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Preliminary Evaluation of Aluminium-Rice Husk Ash Composite for Prophalytic Knee Brace Production

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Abstract: Knee injury is common in contact sports and the drive to prevent or mitigate its effect has gotten research and orthopaedic attention over the years. Currently, knee brace is the most utilized facility for managing knee discomfort, whether as a preventive measure or after meniscus surgery and dislocation. In this study, we carried out a preliminary evaluation on aluminium-rice husk ash (Al-RHA) composite for the solid biomaterial portion of a prophylactic knee brace. Four composites were produced from aluminium and varied proportions of rice husk ash in the ratio of 8:2, 6:4, 4:6 and 2:8, respectively. We employed a two step-stir casting process in the production of the composite and the four composite specimens as well as a control specimen (0% rice husk ash) were subjected to both tensile and compression tests. The displacements, strain, and densities for each test were obtained. The densities of the composites decreased with increase in the percentage volumes of rich husk ash as the value decreased from 193.02kgm^{-3} (for the control sample at 0%) to 164.83kgm^{-3} at 8% RHA addition, respectively. The experimental results for the strain and displacement were validated using finite element analysis (FEA) which confirms the experiment that aluminium-rice husk ash composite gives best mechanical properties for production of the prophylactic knee brace at 4% proportion of rice husk ash.

Keywords: Aluminium Alloy, Composite, Density, Finite Element Analysis (FEA), Kneel Brace, Rice Husk Ash (RHA)

1. Introduction

Of all kinds of knee injury, sport injury accounts for about 71% of the risks involved [1]. In sports involving constant collision such as ice hockey and rugby, contact or non-contact knee injuries are recognized as being particularly high. For example, in football, a report reveals that of all North American football players, 81% sustain knee injuries, and 11–49% of the reported cases are knee joint injuries, with about 64% involving the anterior cruciate ligament [2]; thus, requiring a protective device such as a knee brace to prevent injuries especially during training. Over the years, knee braces have been proven to improve the alignment of the knee joint. The external device is utilized extensively by both recreationally active and competitive athletes, to reduce their risk from knee disorder [3]. Currently used knee braces fall into four categories: the supportive, which aids in stabilizing joints for weight-bearing, the functional brace, used to motorize with the support of a coil or spring; the corrective knee brace design to correct a skeletal deformity such as club foot, and the protective, such as the popular prophylactic knee brace [4]. Of all, prophylactic knee braces are made with the capacity to protect athletes from sustaining devastating injuries. Although there is yet no conclusive evidence about the efficiency of the prophylactic knee braces to protect knee joint ligament from injury, the device helps to protect from inhibiting knee mobility, especially in sports [1].

Generally, the prophylactic knee brace is made from different materials, but the solid portion is often is made of composites to achieve high mechanical strength [5]. An obvious advantage with using composites is attributed to their low weight, high strength and stiffness. Typically, a composite is composed of two parts; the first being a stiff, strong reinforcement that contributes strength and rigidity, and is distributed evenly in a second material, referred to as the matrix, which binds and protects the reinforcements [6]. Material scientists and engineers are working hard to investigate materials that are suitable for producing composites with expected mechanical properties. Some researchers have shown that rice husk offers good mechanical properties when combined with selected materials to form composites, due to the presence of silica. In addition, rice husk is cheap, has low-density, and possesses superior mechanical and physical properties [7]. Rice husk, which is the protective outer layer of the rice grain, is abundant mostly in Asian and African rice growing countries, and the husk is generated as a by-product from rice mills [8].

Previous studies have shown that the raw material contains relevant properties such as silicon (Si), silicon nitride (Si_3N_4), silicon carbide (SiC), silica (SiO_2) and graphene [9]. It also contains both organic and inorganic constituents of 74% and 26%, respectively. The organic components include cellulose, hemi-cellulose, lignin, L-arabinose, methylglucuronic acid, D-galactose, proteins, and vitamins which can be extracted from the husk during charring processes [10]. On the other hand, the major inorganic component of rice husk ash is SiO_2 (80%), while the minor inorganic constituents are; magnesium oxide, iron oxide, sodium oxide, sulphur-trioxide, potassium oxide, calcium oxide and alumina at 0.25%, 0.41%, 0.67%, 0.78%, 1.45%, 3.84% and 3.93% respectively [9]. Futhermore, when subjected to high temperature range during burning process, crystalline and amorphous forms of silica can be obtained from the husk [11]. These interesting properties of rice husk ash have been reported for potential high wear and corrosion resistance in material applications such as the development of low-cost Al-Mg-Si matrix hybrid complexes with complementing reinforcement due to the presence of silicon carbide [12-14].

