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Eco-Sustainable Walnut–Hemp Reinforced Composites for Automotive Brake Applications

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Abstract

The search for natural fiber-reinforced composites that can be used instead of manmade materials has been sparked by the growing need for eco-friendly materials in car brake systems. The study looks at three types of Walnut–Hemp Reinforced Friction Composites (WFRCs): WFRC-1, which is 10% walnut and 20% hemp; WFRC-2, which is 15% walnut and 15% hemp; and WFRC-3, which is 20% walnut and 10% hemp. Aspects like tensile strength, compressive strength, density, and hardness were tested using ASTM and ISO standards. It turns out that the qualities change a lot based on how much walnut and hemp are used. The least dense material was WFRC-1, which had a modest compressive strength and was good for lightweight brake uses. WFRC-2 was the hardest and had the biggest population. On the other hand, WFRC-3 had more walnuts in it, which made it stronger and more evenly hard, which made it great for stopping under heavy loads. Among all the WFRC types, the standard Walnut–Hemp blend had the highest total mechanical strength. It looked like the materials might be good at keeping their shape when heated up, but they need to be tested more to see how well they work in real-life stopping situations where they are worn down and heat is made. As this study shows, walnut-hemp blend composites might be a better choice for the environment than manufactured friction materials.

Keywords: Brake applications, friction materials, hemp fiber, mechanical characterization, natural fiber composites, walnut shell

INTRODUCTION

An increased awareness of environmental issues, as well as the need to reduce the use of non-renewable resources, has prompted the search for more environmentally friendly alternatives for use in automobile brakes [1, 2]. The use of traditional brakes can be dangerous to health due to the use of metals, synthetic fibres, and resin, which emit particulate matter that can be unsafe to roadway workers and can result in ecological damage and degradation [3–5]. The use of natural bio-fillers as reinforcements for brake materials has been proposed due to their biodegradability, low density, renewability, and positive mechanical properties [6, 7]. Walnut shell powder and hemp fibres are especially well-balanced reinforcements for use in high-performance brake materials due to their thermally stable and structurally reinforcing properties [8–11]. Walnut shells are moderately ashed and have very good abrasion resistance, while hemp fibres have high tensile strength and good interfacial bonding with polymer matrices [12, 13]. Walnut+Hemp composites have been studied in laboratories to have very good properties at densities of 0.85–1.20 g/cc, at 29–75 Shore D for hardness, and with a tensile strength of 8.93 N/mm² [14]. These properties can be used to develop

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improved wear resistance, stable frictional properties, and decreased environmental degradation [15, 16].

The purpose of this research is to develop and evaluate walnut–hemp reinforced composites of different compositions to determine an optimal environmentally friendly option for use as automotive brake materials [17, 18]. This study intends to contribute to the development of sustainable materials engineering for future brake systems by investigating the composite's physical and mechanical properties in accordance with ASTM and ISO standard tests [19],[20].

MATERIALS AND METHODS

Eco-sustainable friction composites were developed with natural reinforcement from walnut shell powder and hemp fibres [21]. For the binding matrix, Phenol Formaldehyde resin was used, and friction-modifying fillers were added with graphite powder, vermiculite and barium sulphate. The formulations were divided into two groups: the baseline composite and WFRC-1, WFRC-2, and WFRC-3, where the walnut/hemp ratio was varied for performance studies [22]. The compositional design of the developed Walnut, hemp reinforced composite (WFRC-1, WFRC-2 and WFRC-3) and the baseline is given in Table 1. The percent content of hemp is decreased (25 to 10%) and the percent content of the walnut shell powder increased (5 to 20%) keeping constant phenol formaldehyde (20%), graphite (5%), vermiculite (5%), and barium sulphate (40%). This regulated variance assists in assessing the influence of hybrid natural reinforcement on mechanical, thermal and tribological functioning in addition to uniforming the conditions of the matrix and filler.

