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Evaluation of mechanical, tribological, and physical properties of epoxy composites reinforced with *Borassusflabellifer* and glass fibers

ABSTRACT

The mechanical, physical, and wear properties of hybrid composites developed with Borassusflabelliferfiber and glass fiber as reinforcements to an epoxy resin matrix were investigated. The impact, hardness, water absorption, wear, flexural and tensile properties were studied by different laminate compositions to analyse the effect of hybridization. The composite materials were made using two different formulations where the first one (S1) contained Epoxy resin (60) + Borassusflabellifer (25) + S-Glass fiber (15), the second one (S2) contained Epoxy resin (60) + Borassusflabellifer (20) + S-Glass fiber (20). The important findings revealed that S2 was superior to S1 in a variety of properties tensile strength (S1: 35.58 MPa, S2: 41.54 MPa), impact energy absorption (S1: 5.15 J, S2: 5.54 J), Shore D hardness (S1: 72.33, S2: 74.6), and water absorption (S1: 2.4, S2: 1.2 after 24 hours). In S2, wear resistance was also increased as wear loss was less than that of S1. The high performance of S2 can be explained by the fact that the flabellifer of Borassus and the glass fibers can be adhered to each other better, which leads to an increase in the transfer of loads and a decrease in fibers pulling out. The findings indicate the possibilities of these hybrid composites to be used in structural and tribological systems and provide a compromise of lightweight and durable materials.

Keywords:*Borassusflabellifer, glass fibers, wear properties, polymer composite, and reinforcement*

1. INTRODUCTION

Over the past few years, natural fiber composites have been studied more frequently by researchers because of its outstanding formability, high level of availability, renewability, low cost, and environmentally friendly nature. The extraction of these fibers is commonly done on the different sections of plants or trees through a process that may be either traditional retting process or other sophisticated chemical or biological processes [1,2]. These composite structures are much more attractive in terms of strength-to-weight aspect than non-reinforced materials and are therefore very tempting due to their wide range of industrial usage [3]. Among them, fibers of Borassusflabellifer (Palmyra palm) are cheap and readily available and used as a reinforcing phase to epoxy matrices [4]. The advantages associated with natural fiber-reinforced composites are high specific strength, biodegradability and low weight [5].

Nevertheless, the natural shortcomings of mechanical strength and wear resistance of independent natural fiber composites are a challenge with regard to the strict structural uses. In response to this, there has been the introduction of hybridization of both natural fibers and tougher synthetic fibers or fillers. As an example, there are notable gains in tensile and flexural performance of hybrid composites with banana and coconut fibers of Prosopisjuliflorabark [6], as well as with Prosopis and jute fabrics [7]. Natural fibers system optimization It has also been demonstrated that tribological performance can be optimized in natural fibers; wear behavior of KhasKhas grass and banana fiber hybrids have been effectively modeled using Taguchi techniques [8] and with alumina added to Kevlar-epoxy composites, abrasive wear does decrease [9]. Borassus fibers exhibit better thermal stability and potential following alkali treatment [10], but their standalone performance is not as good.

A number of works have been conducted on the composites of Borassus. Alshahrani et al. [11] examined Borassus sprout fibre and biosilica composites in which tensile strength and toughness of impact are high enough to be used in

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defence and industrial applications. On the same note, Reddy et al. [12] noted an enhanced mechanical properties of sprout center stem fiber composite but with increase in fiber content, the thermal conductivity reduced. Kumar et al. [13] also proved that a maximum of 30% of Borassus petiole fiber content raised the mechanical resistance. Regardless of such advantages, epoxy resins are brittle in nature and require stiffening such as glass fibers. Glass fibers are extremely strong and resistant to thermal results; Madhu et al. [14] discovered that flexural strength was improved 59 percent with the use of glass fiber reinforcement in bagasse-epoxy composites. In addition, Zhang et al. [15] and Abd El-Baky et al. [16] indicated that the incorporation of glass fibers increases the shear strength, compressibility, and stabilizes the friction torque which is more preferred in tribological stability.

Thus, the study will examine the mechanical, wear, and physical properties of a new hybrid composite that will be made of Borassusflabellifer and S-glass fibers in an epoxy matrix. This study aims to combine the environmental friendliness of Borassus with the performance of S-glass, and thus, a synergistic enhancement in properties will be obtained to create a lightweight material that can be used in structural engineering.

2. MATERIALS AND METHODS

The mixture of epoxy LY556 and the hardener HY951 with a ratio of 60:1. To reinforce the Palmyra fiber also known as Borassusflabellifer and s glass fibers, 40% of both ratios of spreads were used [17]. Fiber reinforcement is done with the orientation of fiber is randomized using the 7 mm (25 um with aspect ratio 280:1) Borassusflabellifer and glass fiber filaments. Natural fiber as well as glass fiber is dried appropriately by blowing the fabric with air using mechanical blower to eliminate any moisture. In addition, the fabrication is achieved by fabrication technique as illustrated in Figure 1. Epoxy resin (60) + borassusflabellifer (25) + S-Glass fiber (15) (S1) and Epoxy resin (60) + borassusflabellifer (20) + S-Glass fiber (20) (S2) were used to compose the material. Sample extracts were represented in Figure 2. The samples are being cured at 5Mpa pressure with the curing temperature of 120 ℃ and curing time is 6hrs after post curing is 150 ℃ of 2hrs.

