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EFFECTS OF SAWDUST PARTICLES REINFORCEMENT ON THE MICROSTRUCTURAL, PHYSICAL, AND MECHANICAL PROPERTIES OF CEMENT-BASED COMPOSITES: AN EXPERIMENTAL STUDY

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Abstract: This study investigates the effect of varying sawdust reinforcement volumes on the physical and mechanical properties of Portland cement composites. Sawdust from a local sawmill in Moro, Kwara, Nigeria, was incorporated into cement composites at volume fractions from 40% to 90%. Composites samples were produced for physical, mechanical and microstructural characterizations. Results showed that water absorption increased with higher sawdust content, peaking at 41.78% for 90% sawdust composite, and bulk density also rose, reaching a maximum of 193.33 g/m^3 at 90%. Apparent void volume generally decreased with increasing sawdust content. Optimal mechanical properties were observed at 60% sawdust content, with the highest compressive strength of 20.32 MPa, flexural strength of 8.36 MPa, and fracture toughness of 0.85 MPa.m$^{1/2}$, while hardness decreased with increasing sawdust, peaking at 42.99 HRBS at 40% sawdust. Microstructural analysis using scanning electron microscopy (SEM) revealed a uniform distribution of sawdust particles within the cement matrix, with improved interfacial bonding observed at the optimal 60% sawdust content, contributing to the enhanced mechanical properties of the composite. In conclusion, 60 vol.% sawdust reinforcement is optimal for enhancing the mechanical performance of Portland cement composites, offering a balance between strength and sustainability, suggesting its potential as a cost-effective, eco-friendly reinforcement for cement-based materials in sustainable construction practices.
Keywords: Sawdust reinforcement; Cement composites; Mechanical properties; Microstructural analysis; Sustainable building materials

1. INTRODUCTION

The increasing interest in sustainable construction materials has led to the exploration of natural fibers and waste products as reinforcements in cement composites [1], [2], [3]. Sawdust, a by-product of the timber industry, offers potential as a sustainable reinforcement material due to its abundance and low cost. The products of Wood can generate sawdust waste which has continually contributed to environmental problems [4]. In Nigeria, Sawdust and other agricultural residues/wastes are produced annually and are massively underutilized. Better strength in sawdust applications is achieved with smaller particles [5]. In Nigeria, approximately 1.8 million tons of sawdust are generated annually, necessitating its utilization, marketing, or proper disposal [6]. Unfortunately, this sawdust is often regarded as waste, leading to open burning, dumping in water bodies, or open areas, resulting in environmental pollution [6]. The improper disposal of sawdust generated daily at sawmills is a significant environmental issue [7], highlighting the need for effective management and utilization, as seen in developed countries [8].

In many parts of the world, the use of cement, sawdust, and sand for making floor and wall panels is common. With some adaptations and modifications, sawdust can also be used for eaves, cladding, ceiling, and roofing [9]. Sawdust composites have been utilized in construction for several years; for example, sawdust concrete has been in use for over 40 years [10]. As advancements in concrete technology continue, the application of sawdust in building materials has gained attention over the past few years, offering a solution to environmental problems and contributing to the economic design of sustainable building construction [11], [12], [13]. Also, the desire for energy-efficient, sustainable, and affordable construction and industrial materials has encouraged the advancement of composites using natural fibers and more environmentally friendly materials as matrices [14]. These fibers reinforced composites have significant benefits which include biodegradability, renewability, low density, relatively high specific strength properties, reduced tool wear (less abrasive to processing equipment), and low cost [15].

Previous research has extensively explored the use of sawdust and other wood by-products in cement composites. Gong, Kamdem, and Harichandran conducted compression tests on wood-cement particle composites made from CCA-treated wood, concluding that such materials can be used effectively in applications requiring compressive strength and energy dissipation [16]. Similarly, Suliman et al. found that sawdust can replace sand in concrete, with a 5% replacement providing optimal results without compromising health or structural integrity [17]. Boob's study indicated that sawdust sandcrete blocks with 15% sawdust replacement are advantageous for thermal properties in masonry work [18]. Osei and Jackson observed that increasing sawdust content reduces the compressive strength and density of concrete, suggesting a 16% replacement for lightweight applications [19]. Altwair and Sryh confirmed a decrease in compressive and flexural strength in mortars with up to 15% sawdust, which remains acceptable for many applications [20].