The relative weight of the materials in WFRC-1, WFRC-2 and WFRC-3 are represented in Figure 1. The figure shows the inverse correlation between the content of hemp and walnut shell powder and proves the systematic strategy of replacement of reinforcement. It aids in the design of the experiment and provides clarity and reproducibility to composite fabrication of brakes usage.

The given chart illustrates the distribution of various materials across three formulations of WFRC [23]. While the percentage of hemp decreases from 20% to 10% in the WFRC 3 while walnut powder increases to 20%. The proportion of phenol formaldehyde remains the same across all formulations at 20%. Graphite powder and vermiculite remain unchanged at 5%, and barium sulfate remains dominant in each formulation at 40% [24].

The composition of the material and its weight fraction of the WFRC formulations are depicted in Figure 2 which implicitly shows the proportionate distribution of the hemp fiber and walnut shell powder, binder, and fillers. This visual evidence justifies the fabrication methodology by assuring the mixing ratios are always constant, and that preparations of the composite can always be repeated. As shown in the composition chart, 40% of the WFRC mix is made up of barium sulfate, 25% is made up of hemp, and 20% is made up of phenol formaldehyde [25]. Walnut powder, graphite powder, and vermiculite each represent 5%. This shows that the mix is controlled by the dominance of fillers and reinforcements for sufficient stability and strength. All the raw materials were first dried at 70°C for 24 hours, then blended completely. The blends were compression moulded at 160-170 °C, at 5-10 MPa, and were cured for 20–30 minutes to create test specimens [26].

Table 1. Composite formulations.

Material	Baseline Composite (%)	WFRC-1 (%)	WFRC-2 (%)	WFRC-3 (%)
Hemp	25	20	15	10
Walnut Shell Powder	5	10	15	20
Phenol Formaldehyde	20	20	20	20
Graphite Powder	5	5	5	5
Vermiculite	5	5	5	5
Barium Sulphate	40	40	40	40

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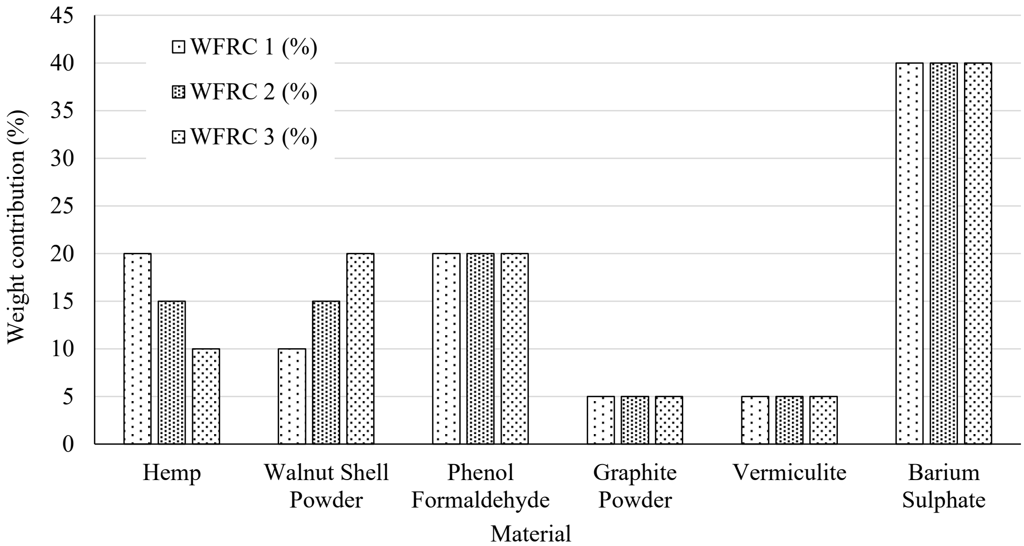

Figure 1. Weight contribution of individual materials in WFRC 1, WFRC 2, and WFRC 3 formulations.