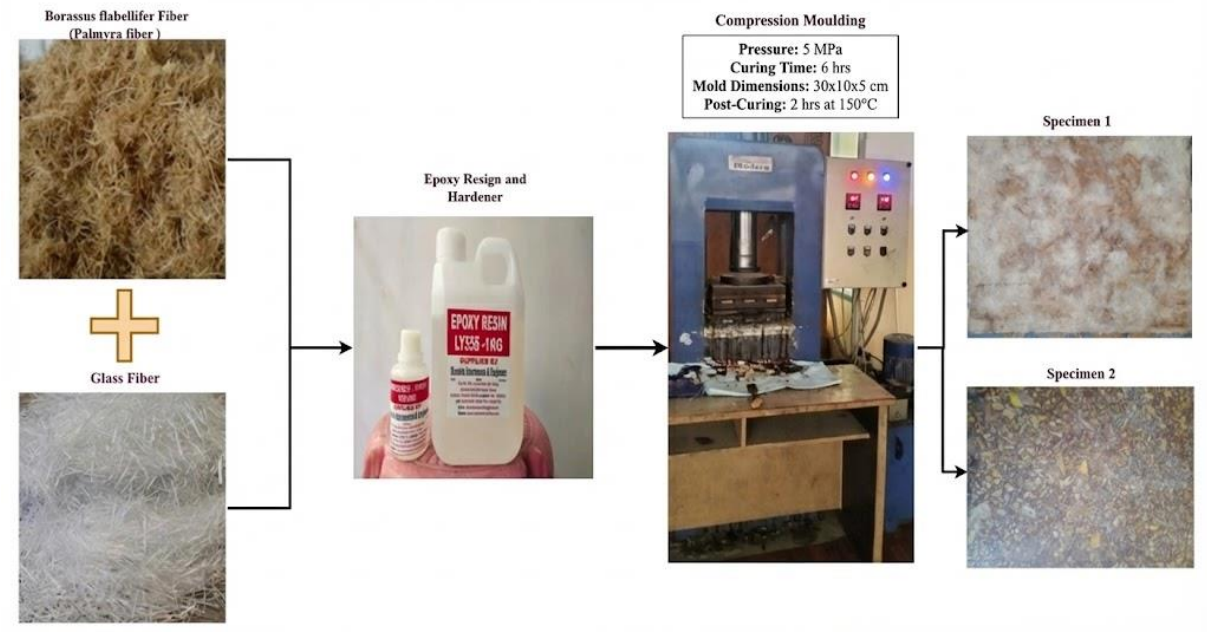

Figure 1.Fabrication procedure of composite samples

The tensile properties of the fabricated composites were evaluated following the ASTM D3039 standard. Hardness testing was performed using a Shore D Hardness Testing Machine, as per ASTM D2240 [18]. The Izod impact test was conducted on a 300 J impact testing machine in accordance with ASTM E23 [19]. The abrasive wear studies were performed at room temperature using a pin-on-disc apparatus, following ASTM G99. Rectangular samples measuring 30 × 10 × 5 mm^3, with a contact area of 300 mm^2, were supported by a flexible arm and positioned against a hardened steel disc covered with 180-grit silicon carbide (Sic) abrasive paper. The water absorption behavior of the composites was assessed using the ASTM D570-98 standard [20].

The degradation behavior of the sample was studied by heating the sample in a nitrogen atmosphere in a PerkinElmer TGA 4000 analyzer at 50℃ to 800℃ with a gas flow rate of 10 ml/min. The required sample to perform TGA analysis is 10-30 mg and the data stored in Pyris Software. Lastly, scanning electron microscopy (SEM) was used to examine the physical and structural features of the composites [21] such as the fiber-matrix interface, fiber orientation and fracture surfaces. SEM was able to give images of surfaces in detail, which showed microstructural conditions of porosity, fracture, void, and fiber pull-outs.