Despite the various potential applications, RHA and aluminium cans are yet to be totally utilized in Nigeria, influencing the choice of the materials for this study which focuses on evaluation of aluminum-rice husk ash metal matrix composite for production of the solid portion of a prophylactic knee brace.

2. Materials and Methods

2.1. Materials

The principal materials used in this research were aluminium beverage cans and rice husk ash. The aluminium cans were obtained from scavengers in Ibadan, Oyo State, while the rice husk was obtained from a rice milling centre in Makurdi, Benue State, Nigeria. Basically, the aluminium can is made up of two aluminium alloys; 5182 ASTM for the lids and 3004 ASTM for the main body. According to a report by Hosford [15], both alloys can withstand pressure up to 0.621N/mm^2. Aluminum was considered as the base material because it is of interest in production of light weight products and biomedical applications due to its high scrap metal value, density (2.7g/cm^3), corrosion resistance, and ability to get recycled and reinforced by heating, which are of interest in the production of knee braces [16].

2.2. Experimental Procedures

The production of the rice husk ash involved a combination of open air burning and closed air burning methods. We used a simple, half-cut metallic drum as burner for the open-air combustion. The obtained rice husk was sun dried for about 5 hours after which 37kg was poured into the drum. 500ml combustible hydrocarbon liquid (paraffin oil) was used to ignite the rice husk in the drum and was left to burn for 24 hours. The long burning process, as expected, changed the colour of the husk from yellow to black due to charring of organic matter. Afterwards, the material was subjected to heat treating in an electric furnace for about 18 hours at a temperature of 850°C to reduce the carbonaceous and volatile constituents of the ash. Consequent of the continuous heat treatment, the completely burnt husk changed from black to greyish pink colour. Thereafter, the rice husk ashes were allowed to cool in the furnace for about 24 hours.

For the aluminium cans, they were thoroughly rinsed in a distilled water and sun dried for about 10 hours. Then, the aluminium cans were charged into a gas-fired crucible furnace and heated to a temperature of 750 ± 30°C. Potassium Chloride (80g) was then added as flux so as to coagulate impurities as slag, which was removed using a perforated ladle. The refined liquid alloy, cooled in the furnace to a semi-solid state at a temperature of about 600°C, was then withdrawn and cast into ingots of 4500g, 4410g, 4320g, 4230g and 4140g (each with a tolerance of ±5g), 100%, 98%, 96%, 94% and 92% of 4500g respectively. An external temperature probe was used throughout to monitor the temperature of the furnace.

Next, two step-stir casting process was performed in accordance with Alaneme [17] to produce the composites. For each of the proportion, the required rice husk ash was preheated at 250°C to remove moisture and to improve wettability with the alloy melt. The aluminium cast ingot was charged into the gas crucible furnace and allowed to melt; starting with the 4140g ingot (92% of 4500g) after which 360g preheated RHA (8% of 4500g) was then added gradually to the molten alloy with continuous stirring for 5-10minutes for proper mixing. The composite slurry was then super-heated to 800 ± 30°C and manually stirred for 10 min to improve distribution of the particulates in the molten alloy. Tensile and compressive test specimens (Figure 1) were then cast from the molten composite in prepared sand moulds, dried by blow torch. The cast was then allowed to cool and solidify in the mold cavities before withdrawal (Figure 1). This process was repeated for other proportions (92% Al with 8% RHA, 94% Al with 6% RHA, 96% Al with 4% RHA, 98% Al with 2% RHA, and 100% Al with 0% RHA) to cast the composites.

Figure 1. *Solidified composites; A: compressive ASTM E9-89a tensile specimen ASTM E8/E8M-09 and B: produced from the aluminium alloys and RHA.*

2.3. Property Tests

The density of each composite was determined using the equation 1 below. The mass (m) of each sample was determined using an electronic weighing balance; the volumes (v) of the compressive test samples were determined by using the formula for calculating the volume of a cylindrical shape (equation 2), while those of the tensile test samples were determined by multiplying the cross-sectional area by the height (volume of a rectangular shape, assuming all the sample is a full rectangular shape).