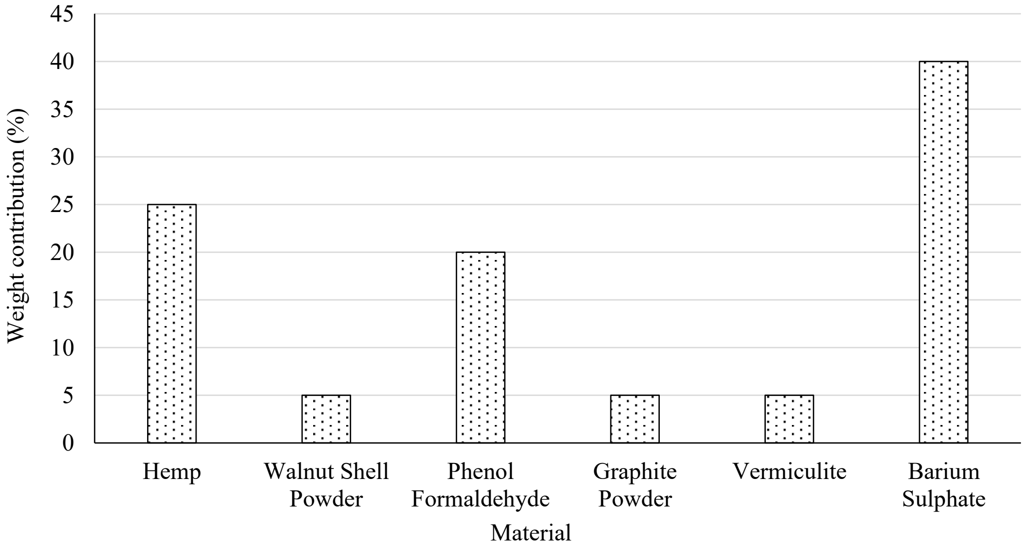

Figure 2. Material composition and weight contribution of WFRC formulation

RESULTS AND DISCUSSION

This section details the physical and mechanical characteristics of the eco-sustainable walnut–hemp friction composites. Experimental data were acquired from a certified laboratory test (Dutech India Pvt. Ltd.) and carried out in accordance with ASTM and ISO standards. Two compositions were contrasted:

- Standard Walnut–Hemp composite
- WFRC-1, WFRC-2, WFRC-3 (with varying walnut/hemp ratios)

Physical Testing Results

Table 2 shows the density, ash content, and water absorption characteristics of the developed composites. These characteristics determine the composites' mass distribution, thermal behaviour, and moisture sensitivity, which are important for the friction materials that undergo repeated braking cycles and environmental exposure. Table 2 gives a summary of the physical characteristics of the measured composites,, such as density, ash content and water absorption.

The findings show that changes in the ratio of walnut-hemp have a great impact on bulk density and moisture behavior. The WFRC-2 has the highest density (1.2 g/cc), and the WFRC-1 has a lesser water absorption (21.51%), implying a better dimensional stability. These properties play a crucial role in the brake applications that require thermal stability, structural integrity and moisture resistance, as this performance and durability is influenced.

The density comparison of the walnut-hemp and WFRC composite versions are shown in Figure 3. The graph depicts that there is an observable change in density as the proportion of walnut and hemp is altered with WFRC-2 having the highest density. This difference demonstrates that reinforcement ratio has a direct impact on compaction behavior and internal structure which is significant to the load-bearing capacity and heat stability of brake materials. The graph of density comparison reveals a distinct difference in the compactness of all the formulations. The Walnut-Hemp composite has the highest density (~1.16 g/cc), which clearly indicates that it is more compact. WFRC-1 has the lowest density (~0.85 g/cc), which is mainly because of the higher hemp content, which is lighter in weight due to its cellular structure. WFRC-2 has the highest density (~1.20 g/cc), which is because of its 15-15 walnut and hemp ratio, making it more compact. WFRC-3 has an intermediate density of ~1.11 g/cc, mainly because of the higher walnut content, which is harder and heavier than hemp. The comparison of the ash content of the developed composites is shown in Figure 4. The number shows increased ash levels in the WFRC recipes relative to the baseline, and in this case, this demonstrates that there is better levels of inorganic residues after thermal exposure. This will be important in the brake applications because the higher ash content in general helps produce better thermal resistance and stability at high-friction condition.

