Mechanical, Morphological and Wear Resistance of Natural Fiber / Glass Fiber-based Polymer Composites

Sumesh K. R. a,*, Sivasubramanian Palanisamy b,*, Tabrej Khan c, Ajithram A. d and Omar Shabbir Ahmed c

Natural fibers along with glass fibers were used as the reinforcement of an epoxy matrix for the betterment of mechanical and wear applications. The combination of overall wt% up to 20 resulted in 23.8 MPa of tensile strength compared to 15.5 MPa for untreated fibers. The wt% of areca fiber (AF) (20 wt%)/glass fibers (GF) (20 wt%) with 5% alkali treatment yielded a maximum tensile strength up to 62.6% in comparison to untreated fiber at lowest percentage of 10 wt%. The increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation. The alkali treated fibers, untreated fiber combinations achieved 33.8% and 26.8% improvement with impact properties. A decrease in the wear loss was shown with the increase in wt% of hybrid fiber incorporation from 20 to 40 wt%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influenced with applying higher loads. The frictional rate was highly increasing with increase in hybrid fiber wt% and also with higher loads applied. The SEM results for treated 20 wt% AF+20 wt% GF with hybrid fiber incorporation observed better results due to improved adhesion of fiber with matrix phase.

DOI: 10.15376/biores.19.2.3271-3289

Keywords: Natural fiber; Epoxy resin; Mechanical testing; Morphological properties; Surface treatments

INTRODUCTION

Natural fibers are getting vital attention in the current global condition due to their biodegradability, low cost, better mechanical properties, and lesser environmental threats. These natural fibers from various waste are used as the filler or reinforcement in enhancing the properties of thermoplastics and thermosetting plastic composites (Mittal et al. 2016; Patel and Parsania 2017; Khan et al. 2018; Rahman et al. 2019). This method will not only reduce the natural waste but also reduce the utilization of plastics, which is highly welcoming. Research and innovations are carried out in development of existing field of polymer composites for betterment in automobile, aerospace, medical implants, flame retardant, corrosion resistance, and other various applications (Sheykh et al. 2017; Muhammad et al. 2019; Oushabi 2019). The natural fibers were extracted from coconut shell, banana plant, sisal plant, pineapple leaf, kenaf, ramie, flax, Aloe vera etc. (Palanisamy et al. 2021; Almeshaal et al. 2022; Sumesh et al. 2023). Lignocellulosic fibers
were incorporated with epoxy, polyethylene, polypropylene, polystyrene, and polyamide for enhancing the matrix properties. Synthetic fibers such as glass, carbon, kevlar fibers, etc., are used abundantly for high end application. The ecological problems such as global warming, and water and soil pollution reduce the usage of this (Nirmal et al. 2015; Chegdani et al. 2018; Senthilkumar et al. 2019; Todkar and Patil 2019).

The incorporation of hybrid natural fiber composites from sisal and coir enhanced the tensile, flexural, and impact strength of epoxy-based composites. Fiber weight percentage of 35 showed the better results (Sumesh and Kanthavel 2020; Ashraf et al. 2023). Hybrid fiber combination of glass and sisal with epoxy resin showed better results at overall wt% of 40 (Ramamoorthy et al. 2015; Junaedi et al. 2023). Hybrid natural fiber combination observed better mechanical properties due to better distribution of fibers in matrix with good adhesion of fiber with matrix phase (Arthanarieswaran et al. 2014; Karuppiah et al. 2022; Kar et al. 2023; Palanisamy et al. 2023b). It was observed that increasing the fiber percentage and adding nano clay particles to an epoxy/glass composite improved the tensile characteristics. The flexural strength of glass epoxy composites was also shown to be improved by adding nano clay to them (Jeyakumar et al. 2017; Basha et al. 2023). The hybrid natural fiber combination with banana and pineapple decreases its tensile, flexural property by overall incorporation of fiber at 50 wt% (Swolfs et al. 2014; Nopparut and Amornsakchai 2016; Palanisamy et al. 2024). Hybrid natural fibers using flax/glass/epoxy also enhanced the tribological behavior of the composites with low wear loss. In the dry sliding wear test using natural fiber composites, natural fiber combination and applied load factor has the highest significance in contributing to the wear properties (Chegdani et al. 2016; Johnson et al. 2019). Fiber addition more than the optimum range will inversely affect the mechanical and wear properties of epoxy-based composites (Singha and Thakur 2008; Nirmal et al. 2012; Shuhimi et al. 2016; Kumar et al. 2019). It was also observed that lignocellulosic fiber has its better application by adding the fibers in equal weight percentages (Satheesh Kumar et al. 2010; Liu et al. 2019; Nanda and Satapathy 2021; Hanan et al. 2023). The areca natural fibers up to 20 wt% observed better mechanical properties with epoxy-based composites (Johnson 2019). The surface treatment using NaOH had a significant contribution in adding to the tensile properties of areca/epoxy based polymer composites (Khan 2018).