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

where

$$v = (\pi r^2 h) \tag{2}$$

Tensile and compression tests were carried out on the Universal Tensile Machine (UTM), model OKH-600 digital display at a speed of 0.45KN/s. Five different tests were conducted and the average fracture load value for each test was taken accordingly, as shown in table 1 and table 2 respectively. The weight, breath, width and length of each tensile piece were taken and recorded, so also were the weight, diameter and height of each compression piece (see dimension of test specimen in table 4).

3. Results and Discussion

3.1. Density

The densities of the composite samples are shown in table 1. Density decreased with increase in the percentage volumes of rich husk ash as the value decreased from 193.02kgm^{-3} (for the control sample at 0%) to 164.83kgm^{-3} at 8% RHA addition. Invariably, the decrease in densities is ascribed to the relatively low density of rich husk ash reported to as, compared to the relatively high density of the aluminum alloy reported to be about 397.114kgm^{-3} and 2700kgm^{-3} respectively [16, 18].

Table 1. *Densities of the composites.*

Proportion (%)	Displacement (mm)	Weight (g)	Density (Kg/m^3)
0	9.37	111.05	193.02
2	11.30	137.91	165.55
4	10.24	118.29	165.54
6	11.51	128.49	182.64
8	13.30	117.77	164.83

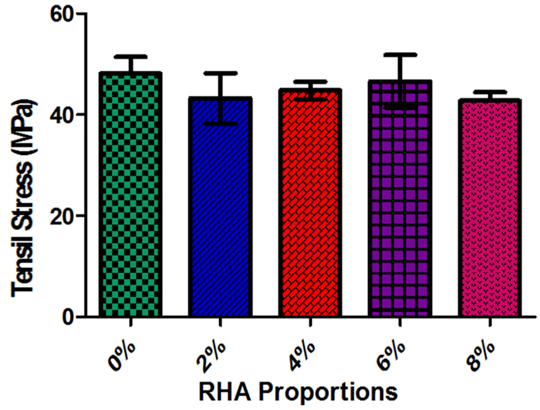


Figure 2. *Variation of Ultimate Tensile Stress (UTS) of Al-RHA.*

3.2. Tensile Test

The results of the tensile test are presented in Figure 2. Just like the density, the ultimate tensile strength (UTS) of the composites decreased from 48.18MPa to 43.28MPa at 0% and 2% proportion of rich husk ash, respectively. The maximum composite tensile strength (48.80MPa) was obtained at 8% rich husk ash addition, revealing that increase in the ash percentage above 4% in the alloy increases the strength, perhaps due to increase in the proportion reinforcements in the matrix. This is an advantage for the composite, implying decreased site for cracking, leading to increase in the tensile strength. This result is against the report made by Usman, A. M et al and Magibalan & Palanisamy et al from their studies [18, 19].

Table 2. *Compression test Result.*

Proportion (%)	Applied loads (KN)	Displacement (mm)	Ultimate tensile stress (MPa)	Strain	Modulus of Elasticity (MPa)	Weight (g)	Density (Kg/m^3)
0	193.12	41.30	206.50	0.41	503.66	152.24	2533.33
2	195.54	36.36	275.17	0.42	655.17	146.80	2440.21
4	211.82	41.30	307.72	0.49	628.00	133.18	2216.03
6	199.52	35.32	282.29	0.41	688.51	147.15	2446.48
8	194. 45	40.61	275.03	0.48	572.98	134.60	2239.55

3.3. Comprehension Test

The comprehensive results of the compression test are presented in Table 2 and the variation of ultimate compression stress, strain modulus of elasticity and density are shown in Figure 3. The variation of compressive strength with addition of rice husk ash indicates that the compressive strength is highest at 4% addition of rich husk ash, which has a value of 307.72MPa compared with the value of the control sample (205.50MPa at 0%) and the last sample where the value decreases to 275.03MPa at 8%. Increase in compressive strength may be due to the base alloy hardening influenced by the rice husk ash particles [18]. However, the decrease at 6% and 8% may be due to some technical errors during testing. Furthermore, the maximum tensile strength in this study (48.80MPa at 8% RHA) is in good agreement with the results reported by Aleneme [17] who used silicon carbide and reported that the UTS increased from 80.84MPa at 0% to 94.21 MPa at 15%.