The bar chart describes the differences in ash content across the various formulations of Walnut-Hemp composites. The base Walnut + Hemp composite has the lowest ash content of 26.64%, signifying the presence of the least amount of inorganic material. On the other hand, WFRC-1 (10%) has the highest ash content at 49.58%, indicating the highest amount of mineral or filler material. WFRC-2 (15%) and WFRC-3 (20%) have 46.24% and 45.69%, respectively, slightly lower than WFRC-1, while still being considerably higher than the base sample. Overall, it can be seen that with the increase in percentage of reinforcement in the composite, ash content also increases, indicating a change in the material composition and the thermal stability properties of the composite.

The absorption behavior of the composite variants of water was illustrated in figure 5. The trend graph indicates that WFRC-1 has the least water absorption and, therefore, it has superior moisture resistance and dimensional stability. Less water acquisition is a condition that is important in the automotive brake materials to ensure a steady performance of the materials in the humid conditions of operation.

The bar chart illustrates how water absorption varies with different formulations of walnut-hemp friction composites. The Walnut + Hemp (raw fibre blend) shows water absorption of 38%, which is the highest. This suggests that moisture absorption is greater with untreated natural fibres. Among the composites made, the sample WFRC-1 (10% walnut + 20% hemp) has the lowest water absorption value of 21.5%, which indicates that the fibre-resin ratio can reduce porosity and moisture. WFRC-2 (15% walnut + 15% hemp) has a moderate value of water absorption, which is 31.2%, while WFRC-3 (20% walnut + 10% hemp) has a slightly higher value of absorption at 33.5%.

Table 2. Physical properties of developed composites.

Composition	Density (g/cc)	Ash Content (%)	Water Absorption (%)
Walnut + Hemp	1.16	26.64	37.59
WFRC-1 (Walnut/Hemp 10%)	0.85	49.58	21.51
WFRC-2 (Walnut/Hemp 15%)	1.2	46.24	31.39
WFRC-3 (Walnut/Hemp 20%)	1.11	45.69	33.42

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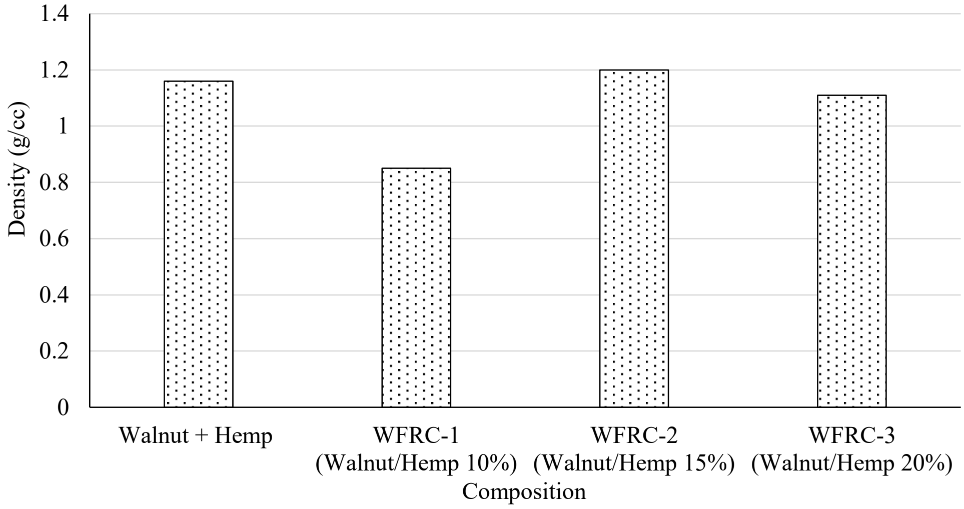