The hydrophilic nature of the natural fibers is a bigger drawback that declines the properties of the polymer-based composites. Surface treatments such as NaOH, KOH, bleaching, and isocyanates reduce the water absorption property and enhance its applications. NaOH or alkali treatment is used in most with the natural fibers due to its effectiveness. Alkali treatment will remove the wax and dust particles from the fiber surfaces, which will enhance the adhesion with plastic composites (Santulli et al. 2023). The treatment also improves the cellulose richness in the fiber, thereby increasing the crystallinity in the combination (Gupta et al. 2016; Abdul Khalil et al. 2017; Mauya et al. 2017; Aslan et al. 2018; Oushabi 2019; Rajeshkumar 2021). The research work related to the combination of areca fiber, glass fiber with epoxy resin is lesser. In this work, mechanical, wear and morphological evaluations of areca fiber/glass fiber/epoxy resin matrix were discussed with the influence of multiple fibers, NaOH treatment.
EXPERIMENTAL

Materials

Areca is the natural fiber (Go green products, Tamilnadu, India) used in this work. S-glass fiber (Seenu and Co, Tamilnadu, India) was used as the synthetic fiber to improve the property of epoxy resin (LY556 grade) (Seenu and Co, Tamilnadu, India). Areca fiber had 0.7 to 0.8 g/cm$^3$ density, tensile strength of 147 to 322 MPa, and Young’s modulus of 1.124 to 3.16 GPa. Hardener (HY951 grade) was added with epoxy resin at 1:10 ratio for proper mixing. Areca fiber and samples after fabrication are shown in Fig. 1. The S-glass fiber is a high strength glass fabric consisting of 4750 MPa of tensile strength, density of 2.49 g/cm$^3$. It has excellent abrasion resistance when used as a composite reinforcement material. All results were taken after the chemical composition testing of individual fibers. The natural fiber was treated with NaOH to reduce the water absorption and impurities present in the fiber. The NaOH pellets (0, 3, 5, and 8 wt%) were diluted in 1000 mL of distilled water, and natural fibers were soaked into it for 4 h at room temperature (Sivasubramanian et al. 2021).

![Fig. 1. a) Areca fiber, b) areca fiber/glass fiber composite](image)

**Table 1.** List of Hybrid Combinations

<table>
<thead>
<tr>
<th>Composite Code</th>
<th>Treatment</th>
<th>Combination</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>5 wt% NaOH treated (T)</td>
<td>10 wt% AF/10 wt% GF</td>
<td>1.42</td>
</tr>
<tr>
<td>A2</td>
<td>Untreated (NT)</td>
<td>10 wt% AF/10 wt% GF</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>5 wt% NaOH treated (T)</td>
<td>15 wt% AF/15 wt% GF</td>
<td>1.54</td>
</tr>
<tr>
<td>B2</td>
<td>Untreated (NT)</td>
<td>15 wt% AF/15 wt% GF</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>5 wt% NaOH treated (T)</td>
<td>20 wt% AF/20 wt% GF</td>
<td>1.68</td>
</tr>
<tr>
<td>C2</td>
<td>Untreated (NT)</td>
<td>20 wt% AF/20 wt% GF</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>5 wt% NaOH treated (T)</td>
<td>25 wt% AF/25 wt% GF</td>
<td>1.64</td>
</tr>
<tr>
<td>D2</td>
<td>Untreated (NT)</td>
<td>25 wt% AF/25 wt% GF</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>5 wt% NaOH treated (T)</td>
<td>10 wt% AF/20 wt% GF</td>
<td>1.61</td>
</tr>
<tr>
<td>C4</td>
<td>5 wt% NaOH treated (T)</td>
<td>30 wt% AF/30 wt% GF</td>
<td>1.62</td>
</tr>
<tr>
<td>C5</td>
<td>5 wt% NaOH treated (T)</td>
<td>40 wt% AF/40 wt% GF</td>
<td>1.65</td>
</tr>
<tr>
<td>C6</td>
<td>3 wt% NaOH treated (T)</td>
<td>20 wt% AF/20 wt% GF</td>
<td>1.68</td>
</tr>
<tr>
<td>C7</td>
<td>8 wt% NaOH treated (T)</td>
<td>20 wt% AF/20 wt% GF</td>
<td>1.68</td>
</tr>
<tr>
<td>C8</td>
<td>Neat Epoxy Resin</td>
<td></td>
<td>1.16</td>
</tr>
</tbody>
</table>
After the required time, fibers were washed in distilled water to remove excess NaOH. Fibers were dried in sunlight for 48 h. To fully dry the fibers, they were heated in an oven for 3 h at 70 °C. The same procedure was followed in previous work (Sumesh and Kanthavel 2020). Finally, the dry fibers were cropped to a fiber length of 30 mm.

