figure 3. Sample C1 the maximum hardness among the composites at 8.96 BHN. This is attributed to the high concentration of waste glass powder (30%), as glass particles are inherently rigid and provide high resistance to surface indentation. As noted by Sara *et al.* (2022), the inclusion of inorganic glass-based reinforcement significantly improves the structural rigidity and wear resistance of polymer matrices. However, a notable dip was observed at Sample C3 (20% bagasse ash, 20% waste glass powder), which recorded the lowest value of 6.99 BHN. This decline suggests a synergy gap where the balanced proportion of organic ash and inorganic glass powder creates a more compliant composite structure compared to the glass-dominant formulations. Wu *et al.* (2019) reported similar findings where specific weight distributions of hybrid fillers can lead to temporary reductions in hardness before the second filler reaches a reinforcing threshold.

The partial recovery in hardness observed in Samples C4 (7.40 BHN) and C5 (7.95 BHN) is attributed, in this study, to the increased silica (SiO_2) content of the sugarcane bagasse ash, as confirmed by the XRF results (Figure 6). At higher SBA loadings (up to 30%), the mineral-rich ash appears to compensate for the reduced waste glass content by forming a denser network of hard particles within the epoxy matrix.

Despite these improvements, all formulated samples remained significantly softer than the conventional NBR control gasket (12 BHN). This explicit gap indicates that while the hybrid composites offer sustainability and sufficient structural strength, their resistance to localized indentation is approximately 25% to 42% lower than industrial standards. In practical sealing applications, a lower BHN may allow the gasket to conform better to flange surface irregularities, though it may also increase the risk of creep or material flow under extreme bolt loads over time.

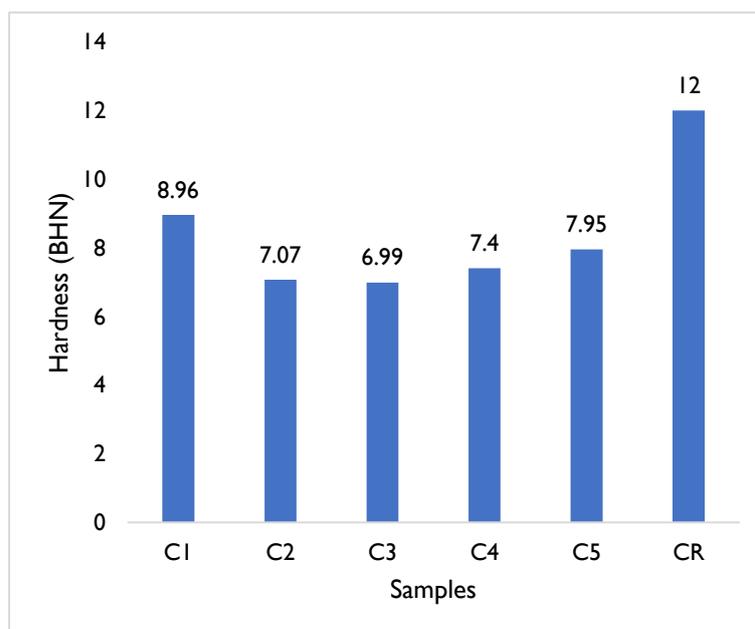


Figure 3: Hardness of various composite samples

3.4 Tensile Test

The tensile strength of the developed hybrid composites ranged from 24.12 N/mm² to 30.91 N/mm², surpassing the commercial NBR benchmark (17.00 N/mm²) across all formulations. Sample C1 achieved the peak tensile strength, identifying it as the optimal loading for maximum load-bearing capacity. A non-linear trend was observed as the bagasse ash content increased from 10% to 30% and waste glass powder decreased from 30% to 10%. While strength initially dipped to 24.12 N/mm² at C3, a secondary rise was recorded for Samples C4 (25.53 N/mm²) and C5 (27.43 N/mm²). This recovery is attributed to the synergistic silica (SiO_2) loading identified in XRF. The finer SBA particles acted as interstitial micro-fillers, complementing the WGP particulates to increase packing density and mechanical interlocking within the epoxy matrix. The peak strength of 30.91 N/mm² outperforms the 22.40 N/mm² reported by Onyenanu *et al.* (2022) for single-filler agro-waste gaskets, validating the efficacy of the hybrid reinforcement strategy. Furthermore, the strength recovery observed in high-ash formulations (C4–C5) aligns with Karademir *et al.* (2025), who noted that high

silica content in organic fillers can compensate for reduced mineral reinforcement by improving the filler-to-filler network.