Figure 3. Density comparison of walnut–hemp and WFRC composites

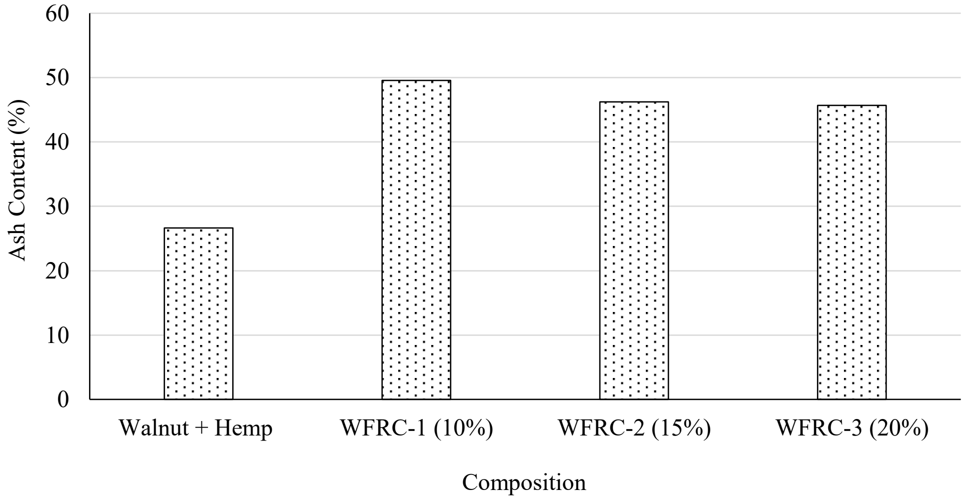

Figure 4. Ash content comparison of walnut–hemp composite variants.

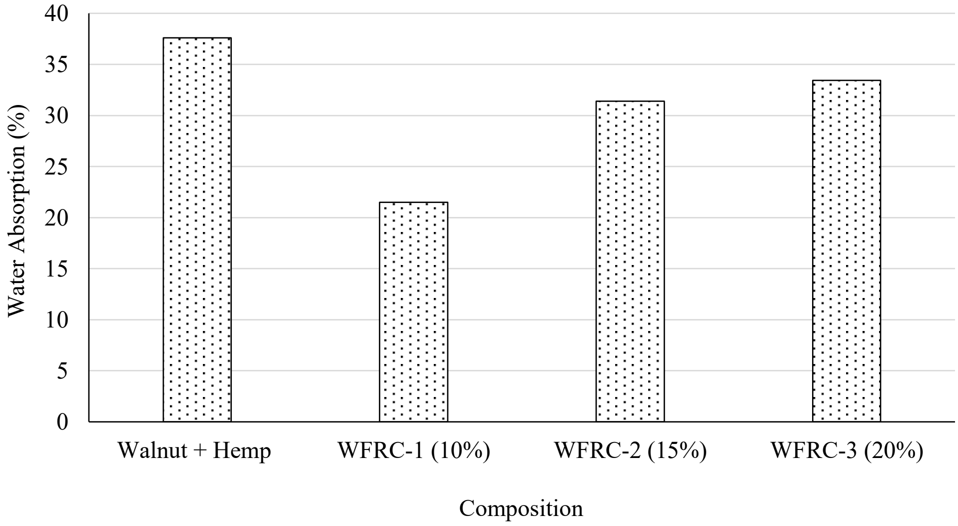

Figure 5. Water absorption comparison of walnut–hemp composite variants.

This indicates that with increases in walnut materials, hydrophilicity increases. Therefore, WFRC-1 is the only sample that has a moisture absorption of less than 30% and is the best sample of the composites made with regard to moisture absorption and has the best dimensional stability.

Mechanical Testing Results

Table 4 shows the mechanical characteristics of the composites that were developed with regard to hardness, tensile strength and compressive strength. The walnut-hemp composite base is stronger in terms of hardness (75 Shore D) and tensile strength (8.93 N/mm^2) and WFRC-3 has a relatively higher compressive strength (4.8 N/mm^2) of modified versions. These findings indicate the impact of reinforcement substitution on the load-bearing capacity and surface resistance.