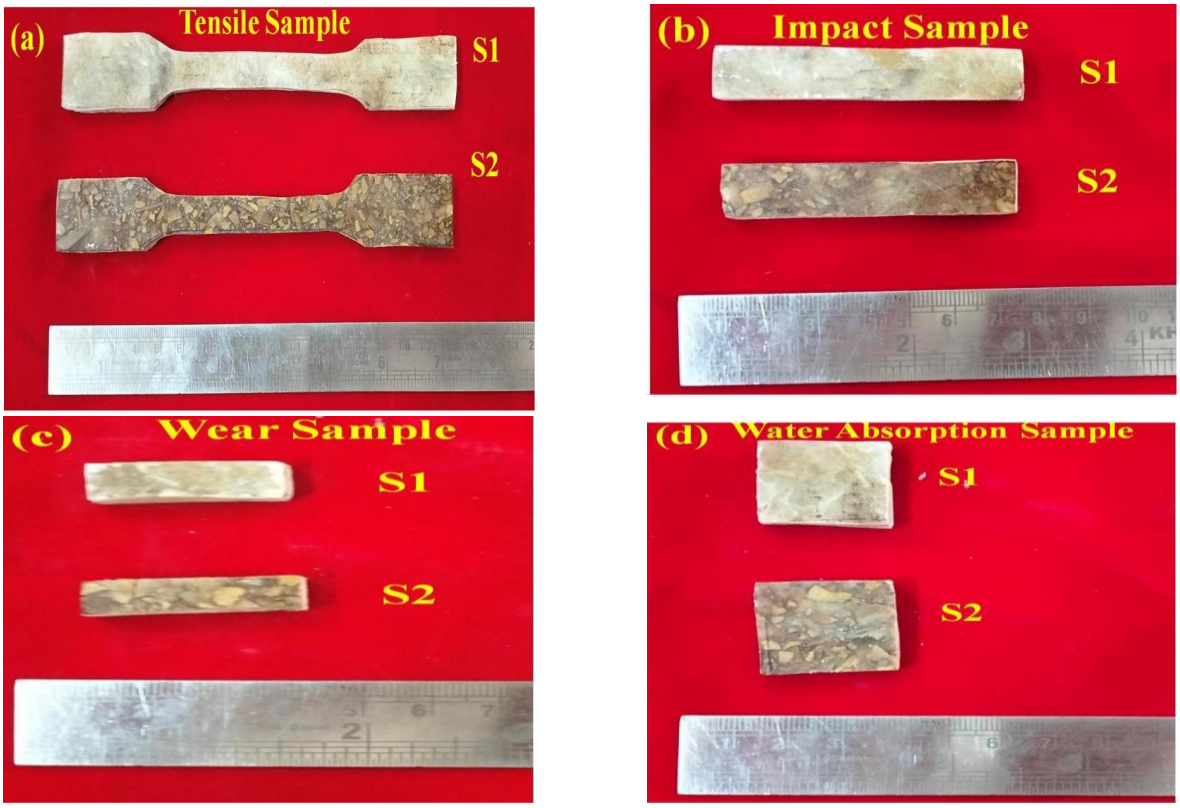

Figure 2. Extracted sample (a) Tensile sample (b) Impact sample (c) Wear sample (d) Water absorption sample

3. RESULT AND DİSCUSSİON

3.1. Tensile propertiesof the composites

Figure 3 illustrates the tensile strength performance of the samples, with S1 exhibiting the lowest value at 35.58 MPa and S2 showing the highest value at 41.54 MPa. This represents a 14.34% improvement in tensile strength for S2 compared to S1. The analysis reveals that increasing the GF weight percentage in the hybrid composite enhances tensile strength. The lower performance of the S1 sample can be attributed to reduced fiber-matrix adhesion, which contributes to its decreased tensile strength [22].

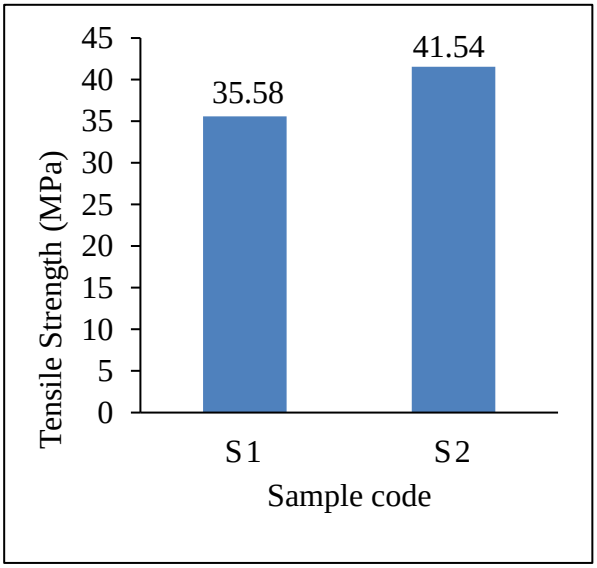

Figure 3. Tensile strength of S1 and S2 composite samples.

3.2. Impact strength of the composites

The impact characteristics of polymer composites play a crucial role in determining the bonding strength between the fiber and matrix. For the S1 and S2 samples, the impact strength ranged from a minimum of 5.15 J to a maximum of 5.54 J, with S2 showing a 7.03% improvement in impact strength over S1, as illustrated in Figure. 4. This improvement can be attributed to the superior interlocking between the matrix and fiber in S2, achieved through the fiber surface, which effectively inhibited fracture propagation during mechanical testing. To enhance energy absorption and manage the weight content of GF, establishing robust connectivity between the fiber and matrix is essential [23].

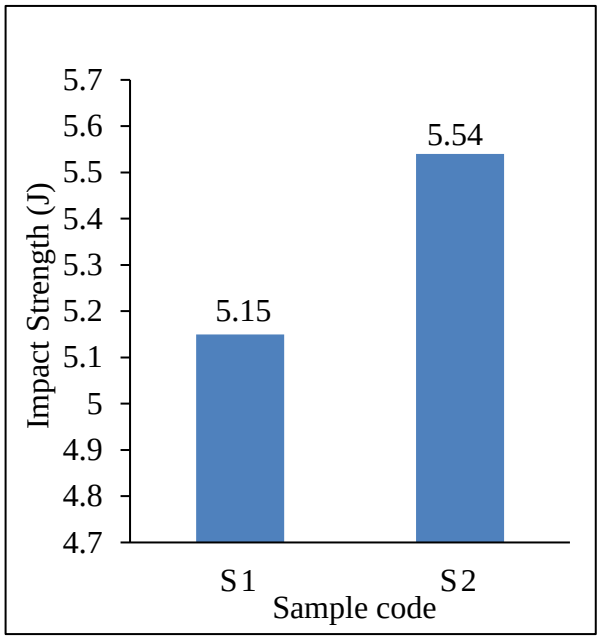

Figure 4. Impact strength of S1 and S2 samples

3.3. Hardness of the composites

The higher hardness of S2 (77.3 HV) compared to S1 (72.33 HV), as shown in Figure 5, can be attributed to its optimized composition. The S2 sample contains 20% S-Glass fiber compared to 15% in S1, and 20% *Borassusflabellifer* fiber compared to 25% in S1. This composition results in a 6.46% increase in hardness for S2 compared to S1. The increased S-Glass fiber content enhances the composite's rigidity and resistance to deformation due to its superior mechanical properties [24], while the reduced Borassus content minimizes flexibility, creating a more rigid matrix. Furthermore, the improved fiber-matrix ratio in S2 enhances stress transfer and bonding, promoting better interlocking within the composite. These factors collectively contribute to the superior hardness observed in S2.