This study aims to investigate the effect of varying volume fractions of sawdust on the physical and mechanical properties of sawdust reinforced Portland cement composites. The research focuses on evaluating key properties such as compressive strength, hardness strength, fracture toughness, and flexural strength. Additionally, physical characterization including apparent void volume, bulk density, and water absorption, as well as micro-structural analysis using scanning electron microscopy, are performed to understand the impact of sawdust reinforcement on the composite's properties. The outcomes of this study will contribute to the existing body of knowledge on sustainable construction materials and provide valuable insights into the design and application of sawdust reinforced cement composites. By comprehensively analyzing the physical, mechanical, and micro-structural properties, this research seeks to establish an optimal balance between material sustainability and performance.

2. MATERIALS AND METHODS

Materials

The sawdust used in this study (Figure 1) was sourced from at sawmill in Moro Local Government Area, Kwara, Nigeria. The sawdust, without pretreatment, was soaked in water for 24 hours and then air-dried to approximately 5% moisture content (Figure 4). Once dried, the sawdust was sieved using the Searchtech instrument sieve shaker to obtain particles with sizes ranging from 0.18 mm to 0.9 mm, which were then used in the composite brick production. The Portland cement employed in the preparation of the composites was purchased from a cement store in Ilorin, Kwara State. Additionally, a wooden mold with inner dimensions of 100 mm x 25 mm x 25 mm, corresponding to the shape and size of the samples produced, was fabricated in the mechanical workshop at Kwara State University, Malete. The sawdust and Portland cement were thoroughly mixed to produce the composite bricks.


Figure 1: Sawdust particles

Sample Preparation

The sawdust was soaked in water for 24 hours and then air-dried to approximately 5% moisture content (Figure 4). The dried sawdust was sieved using a Searchtech instrument sieve shaker to obtain particle sizes ranging from 0.18 mm to 0.9 mm, which were used in the composite brick production. The composite specimens were prepared by mixing the treated sawdust and Portland cement in the proportions listed in Table 3. The required proportions of sawdust and Portland cement were measured using a HT series electronic balance.

Table 1: Composite Preparation by Volume %

Composite brick	Sample A (vol.%)	Sample B (vol.%)	Sample C (vol.%)	Sample D (vol.%)	Sample E (vol.%)	Sample F (vol.%)
Fiber composition	40	50	60	70	80	90
Matrix composition	60	50	40	30	20	10

Sawdust compositions of 40%, 50%, 60%, 70%, 80%, and 90% were mixed with Portland cement compositions of 60%, 50%, 40%, 30%, 20%, and 10%, respectively. The measured sawdust and Portland cement were thoroughly mixed, followed by the addition of water, and mixed again until a uniform consistency was achieved. The mixture was then uniformly distributed into forming moulds of the desired size and compacted. After compaction, the samples were ejected from the moulds and allowed to set for a while (Figure 2a). A total of 90 composite brick samples were produced and left to cure in polythene bags for 28 days (Figure 2b). After curing, samples (100mm × 25mm × 25mm) were taken for physical, mechanical and micro-structural tests. Notches (a = 7 mm) were created in samples for fracture toughness testing.


(a) (b)

Figure 2: (a) Composite brick produced and (b) Curing of composite bricks in polyethylene bags

Physical Characterization Tests

Physical characterization tests were conducted to evaluate the physical properties of the composite bricks. These tests included apparent void volume, Water Absorption, and Bulk Density tests. The procedure involved submerging composite bricks of different volume percentage compositions in water for 24 hours, then removing them from the water, wiping off visible surface water with a towel, and weighing them to record the wet mass. The saturated bricks were measured again after the water absorption period. Physical parameters were measured based on the method specified by ASTM C948-81 [21]. The apparent void density was calculated using Equation 1:

$$\text{Apparent void density (\%)} = \frac{W_s - W_d}{W_s - W_i} \times 100 \quad (1)$$

where W_i is the specimen's mass immersed in water, W_d is the dry specimen's mass after 2 months out of water, and W_s is the saturated specimen's mass with a dry surface. Water absorption was determined by measuring the dry mass of the composite brick (composed of sawdust reinforced Portland cement) and then immersing it in water for not less than 24 hours. The mass was measured again after surface drying, specifying this as the saturated specimen's mass with a dry surface. The water absorption percentage was calculated using Equation 2:

$$\text{Water Absorption (\%)} = \frac{W_s - W_d}{W_d} \times 100 \quad (2)$$

where W_d is the dry specimen's mass after 2 months out of water, and W_s is the saturated specimen's mass with a dry surface. The bulk density was determined using calculated using Equation 3:

$$\text{Bulk density } (g/cm^3) = \frac{W_d}{W_s - W_i} \times \rho_w \quad (3)$$

where ρ_w is the bulk density of water.