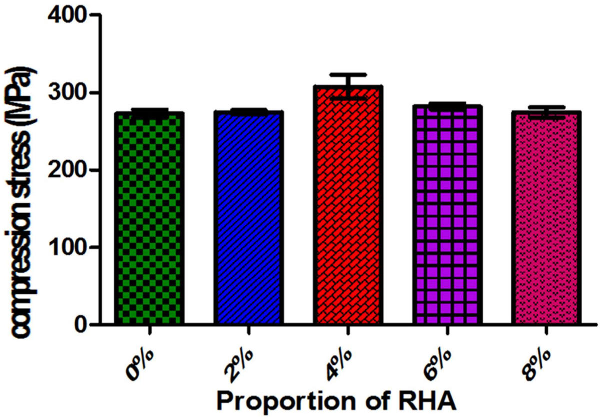
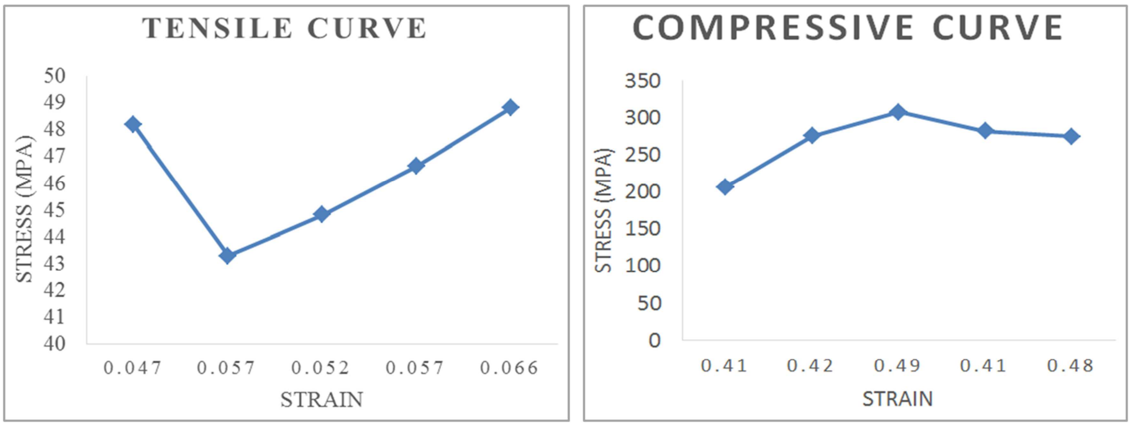


Figure 3. *Variation of Ultimate Compressive Stress (UCS) of Al-RHA.*



(a) (b)

Figure 4. *Stress-strain curve depicting the variation in the (a) tensile and (b) compressive test results.*

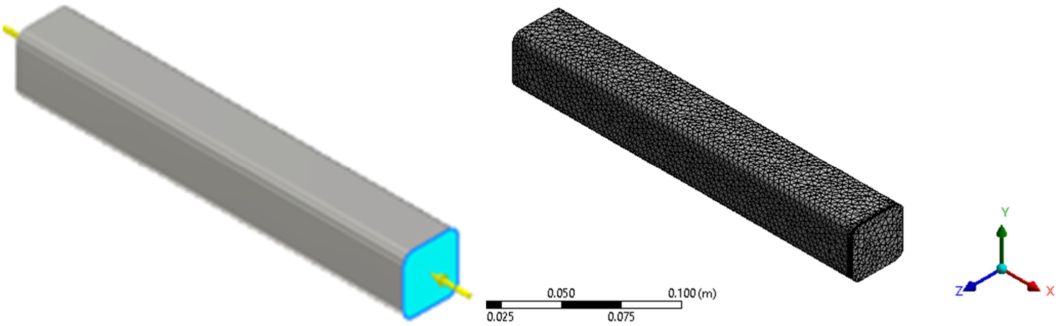


Figure 5. *Developed 3D model of the composite showing direction of applied compressive force (left) and the mesh fineness (right).*