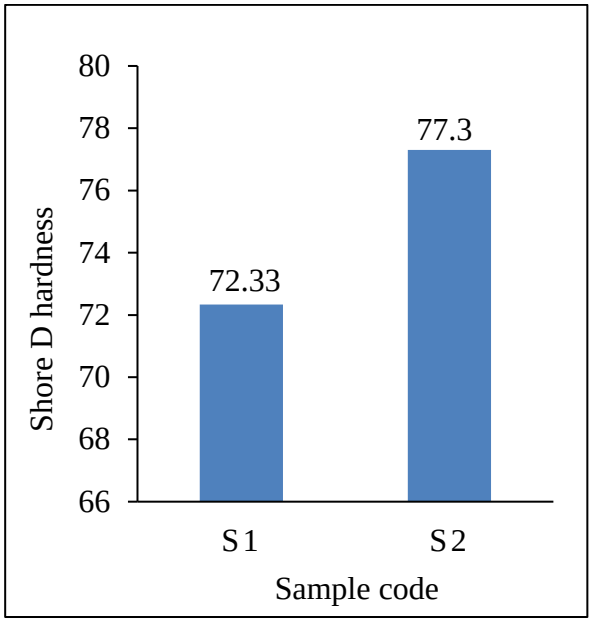

Figure 5. Hardness of S1 and S2 samples

3.4. Wear performance of the composites

Table 1 emphasizes the influence of load on wear performance, revealing that wear properties, including frictional force and height loss, tend to rise under wear parameter conditions [25]. This behavior is attributed to the formation of a polymeric film on the counter steel disc, combined with the high strength, low elongation at break, low density, and high tensile modulus of the fibers. In epoxy composites reinforced with *Borassusflabellifer* fibers and S-glass fibers, the abrasive damage to manufacturing equipment is significantly reduced. This reduction is primarily due to the soft nature of *Borassusflabellifer* fibers, attributed to their moderate cellulose content, and the structural compatibility of S-glass fibers with the epoxy matrix, which minimizes surface wear during processing.

Figure 6 illustrates the friction forces for two composite configurations such as S1 and S2 under applied forces of 10 N, 20 N, and 30 N. S1 demonstrates higher friction forces across all loads, with a significant increase as the applied force rises. This behavior is likely due to the higher content of *Borassusflabellifer* fibers (25%), which are softer and more prone to deformation under stress. In contrast, S2, with a balanced composition of *Borassusflabellifer* fibers (20%) and S-glass fibers (20%), exhibits relatively lower friction, benefiting from the enhanced stiffness and load-bearing capacity of S-glass fibers. Despite these differences, polymer composites generally exhibit high friction combined with reduced wear resistance, primarily due to the brittleness of the reinforced fibers [26].

Furthermore, S1 experiences greater height loss compared to S2 due to its higher content of *Borassusflabellifer* fibers, which are low density and softer in nature [27]. The increased proportion of these natural fibers (25%) makes S1 more prone to deformation and material removal under applied loads. Additionally, the lower proportion of S-glass fibers (15%) in S1 reduces its structural reinforcement and wear resistance, as S-glass fibers play a crucial role in enhancing stiffness and strength [28]. In contrast, S2, with a more balanced mix of *Borassusflabellifer* fibers (20%) and S-glass fibers (20%), distributes the load more effectively, leading to improved wear less height loss.

Table 1.Wear properties of S1 and S2composite samples

S.No	Load (N)	Speed (rpm)	Time (sec)	Frictional force (N)	Height loss (μ)
S1	10	450	150	5.6	15
	20			9.8	50
	30			17.8	65
S2	10	450	150	6.1	10
	20			12.6	30
	30			17.1	45