Macro-Mechanical Characterization Tests

The macro-mechanical tests included hardness, compressive strength, flexural strength, and fracture toughness tests. Compressive strength, flexural strength, and fracture toughness were carried out using the Instron 3369 universal testing machine on 5 samples for each volume percentage reinforcement. The hardness test was conducted using the HR-150A Rockwell hardness tester on 5 samples of each volume fraction of reinforcements.

The compressive strength (σ) test was performed using a universal mechanical testing machine (Instron 3360 series, MA, USA) with a 50 kN load cell at the Mechanical Engineering Laboratory, Kwara State University, Malete. The test focused on the maximum load causing failure of the specimen at a loading rate of 2.0 N/s up to fracture. Testing of samples were carried out at temperature and average relative humidity of ~30ºC and of 65% respectively. The compressive strength was determined using equation 4 [22]:

$$\sigma = \frac{P}{A} \quad (4)$$

where P is the peak load at the onset of fracture and A is the initial cross-sectional area of the specimens. The flexural strength of the composite was determined using a three-point-bend test arrangement. The specimen was loaded in a three-point bending configuration with a loading span of 60 mm until fracture. The flexural strength was calculated using equation 5 [23]:

$$\sigma_f = \frac{3PL}{2BH^2} \quad (5)$$

where σ_f is the flexural strength, P is the peak load at onset of fracture, L is the loading span, B is the specimen's breadth, and H is the specimen's height.

A fracture toughness test, important for predicting the composite's resistance to crack propagation, was conducted using a single edge notched bend (SENB) specimen loaded in three-point bending configuration (Figure 3). The fracture toughness was calculated using Equation 6 [24]:

$$K_{IC} = f\left(\frac{a}{W}\right)\sigma\sqrt{\pi a} \quad (6)$$

where K_{IC} is the fracture toughness of the specimen, $f\left(\frac{a}{W}\right)$ is a compliance function for a rectangular SENB test obtained in the ASTM E399 [25], σ is the flexural stress at the peak load, and a is the crack length.

Hardness test was done to measure the ability of the composites to withstand localized permanent deformation. The Rockwell hardness test was conducted using the HR-150A Rockwell hardness tester and the average hardness was calculated using Equation 7:

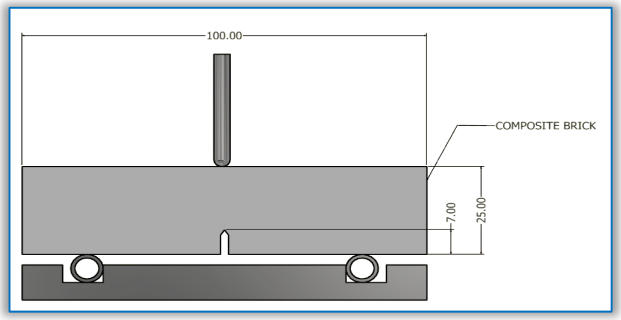


Figure 3: Schematic of a notched specimen used for determining fracture toughness

$$H_{avg} = \frac{1}{n}\sum_{i=1}^{n} H_i \quad (7)$$

where H_{avg} is the average hardness measurement, H_i are the individual hardness numbers, and n is the number of hardness measurements [26].

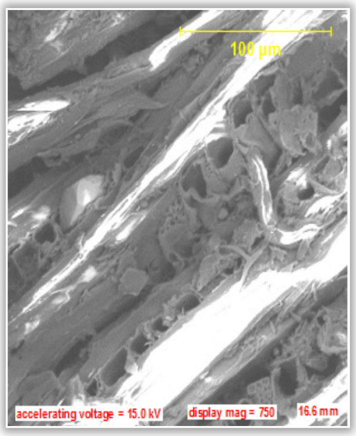
Micro-Structural Characterization Test

Microstructural characterization was performed using an ASPEX 3020 scanning electron microscope (SEM). The SEM setup includes an electron column, sample chamber, EDS detector, electronics console, and visual display monitors. High-energy electrons produce signals at the solid specimen's surface, revealing information about the external morphology of the composite samples [27].