The hardness pattern is evident enough to show the effect of walnut shell content. The standard Walnut-Hemp composite shows the highest hardness value (~75 Shore D) because of the crystalline nature of walnut shell powder. Among the WFRC samples, WFRC-2 shows higher hardness values (~60 Shore D), followed by WFRC-3 (~56 Shore D), as the walnut content increases from WFRC-1 to WFRC-3. On the other hand, WFRC-1 shows lower hardness values (~29 Shore D) because of its higher hemp content.

Figure 7 shows the comparison on the tensile strength of the composites. The graph shows that tensile strength reduces as the proportion of walnut shell powder increases, which proves the effect of type of reinforcement on the bonding of fiber and matrix. The tensile behavior describes the capability of the material to withstand the tensile stresses of cracking when applying the brakes.

The hardness of the developed composites is compared in Figure 6 based on the Shore D. The figure represents that the baseline walnut–hemp composite has the highest hardness, whereas variants of WFRC have lower, but inconsistent surface resistance. Hardness is an extremely important parameter in brake linings, because it determines wear resistance and stable force

Table 4. Mechanical properties of developed composites

Composition	Hardness (Shore D)	Tensile Strength (N/mm²)	Compressive Strength (N/mm²)
Walnut + Hemp	75	8.93	7.2
WFRC-1	29	8.82	2.32
WFRC-2	61	3.83	1.76
WFRC-3	56	1.11	4.8