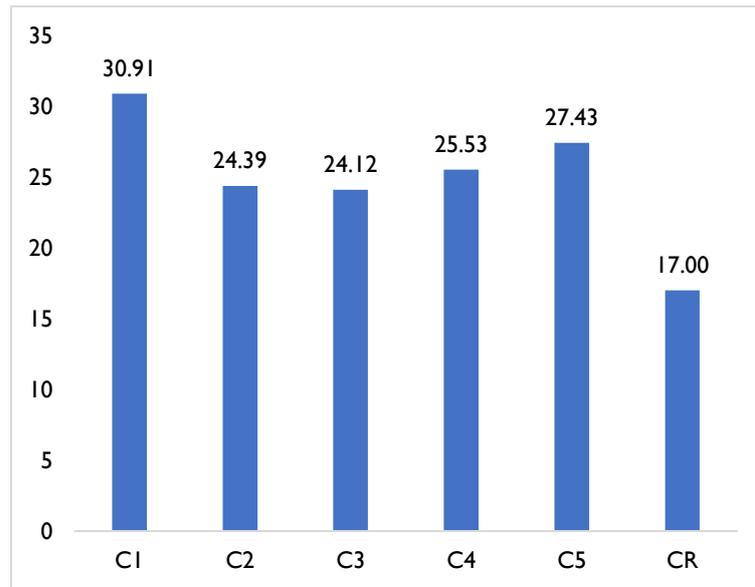


Figure 4: Tensile stress of various composite samples

3.5 Thermal Resistance Test

Thermal resistance results are presented in Figure 7. All hybrid composite samples exhibited higher heat resistance than the NBR control gasket, which has a maximum service temperature of about 120°C. Sample C1 showed the highest thermal endurance, withstanding temperatures up to 170°C before visible degradation occurred. This indicates that the combination of epoxy resin with a high proportion of waste glass powder significantly enhances the thermal stability of the composite. The superior performance of Sample C1 can be attributed to the high silica content of waste glass, which resists thermal softening and delays matrix degradation.

As the waste glass content decreased from Sample C1 to Sample C5 and bagasse ash content increased, a gradual reduction in thermal resistance was observed. Although bagasse ash contains thermally stable oxides, its irregular particle structure and weaker interaction with the epoxy matrix may reduce its ability to resist heat-induced deformation compared to glass particles. Similar improvements in thermal resistance have been reported in silica-rich composite systems, where inorganic fillers act as heat barriers and slow down thermal degradation according to Kadhim *et al.* (2022).

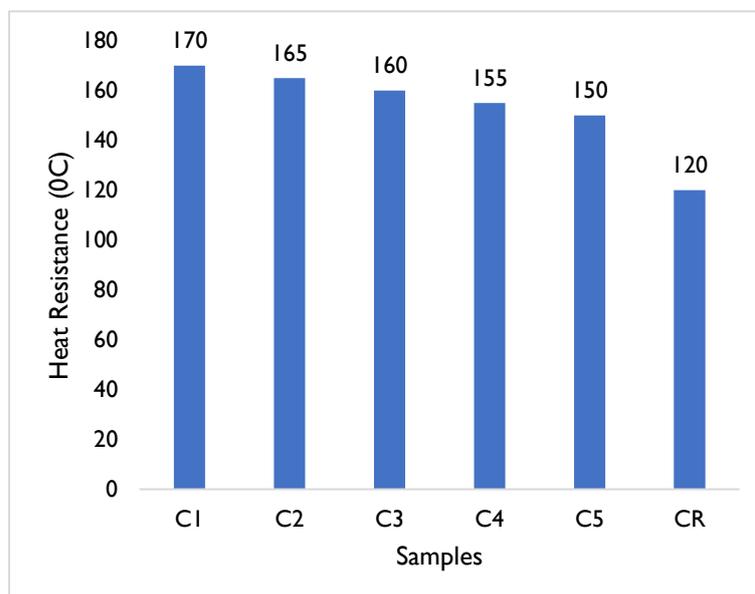


Figure 5: Heat resistance of various composite samples

3.6 XRF Analysis

The elemental composition of the optimal composite sample (C1), as determined by X-ray fluorescence (XRF) analysis, is presented in Figure 6. The results show that the composite is predominantly composed of silicon (55.42 wt%), oxygen (18.76 wt%), and aluminum (8.98 wt%), with minor contributions from calcium, iron, potassium, magnesium, and sodium.

The high concentrations of silicon (Si) and oxygen (O), present mainly as silica (SiO_2), are the defining factor for the superior performance of Sample C1. This silica-rich composition originates from the 30% waste glass powder content. In this study, the elevated SiO_2 content directly corresponds with the highest hardness (8.96 BHN) and tensile strength (30.91 N/mm²) recorded among all samples. The rigid silica particles act as load-bearing reinforcements within the epoxy matrix, restricting matrix deformation and improving resistance to mechanical loading.