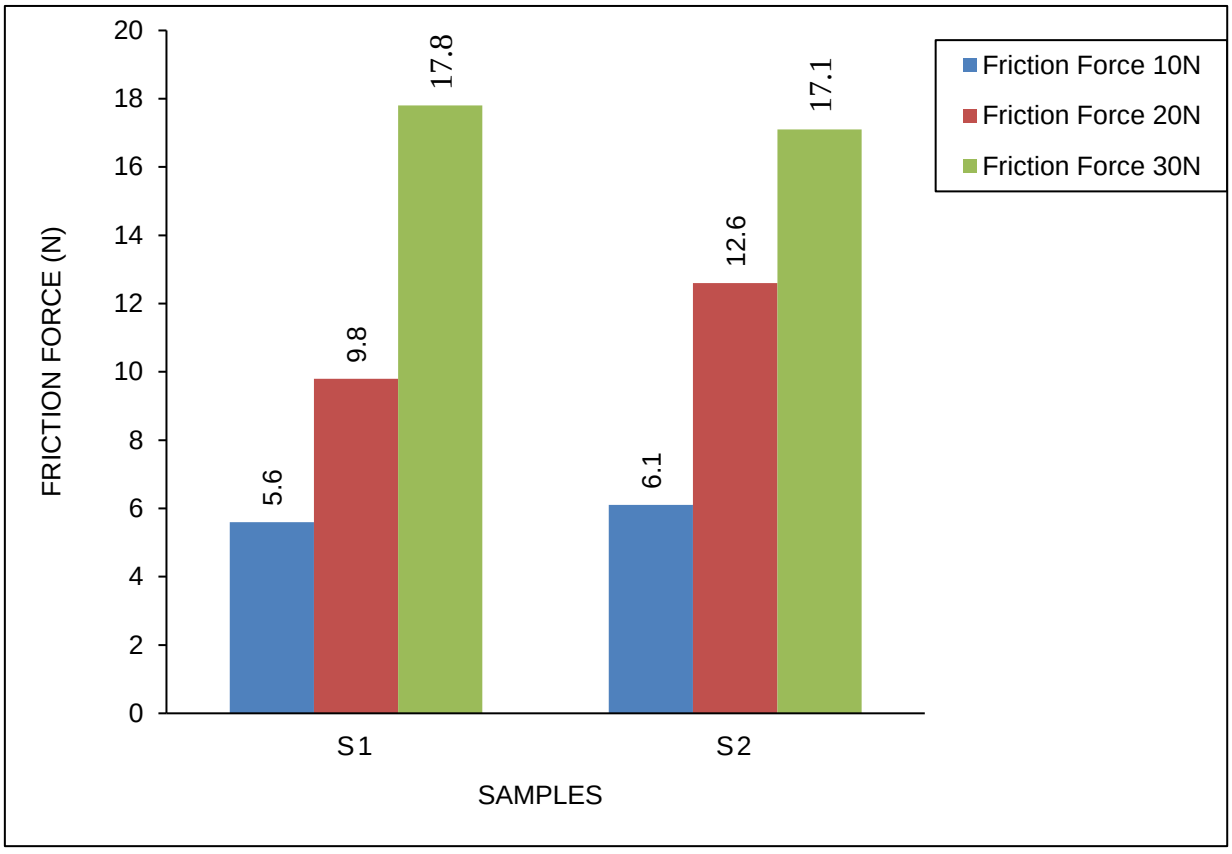

Figure 6.Frictionforce of S1 and S2composite samples

3.5. Water absorption of the composites

The water absorption behavior of samples S1 and S2 was monitored over 24 hours at 30-minute intervals. The results indicate that S1 absorbs more water compared to S2, which may be attributed to the higher amount of impurities present in the *Borassusflabellifer* fibers. As shown in Figure 7, the weight of the composites increases with immersion time [29]. This trend highlights that S1 exhibits higher water absorption due to its greater content of *Borassusflabellifer* fibers (25%). These natural fibers are hydrophilic, possess a porous structure, and contain hydroxyl groups that readily bond with water molecules, leading to increased water absorption. In contrast, S2, with a lower proportion of *Borassusflabellifer* fibers (20%) and a higher proportion of S-glass fibers (20%), absorbs less water. S-glass fibers are hydrophobic, which helps limit water absorption [21]. This balanced composition enhances the water absorption resistance of S2 compared to S1.

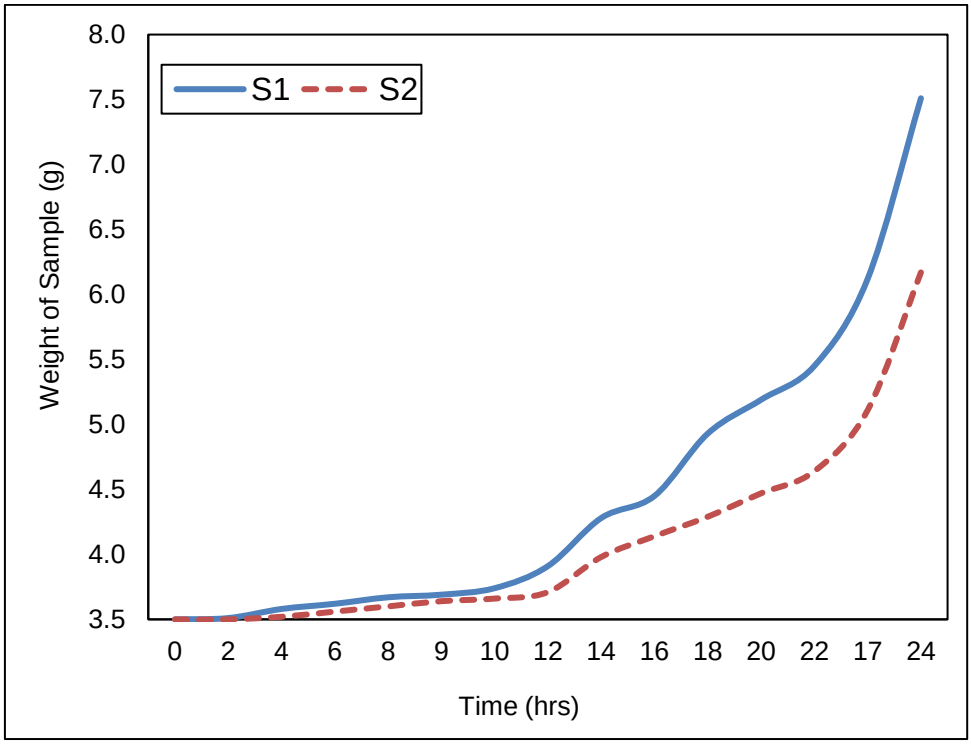

Figure 7.Water absorption samples of S1 and S2composite samples.