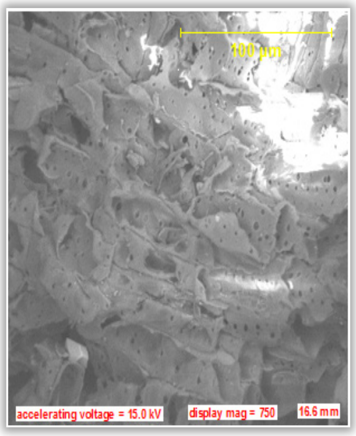
3. RESULTS AND DISCUSSION

Microstructural Analysis

The SEM images of the sawdust particles (Figure 4a – 4c) revealed detailed information about their morphology and surface characteristics. The sawdust particles exhibit an irregular shape with a rough surface texture. This roughness can contribute to better mechanical interlocking with the cement matrix, potentially enhancing the bonding and overall strength of the composite. Detailed examination shows the presence of natural wood fibers and cellular structures typical of lignocellulosic materials. These features are important for understanding the interaction between the sawdust and the cement matrix, especially in terms of moisture absorption and mechanical bonding [28]. The images indicate that sawdust has a porous structure which contributes to its ability to absorb water.



(a)



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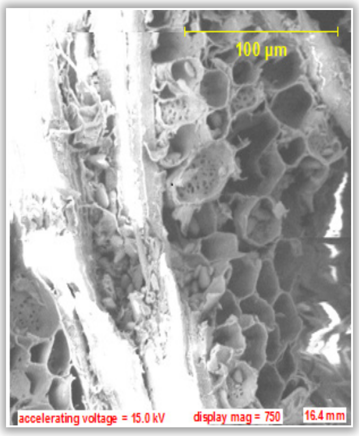

(c)

Figure 4: Scanning electron micrograph for (a) 0.28 mm, (b) 45 mm and (c) 90 mm sawdust mesh size

The SEM images of the composite specimens (Figure 5) provide insights into the distribution and interaction of sawdust particles within the cement matrix. The interface between the sawdust particles and the cement matrix appears to be well-bonded at 50 – 60 vol.% of reinforcement, as evidenced by the lack of significant gaps or voids at the interface. This strong interfacial bonding is crucial for effective load transfer between the matrix and the reinforcement, contributing to the composite's mechanical properties. At 50 -70 vol.% of reinforcement, the sawdust particles are uniformly dispersed throughout the matrix. This is essential for ensuring consistent mechanical properties across the composite. The clustering of particles as observed in 80 and 90 vol.% reinforcement could lead to stress concentration points, potentially weakening the composite. At higher volume fractions of reinforcements, some micro voids and pores were observed within the matrix. This can affect the composite's mechanical properties, particularly its compressive strength and durability.