3.4. Computational Validation

This section presents a computational validation of the compressive test on the composite using finite element analysis (FEA). A realistic 3D model of the composite (figure 5) was developed on Autodesk Inventor Professional 2019 software following physical measurement of the composite produced for the experiment. The static simulation was performed to validate the results for strain and displacement behaviours obtained from the experiment. The "Compression only" constrain option was imposed in x-direction to ensure total deformation of the composite model, and compressive load was applied to the model at different proportion of rice husk ash (see table 2). After a convergence study, a mesh of 36394 nodes and 21380 elements was used. Also, a displacement convergence rate of 0.233% was obtained on the Von Morh stress curve. Aluminum composite was selected for the material, and the properties computed were in close range to the properties of the actual produced composite (see in tables 3 and 4).

Table 3. *Description of the 3D model dimension.*

Symbol	Description	Dimension (mm)
G	Gauge length	50
B	Length of grip distance	100.0
L	Overall length	200.0
W	Width of narrow parallel	12.5
C	Width of grip section	20.0
T	Thickness	12.5
A	Length of reduced section	57.0
R	Radius of fillet	12.5
D	Diameter	30.0
H	Height	85.0

Table 4. *Physical properties used in the finite element simulation of the idealistic aluminum-rice husk composite.*

Material properties	Magnitudes
Mass Density	2.7 g/cm^3
Yield Strength	275 MPa
Ultimate Tensile Strength	310 MPa
Young's Modulus	68.9 GPa
Poisson's Ratio	0.33 ul
Shear modulus	25.9023 GPa
Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5

3.5. Finite Element Analysis of Stress and Displacement

As shown in figure 6A, at 0% proportion of rice husk, the maximum displacement of the material from its original length (200 mm) under a compressive load of 193.12KN is 34.53 mm, approximately 35.0 mm. When compared with the experimental value of 41.30 mm presented in table 2, there was significant difference of about 6.00 mm lesser compression. However, the difference in strain values was not wide. The simulation in figure 6A' shows an equivalent strain of 0.45 ul compared to a value of 0.41 ul gotten from the experiment. Notably, the simulation reveals that the composite would begin to resist shear at a displacement of 35.53 mm for a load not exceeding 193 KN. Also, there is uniform stress distribution across different regions in the composite model as seen in figure 6A, and the maximum stress appears at the extreme, precisely at the point of contact between the composite and the load. In addition, there is zero or very minimal displacement at the centre of the composite model due to less stress in response to the applied load.

The displacement and equivalent strain for a load of 195.54 KN at 2% proportion of rice husk is presented in figure 6B and B', respectively. The result shows little variation when compared to the outcome of applied load at 0% proportion of rice husk ash. However, the experimental and computational variables were in closer range with values of 36.36 mm and 0.42 ul, and 34.96 mm and 0.46 ul, for the displacement and equivalent strain, respectively. Obviously, both the displacement and strain increased with increased proportion of rice husk and with slight increase in the load magnitude.

At 4% proportion of rice husk ash (shown in figure 7C) a load of 211.82 KN was applied to the composite model as done in the experiment. Here, the composite model displaced 37.87 mm from the 200 mm original length with approximate strain value of 0.50 ul, equal to the obtained value from the experiment. From the density reading in the experiment, the composite is claimed to have the lowest density at this applied load and range of strain. The computational validation is most precise at this range of rice husk proportion. Accordingly, at 6% proportion of the rice husk, shown in figure 7C', a load of 199.52 KN was applied to the composite model. The experimental and computational results in this case are also in close range with values of 35.32 mm and 0.41ul, and 35.68 mm and 0.5ul for maximum displacement and equivalent strain, respectively.