3.6.TGA of the composites

Figure 8 shows the TGA curves of composite samples made from *Borassusflabellifer* and S-glass fibers. Both composites exhibited significant decomposition behavior during the analysis. The samples underwent a single-stage thermal degradation process across a temperature range of 29.6°C to 993.83°C.

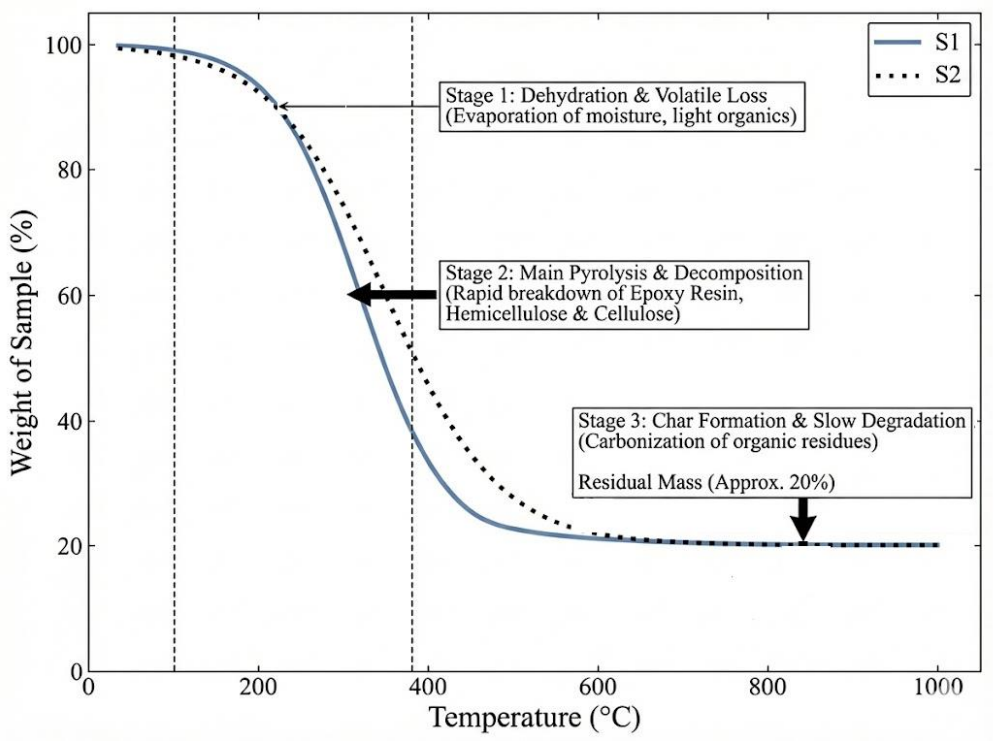

Figure 8..TGA samples of S1 and S2 composite samples

The initial weight loss observed between 29.6°C and 226°C was attributed to the evaporation of moisture absorbed by the composite material, with no significant thermal degradation occurring before 226°C [30]. Beyond this temperature, thermal stability gradually decreased, and fiber decomposition began. Between 226°C and 505°C, the composites experienced a second stage of breakdown, where removal of lignin, hemicellulose, and waxes was facilitated, particularly in the S2 samples [27]. A third stage of decomposition occurred between 505°C and 993.85°C, during which the remaining fiber content stabilized. At this stage, the residual mass balanced at approximately 4.8 g for the S1 sample and 8.9 g for the S2 sample.

The derivative thermogravimetric (DTG) curves of both S1 and S2 are shown in Figure 9. During thermal decomposition, various chemical reactions occur at different temperatures, potentially involving mass loss associated with endothermic or exothermic processes. Both S1 and S2 samples exhibited major thermal degradation between 370°C and 390°C. The S2 composite, which contained a higher proportion of S-glass fibers, showed a sharper DTG peak and greater thermal stability compared to S1 [17]. Decomposition for both samples began around 250°C and was largely complete by 450°C. Overall, increasing the S-glass fiber content enhanced the thermal resistance of the composite, while the Borassus fibers contributed to maintaining the material's eco-friendly characteristics.

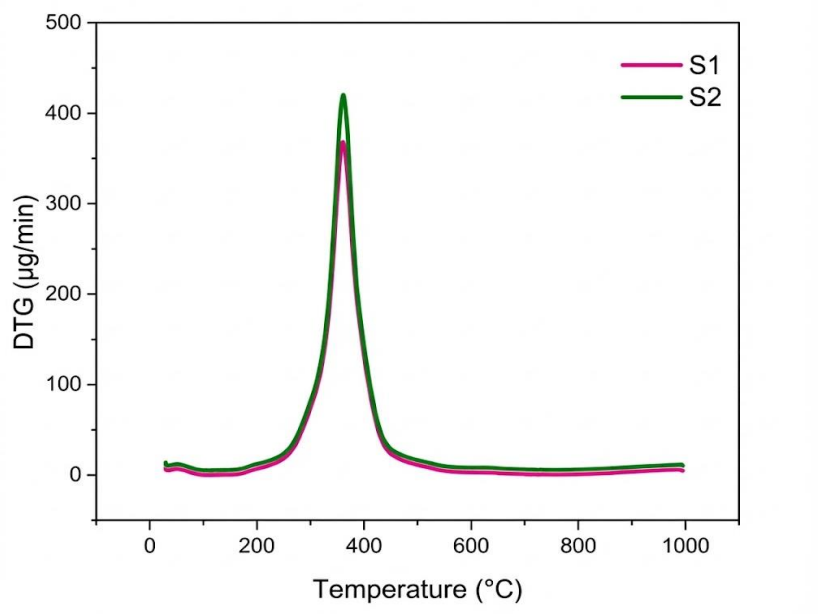

Figure 9.*DGA samples of S1 and S2 composite samples.*

3.7. Scanning Electron Microscopy Analysis (SEM of the composites)

Figures 10(a) and 10(b) present the SEM images of composite samples S1 and S2, respectively. In Figure 10(a), a greater extent of fiber pull-out and visible fiber shearing can be seen, indicating weak bonding between the fiber and the matrix [28].