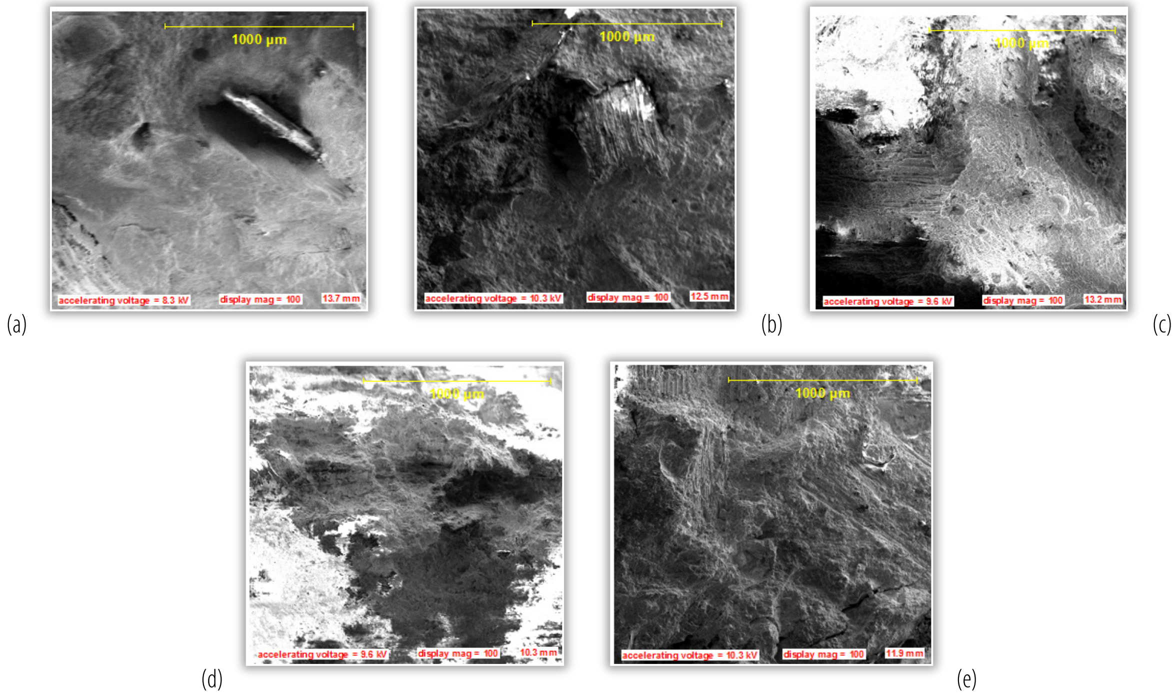

Figure 5: Scanning electron micrograph for (a) 50 vol.%, (b) 60 vol.%, (c) 70 vol.%, (d) 80 vol.% and (e) 90 vol.% reinforced composites.

Physical characterization

The water absorption test results for the sawdust reinforced cement composites (Figure 6) indicate a significant increase in water absorption as the volume fraction of sawdust reinforcement increases. Specifically, the water absorption values range from a minimum of 1.44% at 40 vol.% sawdust to a maximum of 41.78% at 90 vol.% sawdust. This trend can be attributed to the inherent properties of sawdust and its interaction with the cement matrix. Sawdust, being an organic material, has a higher porosity and affinity for water compared to the cement matrix [29]. As the proportion of sawdust increases, the overall porosity of the composite increases, allowing more water to be absorbed.

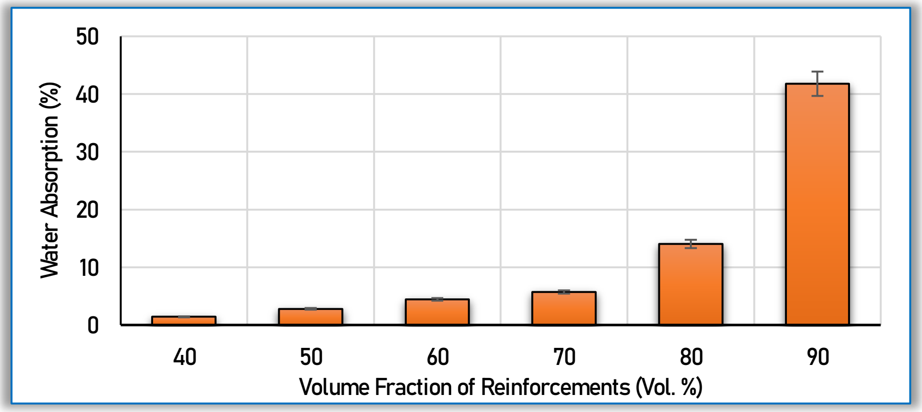

Figure 6: Water absorption of composites with various volume fraction of sawdust reinforcements

The bulk density results presented in Figure 7 reveal an increase in bulk density with a higher volume fraction of sawdust, showing a maximum of 193.33 g/cm^3 at 90 vol.% and a minimum of 28.68 g/cm^3 at 40 vol.%. This trend indicates that incorporating more sawdust, which is less dense than cement, results in a composite material with higher bulk density. The increase in bulk density with higher sawdust content suggests that the composite's porosity decreases as sawdust volume increases, leading to a denser packing of particles. This can be attributed to sawdust's ability to fill voids more effectively than cement alone, despite its lower intrinsic density. Thus, while higher sawdust content enhances bulk density, it is crucial to consider its impact on other mechanical properties for specific applications.