Aluminum (8.98 wt%) and calcium (3.81 wt%), occurring primarily as aluminum oxide (Al_2O_3) and calcium oxide (CaO), are largely contributed by the sugarcane bagasse ash. These oxides function as secondary reinforcements, enhancing matrix stiffness and contributing to improved load transfer between the fillers and the epoxy resin. Their presence explains the balanced combination of strength and toughness observed in Sample C1, despite its high glass content.

The minor oxides detected (Fe_2O_3 , MgO , Na_2O , and K_2O) further support interfacial stability by promoting filler–matrix interaction and thermal resistance. This mineral-dominated composition also accounts for the superior thermal performance of Sample C1, which remained stable up to 170°C. Unlike the NBR control gasket, which exhibited thermal degradation at approximately 120°C, the abundance of thermally stable inorganic oxides in Sample C1 limits rapid softening and degradation of the epoxy matrix.

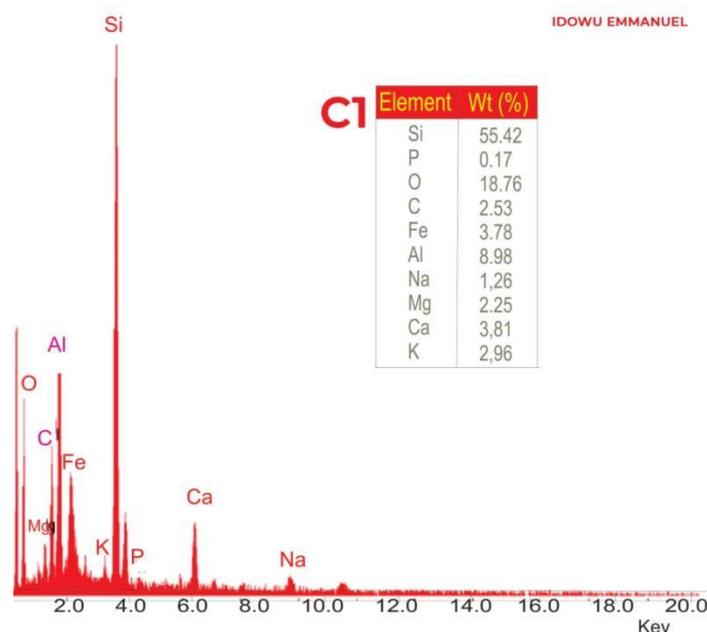


Figure 6: XRF Spectrometer of the best composite sample (C1)

3.7 SEM Analysis

This was performed on Sample C1 (10% bagasse ash, 30% waste glass) to examine its microstructural features and correlate them with the recorded mechanical and thermal results. SEM micrographs captured at high magnifications of 5,000x, 6,000x, and 7,000x revealed detailed surface and interfacial characteristics of the hybrid system.

At 5,000x magnification, the micrograph shows a generally rough and irregular surface morphology with dispersed filler particles deeply embedded within the epoxy matrix. The fillers appear mostly well-distributed, indicating effective mixing and reasonable interfacial contact between the waste glass powder, bagasse ash, and

the resin. This microstructural arrangement justifies the peak tensile strength (30.91 N/mm²) and hardness (8.96 BHN) recorded for Sample C1, as the matrix is able to effectively transfer loads to the reinforcing particles.

At 6,000x magnification, localized defects become more evident. Small micro-voids and regions of partial filler pull-out were observed, suggesting areas of weak interfacial bonding between specific filler particles and the epoxy matrix. These features act as potential stress concentration points within the composite structure. Furthermore, these voids provide the physical basis for the 0.04% porosity measured during testing, as they represent internal air pockets where the resin failed to fully encapsulate the hybrid fillers.

At 7,000x magnification, finer surface features become visible. The micrograph reveals a predominantly rough topography, which favors mechanical interlocking between the fillers and the matrix. However, isolated micro-voids and small honeycomb-like features are also observed. Despite these localized imperfections, the fillers remain largely anchored within the matrix, which contributes to the observed thermal stability (170°C) and confirms the suitability of Sample C1 for sealing applications requiring a balance of mechanical strength, thermal resistance, and structural integrity.