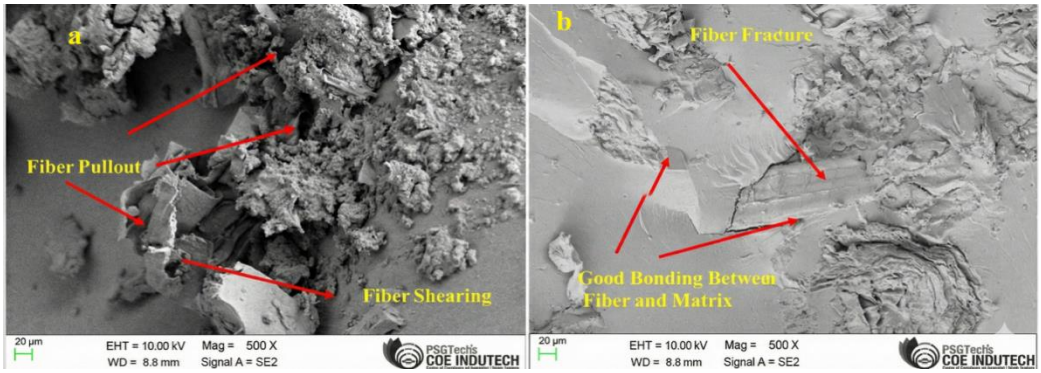

Figure 10.SEM analysis of the composites. A:composite S1.b:composite S2.

This observation aligns with the tensile test results, which suggest inadequate interfacial adhesion in the S1 sample. On the other hand, Figure 10(b) reveals reduced fiber pull-out compared to Figure 10(a), with clear signs of fiber breakage [29]. This suggests a much stronger interaction between the fiber and matrix, allowing for better stress transfer during mechanical loading. The presence of fiber fracture rather than pull-out indicates that S2 has a more effective fiber-matrix bond, likely due to an optimal fiber content in the composite formulation [31].

3.8. Wear Analysis based SEM Images

The cross-section of the fiber of *Borassusflabellifer*was flattened as indicated by the section marked multi cellular structure (Fig 11a). Such natural fibers are porous and less wear resistant than the matrix; when subjected to sliding loads, the porous fibers tend to defibrillate or crushing (as the texture would be rough), and provide localized points of weakness in which debris generation is initiated. The non fibrous layer was used to denote areas of the epoxymatri (Fig 11b). Samples containing less glass (S1) have a more likely time to be micro-ploughed or micro-cut by abrasive particles resulting in deeper grooves and loss of material. The smooth regions were normally seen in the S2 sample (greater content of glass) (Fig. 11c). This smoothness indicates the shift of abrasive wear to milder adhesive wear. The hard S-glass fibers are useful in transferring the normal load and the counterface is not easily penetrated into the soft matrix, thereby lowering the overall wear rate. The existence of loose debris (apparently as white particles) indicates a three-body abrasion mechanism, with fragments of broken fibers rolling between the surfaces, and further polishing the matrix.