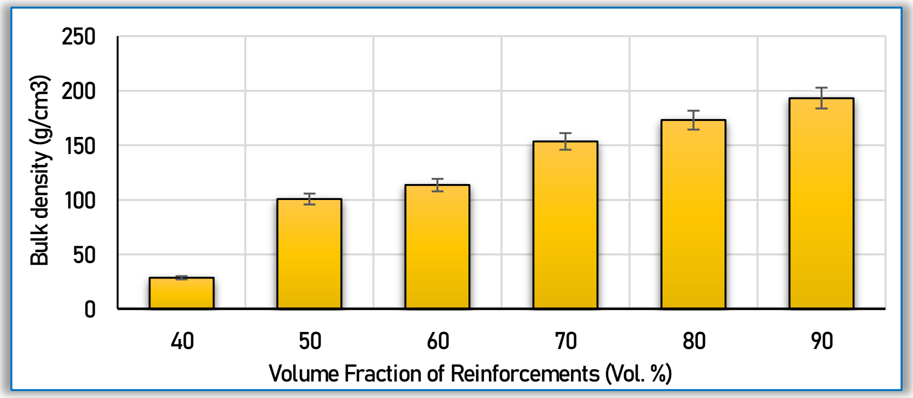

Figure 7: Bulk density of composites with various volume fraction of sawdust reinforcements

Figure 8 presents the apparent void volume results. It indicates that the composites exhibit a decreasing trend in void volume with increasing sawdust content. The highest void volume at 50 vol.% sawdust (93.41%) and the lowest at 90 vol.% sawdust (73.56%) suggest that higher sawdust content contributes to better filling of void spaces within the composite matrix. This reduction in void volume with increasing sawdust can be attributed to the smaller particle size and better packing density of sawdust, which minimizes the gaps that typically exist in a cement matrix. Consequently, higher sawdust volumes lead to composites with lower porosity, potentially enhancing certain mechanical properties, though the trade-off with other properties must be considered.

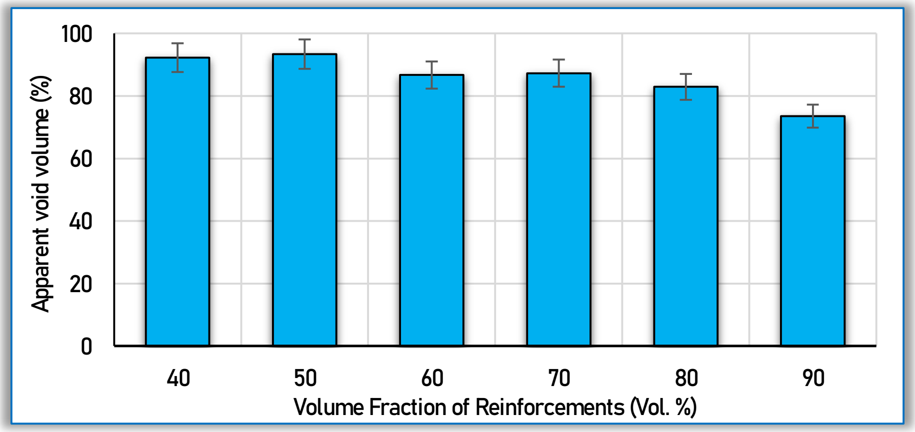

Figure 8: Apparent void volume of composites with various volume fraction of sawdust reinforcements

Mechanical characterization

The compressive strength results (Figure 9) shows that the composite achieves a peak strength of 20.32 MPa at 60 vol.% sawdust, indicating that up to this proportion, the addition of sawdust enhances the material's compressive strength. This increase can be attributed to the optimal interaction between sawdust fibers and the cement matrix, improving load distribution and structural integrity [30], [31]. However, beyond 60 vol.% sawdust, the compressive strength decreases, suggesting that excessive sawdust content leads to a reduction in the binding effectiveness of the cement matrix and an increase in voids and weak points within the composite. This decline at higher sawdust volumes indicates a threshold beyond which the benefits of sawdust reinforcement are outweighed by the detrimental effects on the composite's structural cohesion and load-bearing capacity [19].

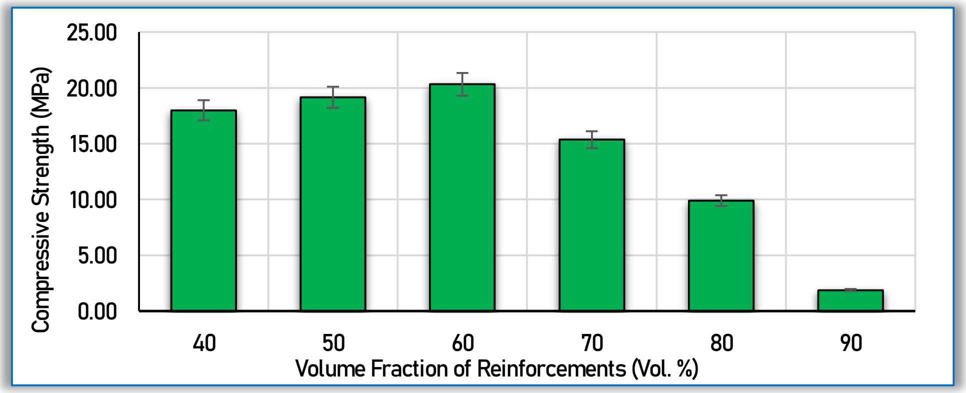

Figure 9: Compressive strength of composites with various volume fraction of sawdust reinforcements