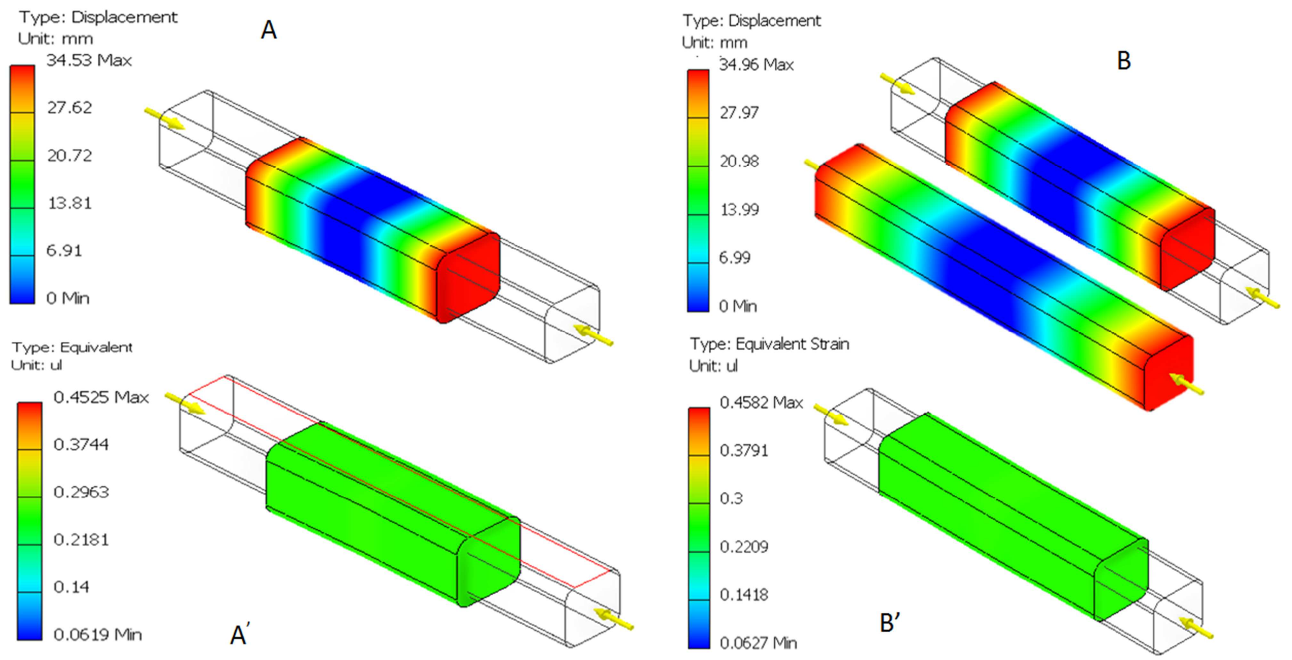


Figure 6. *Static simulation for displacement (A and B) and equivalent strain (A' and B') for loads of 193.12KN (left) and 195.54 KN (right) respectively.*

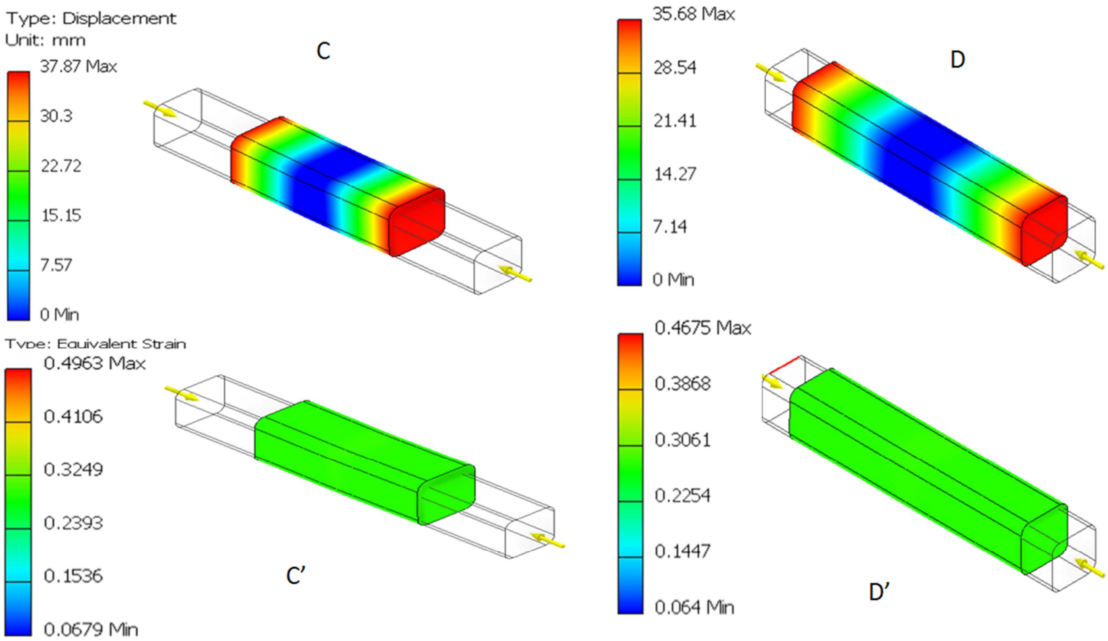


Figure 7. *Static simulation for displacement (C and D) and equivalent strain (C' and D') for loads of 211.82 KN (left) and 199.52 KN (right) respectively.*