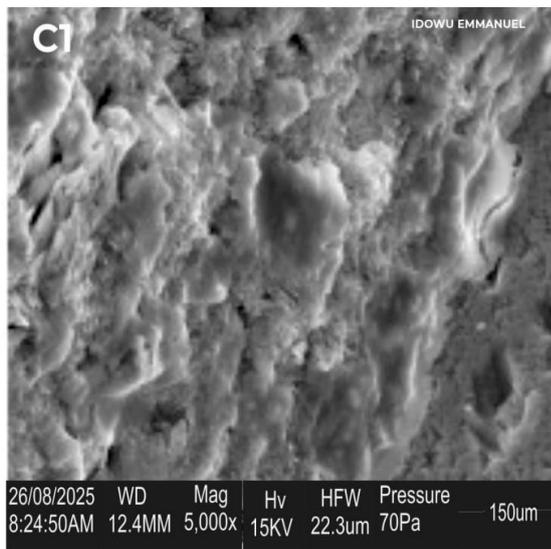


Plate 3: SEM micrograph of sample C1 at 5,000x

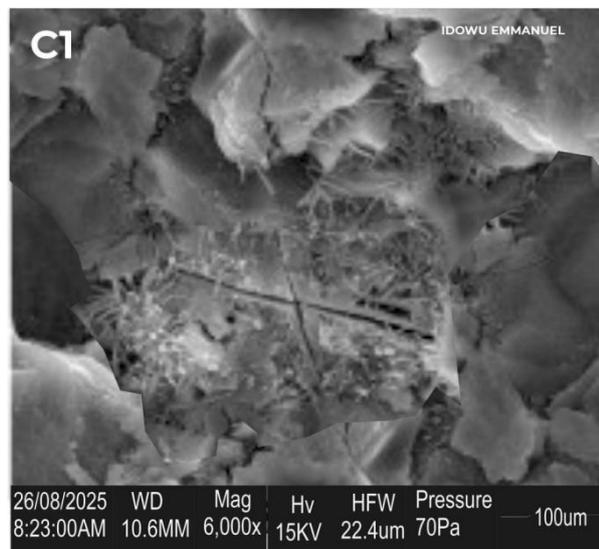


Plate 4: SEM micrograph of sample C1 at 6,000x

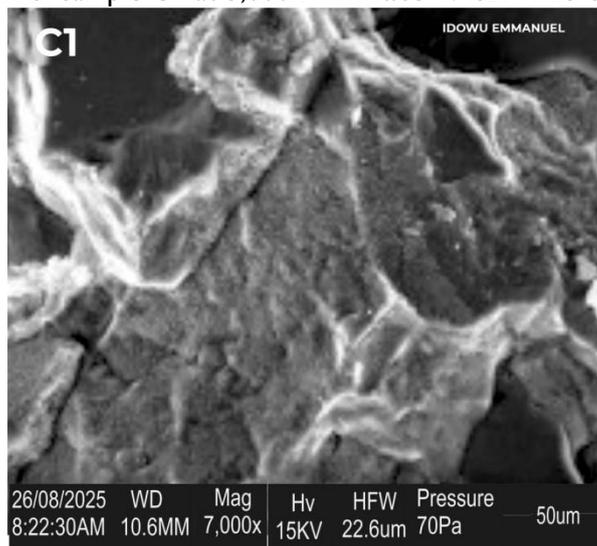


Plate 5: SEM micrograph of sample C1 at 7,000x

4. Conclusion

This study successfully developed and characterized a sustainable hybrid composite gasket utilizing sugarcane bagasse ash (SBA) and soda-lime waste glass powder (WGP) with the hand lay-up technique. The research effectively closes the existing gap regarding the poor mechanical performance of single-filler agricultural waste composites by identifying a synergistic optimum at a 10:30 weight fraction (Sample C1). This formulation

yielded a peak tensile strength of 30.91 N/mm² and a Brinell hardness of 8.96 BHN, significantly surpassing the commercial NBR benchmark's tensile capacity of 17 N/mm².

This enhanced mechanical performance is directly attributed to the high silica content of the waste glass reinforcement and the superior interfacial bonding strength observed between the fillers and the epoxy matrix. Microstructural analysis at 7,000x magnification confirmed that the use of fine particulates (SBA < 75 µm and WGP < 150 µm) promoted high packing efficiency and mechanical interlocking, resulting in very low porosity values ranging from 0.01% to 0.04%. This structural density effectively addresses the research gap concerning permeability and mechanical failure in waste-derived sealing materials.

Thermal resistance tests confirmed that the hybrid composites maintain structural integrity up to 170 °C, surpassing the 120 °C threshold of conventional NBR. While the 170°C limit is noted as a moderate threshold compared to the extreme thermal demands of internal combustion engine combustion chambers, the composite is highly suitable for medium-temperature applications such as automotive cooling systems, industrial low-pressure steam pipelines, and hydraulic housings. Hence, while this study successfully validates the immediate physico-mechanical viability of the composite, future research should include comparative post-thermal SEM analysis to visually map heat-induced degradation patterns, as well as evaluate the creep property to determine long-term deformation stability under constant compressive stress.

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