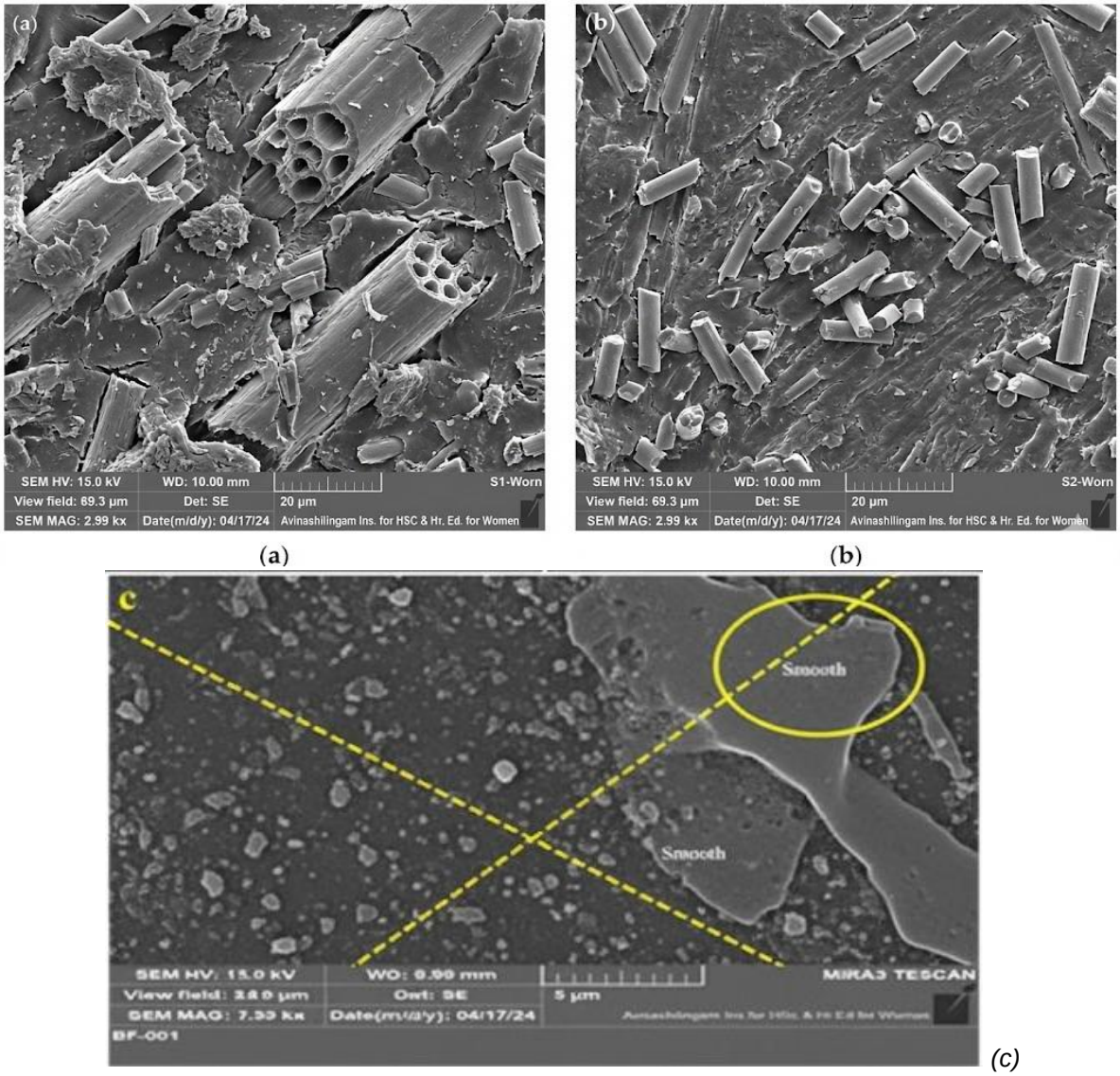

Figure 11.SEM analysis of wear sapmle composites S1 (a) and S2 (b) & (c)

4. CONCLUSION

The experimental study of hybrid epoxy composite under the influence of Borassusflabellifer and glass fibers has shown that fiber hybridization has a great importance on the overall performance of the material. Of the samples of fabricated samples, S2 had better tensile strength (41.54 MPa), which is 14.34 percent higher than S1 (35.58 MPa), impact energy absorption (5.54 J), which is 7.03 percent higher than S1 (5.15 J), and Shore D hardness (74.6), which is 6.46 percent higher than S1 (72.33). S2 also showed minimum rate of water absorption (1.2) after 24 hours which was half of S1 (2.4). Also, it was shown that S2 had the best wear resistance, and wear loss is lower than in S1. Such mechanical and physical improvements may be explained by the synergistic impact of natural and synthetic fiber reinforcement on the epoxy matrix which leads to better adhesion and load transmission between the fibers. These hybrid composites have potential uses in automotive, marine and building industries, where a strength, durability and moisture resistance balanced system is needed.

Author contributions

T. Varun Kumar: Conceptualization, Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. V.P. Suresh Kumar: Methodology, Investigation. Nadir Ayrilmis: Conceptualization, Methodology, Investigation, Writing – review & editing.All authors reviewed the manuscript.

Availability of data and materials

Data is available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent to publish

Not applicable.

Competing interest

No competing interests are disclosed by the author.

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IZVOD

PROCENA MEHANIČKIH, TRIBOLOŠKIH I FIZIČKIH SVOJSTAVA EPOKSIDNIH KOMPOZITA OJAČANIH VLAKNIMA VRSTE *BORASSUS FLABELLIFER*I STAKLENIM VLAKNIMA

Ispitana su mehanička, fizička i svojstva habanja hibridnih kompozita razvijenih sa vlaknima vrste Borassus flabellifer i staklenim vlaknima kao ojačanjem matrice epoksidne smole. Proučavana su svojstva udara, tvrdoće, apsorpcije vode, habanja, savijanja i zatezanja pomoću različitih sastava laminata kako bi se analizirao efekat hibridizacije. Kompozitni materijali su napravljeni korišćenjem dve različite formulacije, gde je prva (S1) sadržala epoksidnu smolu (60) + Borassus flabellifer (25) + S-staklena vlakna (15), a druga (S2) epoksidnu smolu (60) + Borassus flabellifer (20) + S-staklena vlakna (20). Važni nalazi su pokazali da je S2 bio superiorniji od S1 u različitim svojstvima: zatezna čvrstoća (S1: 35,58 MPa, S2: 41,54 MPa), apsorpcija energije udara (S1: 5,15 J, S2: 5,54 J), tvrdoća po Šoru D (S1: 72,33, S2: 74,6) i apsorpcija vode (S1: 2,4, S2: 1,2 nakon 24 sata). Kod S2 je takođe povećana otpornost na habanje, jer je gubitak od habanja bio manji nego kod S1. Visoke performanse S2 mogu se objasniti činjenicom da se flabelifer Borassus-a i staklena vlakna mogu bolje prilepiti jedno za drugo, što dovodi do povećanja prenosa opterećenja i smanjenja izvlačenja vlakana. Rezultati ukazuju na mogućnosti upotrebe ovih hibridnih kompozita u strukturnim i triboloških sistemima i pružaju kompromis između laganih i izdržljivih materijala.

***Ključne reči**: Borassus flabellifer, staklena vlakna, svojstva habanja, polimerni kompozit i armatura*

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