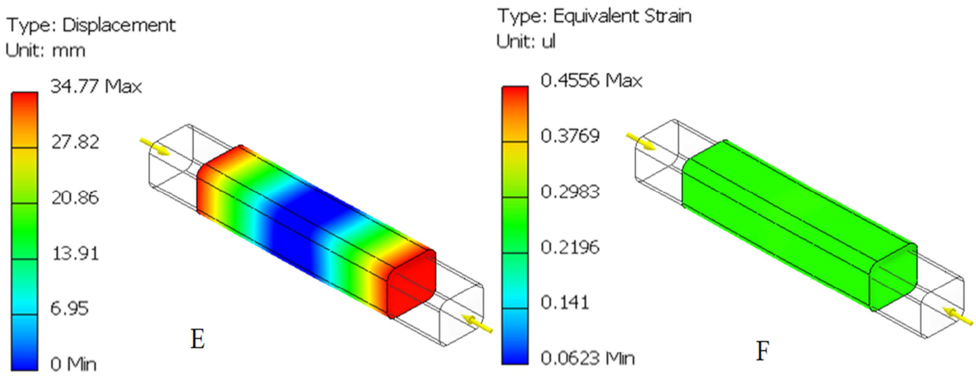


Figure 8. *Static simulation for displacement (E) and equivalent strain (F) for a load of 194.45 KN at 8% proportion of RHA.*

To complete the validation, a final compressive load of 194. 45 KN was applied to the model at 8% of rice rusk. The result here is similar to the computational result at 0% of rice husk, though with higher values of maximum displacement and equivalent strain. As shown in figure 8, the maximum displacement in the composite model is smaller (34.77mm) compared to the experiment (40.61 mm), but the maximum strain is in relatively good agreement with values of 0.48 ul and 0.46 ul for experiment and simulation, respectively. It is important to note that the stress behaviour on the composite material for the different loads and varying proportion of rice husk was similar all through the simulations, except for the minimal difference in the displacement and strain. Considering the overall length of the composite (200 mm), the displacements can be said to be in reasonable range; the overall maximum displacement is 37.87mm, approximately 19% reduction.

4. Conclusion

In this study, we investigated the suitability of aluminum-rice husk ash for production of the solid portion of prophylactic knee brace. Rice husk ash was experimentally infused into molten aluminum at varying proportions from 2 to 8% to determine at what proportion the composite would exhibit the required density property for knee brace production reported in literature. The compressive and tensile tests reveal that the composite exhibits the best density at 4% proportion of rice husk ash with a value of 2216.03 Kg/m^3. Furthermore, the experimental results for the displacement and strain for the five applied loads were validated through finite element simulations. The validation confirms the assertion from the experiment that the composite has best mechanical properties at 4% proportion of RHA, and the simulated displacement and strain in all cases were generally in close range with the experiment. The composite in this work is expected to be used with other materials such as foam, plastic, or elastic material and straps to give the expected protective measure, especially to prevent unusual rotation, implying that the displacement in the test sample must be minimal. This goal was achieved since the composite's overall maximum displacement was confirmed from both the experiment and simulations as 37.87mm of the 200mm overall length. The minimum displacement implies that the composite is less stiff, which is a desired property for the proposed knee brace.

5. Recommendation

This work examines the performance of a novel composite material consisting of an aluminum alloy reinforced with rice husk waste material for production of the solid component of a prophylactic knee brace. The current paper reports, in particular, the preliminary and technical evaluation of the composite that could make it of potential interest for future work. Therefore, subsequent evaluations should provide close connection between the composite microstructure, the properties and performance, which is the next phase of our study.

Conflict of Interest

The authors declare that they have no competing interests.

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