The flexural strength results are presented in Figure 10. The results shows that the composite with 60 vol.% sawdust achieves the highest flexural strength of 8.36 MPa. This indicates a beneficial relationship between sawdust content and flexural strength up to this proportion, where the fibres enhance the composite's resistance to bending forces by effectively distributing stress and reinforcing the cement matrix. However, beyond 60 vol.% sawdust, the flexural strength decreases. This decline is likely due to excessive sawdust content, which leads to inadequate bonding with the cement matrix, increased porosity, and weakened structural integrity [32]. Therefore, while moderate sawdust reinforcement improves flexural strength, an overabundance results in decreased performance due to reduced matrix cohesion and increased defect sites.

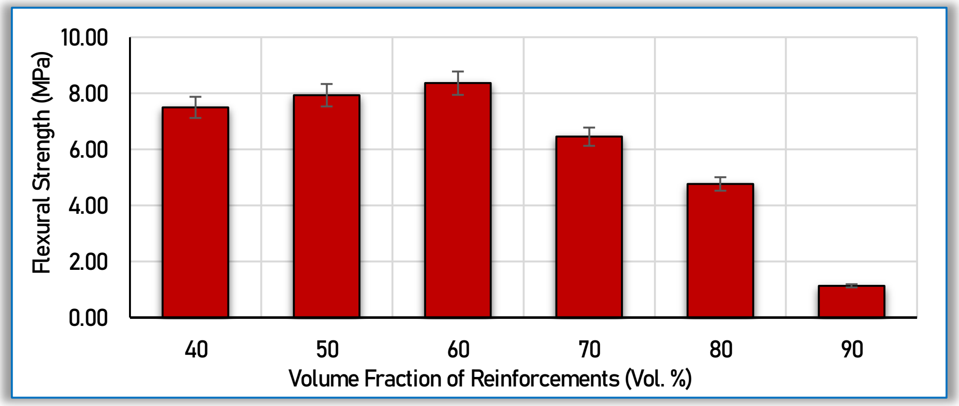

Figure 10: Compressive strength of composites with various volume fraction of sawdust reinforcements

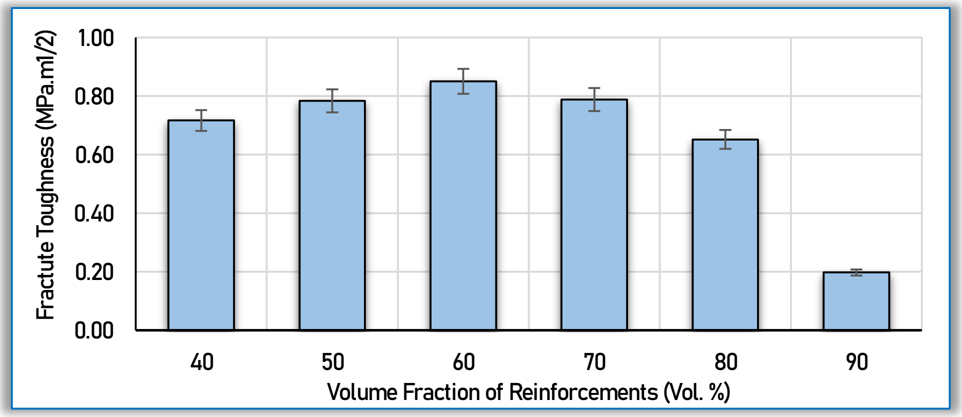

Figure 11: Fracture toughness of composites at different volume fraction of sawdust reinforcements

The fracture toughness results (Figure 11) indicate that the composite with 60 vol.% sawdust has the highest value of 0.85 MPa.m$^{1/2}$. As the sawdust content increases up to 60 vol.%, there is a notable improvement in the composite's fracture toughness. This enhancement is due to the sawdust fibers effectively bridging cracks and reinforcing the cement matrix [24]. However, when the sawdust content exceeds 60 vol.%, the fracture toughness decreases. This reduction is likely caused by an overabundance of sawdust, which results in poor bonding with the cement matrix, increased porosity, and reduced structural integrity. Therefore, while an optimal amount of sawdust reinforcement enhances fracture toughness, too much sawdust weakens the composite.