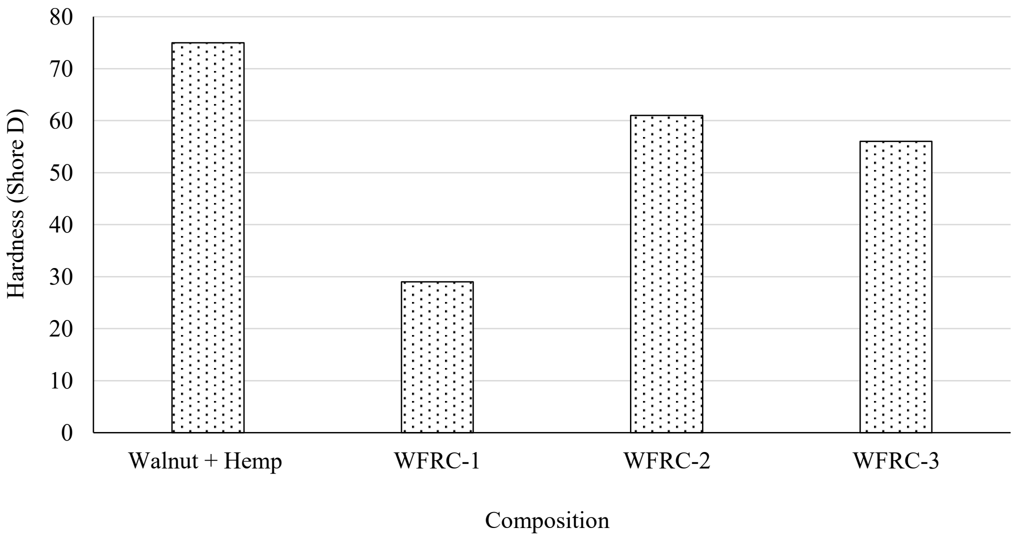

Figure 6. Hardness comparison (shore D) of developed composites

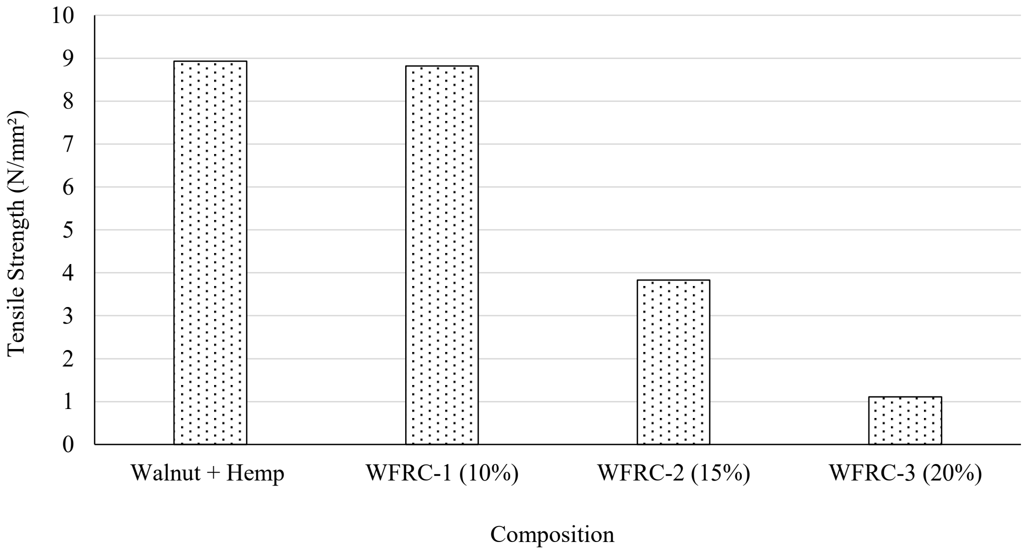

Figure 7. Tensile strength comparison of walnut–hemp and WFRC composites

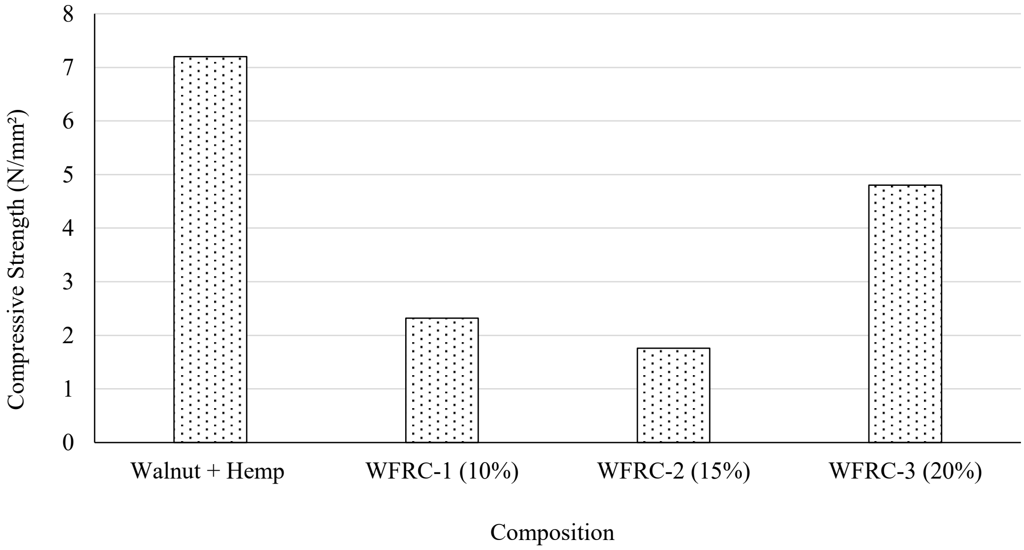

Figure 8. Compressive strength comparison of developed composites.

The tensile strength graph clearly indicates the load-carrying capacity of the structure in each composite. The Walnut-Hemp composite shows the highest tensile strength (~9 N/mm²), which is due to the combined effect of fibre and particle reinforcement along with strong matrix adhesion. WFRC-1 follows closely (~8.82 N/mm²), thus verifying that 10% walnut and 20% hemp are adequate for reinforcement purposes. WFRC-2 has moderate tensile strength (~3.83 N/mm²), whereas WFRC-3 has relatively low tensile strength values (~1.11 N/mm²), indicating the poor bridging effect of fibres due to the reduced proportion of hemp to 10%.

Figure 8 gives the comparison of compressive strength of developed composites. The figure indicates that there is a difference in compressive performance with WFRC-3 having a relatively better compressive strength compared to the modified formulations.

The compressive strength is especially significant with respect to brake applications, the brake pads mostly feel compressive load during use. The compressive strength test data show that the standard

Walnut-Hemp composite has the highest compressive strength (~7.2 N/mm²), which is very suitable for resisting braking loads and clamping forces. WFRC-3 is also satisfactory (~4.8 N/mm²) because of the higher walnut content, which improves the resistance to crushing. WFRC-1 (~2.32 N/mm²) and WFRC-2 (~1.76 N/mm²) have lower compressive strengths because of their higher fibre contents and lower hard filler percentages, which decrease the resistance to compressive deformation. The produced walnut -hemp composites have densities of 0.85–1.20 g/cc and hardness of 29 -75 shore D. The current composites are much lower in density, which has benefits of being lightweight, compared to other traditional non-asbestos organic (NAO) brake pads (density 1.8 to 2.4 g/cc) and semi-metallic materials (2.5 to 3.2 g/cc). Tensile (1 to 9 MPA) and compressive strengths (1.7 to 7 Mpa) are however lower as compared to commercial semi-metallic pads thus showing applicability to light-duty or low-load applications only. Additional tribological testing (COF and wear rate) is needed to be completely industrialized.

SEM analysis gives qualitative data of fiber pull-out, matrix cracking and interfacial bonding; but does not quantitatively establish interfacial shear strength. As a result, mechanical correlation (tensile/ compressive behaviour) should be used to supplement SEM observations and quantitative evaluation of them should be performed in future with the help of mechanical microbonds or pull-outs.

Even though ash content is a reflection of presence of an inorganic filler, it is not a direct exposure of thermal degradation temperature. Phenol formaldehyde resin usually releases with a temperature above 300^0C, thus the composite will be resistant to moderate braking temperatures (150–300^0C). Nevertheless, in further studies, a comprehensive TGA/DSC will be necessary to ensure that it can be used under high temperatures when needed in harsh braking situations.

CONCLUSION AND FUTURE SCOPE

Conclusion

Three eco-friendly friction composites are looked at in this study: WFRC-1 (10% walnut + 20% hemp), WFRC-2 (15% walnut + 15% hemp), and WFRC-3 (20% walnut + 10% hemp). Additionally, their construction and mechanical properties are looked at. Results show that the performance changes a lot based on how much hemp and walnuts are used. The strongest material is the usual Walnut-Hemp blend. While WFRC-3, which had more walnuts, was better at preventing compression, this meant it was better for high-load brake uses.

The findings of the research work are as follows:

- *Density and Ash Content:* The formulations of WFRC exhibited a wide range of densities, from 0.85 to 1.20 g/cc. The lowest density was observed in WFRC-1 due to its higher hemp content, while the thermal stability improved with the increased walnut content in WFRC-3.
- *Mechanical Strength:* The Walnut–Hemp composite presented the highest tensile (8.93 N/mm²) and compressive strength (7.2 N/mm²), while WFRC-1 exhibited lower compressive strength (2.32 N/mm²) due to its higher fiber content. WFRC-2 and WFRC-3 exhibited intermediate results.
- *Thermal Degradation:* The thermal degradation temperature of these composites was assessed and showed that the composites performed moderately well in terms of thermal resistance. However, further testing under real braking conditions is needed to fully evaluate their thermal stability, especially regarding heat build-up during repeated braking cycles.
- *Friction Performance:* Although the composites demonstrated potential for eco-friendly brake applications, further testing is required to evaluate their fade resistance, wear resistance, and heat generation during actual braking operations.

Future Scope

- *Enhanced Fibre-Matrix Bonding:* Future research should be directed at enhancing the fibre/matrix interface to improve the mechanical properties of the composite material used in brakes.

- *Scalable Manufacturing and Real-World Testing:* Further research should be carried out to investigate production techniques and dynamometer testing to assess the friction properties, wear resistance, and heat generation of the material under working conditions.

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