Figure 12 presents composite hardness at different volume fractions of sawdust. The results reveal a decreasing trend as the volume of sawdust fiber increases. The composite with 40 vol.% sawdust exhibits the highest hardness value of 42.99 HRBS, while the composite with 90 vol.% sawdust shows the lowest hardness value of 24.4 HRBS. This decline in hardness with increasing sawdust content can be attributed to the softer nature of sawdust compared to Portland cement. Higher fiber content results in a larger proportion of the composite being occupied by the less rigid sawdust, leading to an overall reduction in hardness [33]. Additionally, increased sawdust content may cause higher porosity and weaker interfacial bonding within the composite, further contributing to the observed decrease in hardness [34].

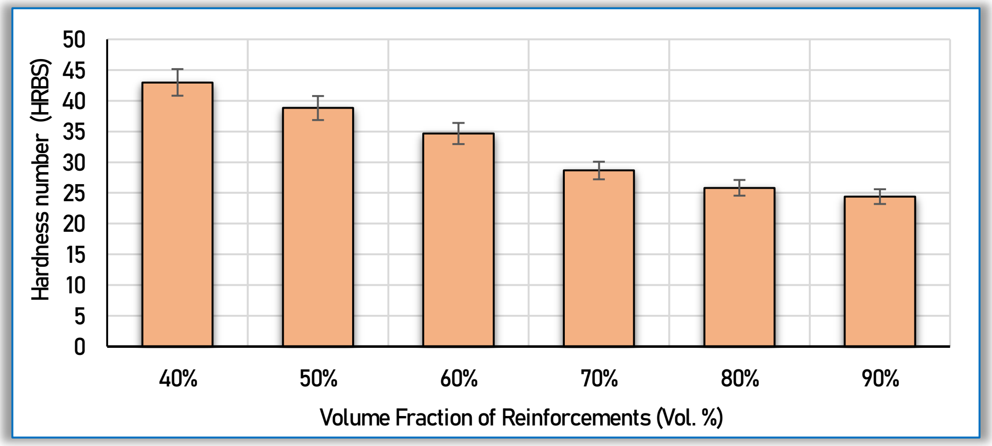

Figure 12: Composite hardness at different volume fraction of sawdust reinforcements

4. SUMMARY AND CONCLUSION

- This study investigated the effects of varying volume fractions of sawdust reinforcement on the physical and mechanical properties of Portland cement composite bricks. Sawdust was mixed with Portland cement to form composites with fiber content ranging from 40 to 90 vol.%. Physical characterization tests, including water absorption, bulk density, and apparent void volume, alongside mechanical tests for compressive strength, flexural strength, fracture toughness, and hardness, were conducted.
- The water absorption test revealed an increase in water uptake with higher sawdust content, peaking at 41.78% for 90 vol.% sawdust, indicating the hydrophilic nature of sawdust. Bulk density results showed an upward trend with increasing fiber content, reaching a maximum of 193.33 kg/m³ at 90 vol.% sawdust. Apparent void volume generally decreased with higher fiber content, suggesting better packing and reduced porosity at lower fiber contents.
- Mechanical tests demonstrated that the compressive strength and flexural strength both peaked at 60 vol.% sawdust, with values of 20.32 MPa and 8.36 MPa, respectively, before declining at higher fiber contents. Similarly, fracture toughness was highest at 60 vol.% sawdust with a value of 0.85 MPa.m$^{1/2}$, while hardness exhibited a decreasing trend with increasing sawdust content, the highest value being 42.99 HRBS at 40 vol.% sawdust.
- The optimal sawdust content for reinforcing Portland cement composites, based on this study, is 60 vol.%. At this fiber content, the composites exhibit the best balance of compressive strength, flexural strength, and fracture toughness. However, increasing the fiber content beyond 60 vol.% results in reduced mechanical properties, likely due to increased porosity and weaker fiber-matrix bonding.
- These findings suggest that sawdust, when used in appropriate proportions, can be a viable reinforcement material for eco-friendly and sustainable building materials, effectively addressing both environmental waste management and material performance requirements.

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