**Fabrication**

The areca and glass fibers were weighed using a weighing scale for different weight ratios of composition plate. A hand laying technique is used for the fabrication of composites with epoxy and hardener mixed at a 10:1 ratio. The required fibers were fixed in a square mould of 200×200×6 mm dimension. Epoxy resin along with hardener was poured into it and mixed well. A total of thirteen combinations with areca/glass fibers were used in this research with and without alkali treatment. The list of hybrid combinations is shown in Table 1.

**Mechanical Testing**

The universal testing machine (UTM) was used for finding tensile properties and flexural properties of epoxy-based composites. The tensile testing was calculated using ASTM D638-14 standard with gauge length 50 mm and crosshead speed of 5 mm/min (Sumesh and Kanthavel 2020). The test was performed using displacement control method. Similarly flexural and impact test followed ASTM D790-17, ASTM D256-10 standards (Karuppiah et al. 2020; Sumesh and Kanthavel 2020, 2022). Three-point bend testing was used for finding the flexural properties with span to depth ratio at 16:1 and crosshead speed of 2 mm/min. The impact test was used for finding the energy absorbed by the specimen with a notch width of 2.5 mm. All the results were plotted using Originpro 8.5 software.

**Wear Testing**

A pin on disc machine was used for detecting wear resistance and coefficient of friction for natural hybrid composites with ASTM G 99 standard. The EN 31 steel counter disc was used for this testing, polished with SiC abrasive paper of grade 1200, followed by areca composites with grade 800 polishing. Here in the experiment the applied load was changed from 10, to 15, to 20 N with constant sliding distance of 500 m and sliding speed 0.5 m/sec for finding the results.

**SEM, XRF, and FTIR Testing**

The SEM testing (Carl Zeiss EVO 18) was taken for finding the distribution of fibers in epoxy resin before and after performing the wear test. The influence of fiber distribution in matrix and applied load influence with combination will be detected here. Gold sputter coating was performed for passing electron beams through non-conducting samples (Palanisamy et al. 2023a). The SEM results were taken after the whole wear testing from 10 to 20 N applied load, by dipping in liquid nitrogen to get brittle sample and then breaking the composite sample. These broken samples were taken for SEM analysis. The tensile and impact testing setup is shown in Fig. 2. The X-ray fluorescence spectroscopy (XRF) testing was undertaken for finding the chemical composition in the composite sample. It is an S4 Bruker model machine having specifications of X ray tube collimators with 4 Kw Rh, 0.34 to 0.45°. The Fourier transform infrared testing was done using an NEXUX 6800-50 machine having spectral resolution 2 cm⁻¹ and wave number ranging from 500 to 4000 cm⁻¹ for detecting the functional groups evolved in areca fibers with surface treatment of NaOH.
RESULTS AND DISCUSSION

Tensile Testing
The tensile strength of the areca fiber/glass fiber/epoxy resin combination exhibited significant improvement in the strength with hybrid fiber incorporation and 5% alkali treatment (Fig. 3a). The initial combination of areca fiber (10 wt%)/glass fibers (10 wt%) observed 23.8 MPa of tensile strength compared to untreated fibers with 15.5 MPa. The overall wt% up to 40% with 5% alkali treatment showed maximum tensile strength up to 41.4 MPa. The same combination with untreated areca fibers showed a tensile strength of 27.3 MPa. The alkali treatment removes the wax and other waste from the natural fiber, which brings better compatibility with glass fiber/epoxy resin combination (Ramamoorthy et al. 2015). Tensile strength observed maximum properties at hybrid natural fiber combination at 40 wt% (Swolfs et al. 2014; Abdul Khalil et al. 2017). Increase in hybrid fiber incorporation improved the tensile strength from 15.5 to 27.3 MPa in untreated natural fibers. Increase in the fiber incorporation provided an even distribution of fibers in the epoxy resin matrix that enhances the tensile properties (Gupta et al. 2016; Aslan et al. 2018). Alkali treatment provided surface roughness to the fibers with less hydrophilic nature, which created good adhesion with an epoxy/hybrid fiber phase (Swolfs et al. 2014; Khan et al. 2021). Tensile modulus was enhanced with the increase in hybrid fiber incorporation of areca and glass fibers with overall wt% up to 50 (Fig. 3b). The tensile modulus is highly associated with the reinforcement addition (Todkar and Patil 2019). This property also showed decline in the value with the untreated natural fiber composites. Untreated fibers provided non homogenous distribution with high surface deformation, which can result in a decrease in the mechanical properties of epoxy-based composites (Nirmal et al. 2015). The tensile strength of epoxy resin was found to be 21.2 MPa, whereas most of the combinations showed better results than that.
Elongation at break did not change much with the increase in hybrid fiber incorporation with epoxy-based matrix (Fig. 3c). Similar to other results, non-treated fibers showed lower percentage values. The surface abnormalities in the untreated areca fiber combination resulted in low elongation at break.

**Flexural Testing**

The flexural strength of areca/glass fiber/epoxy resin combinations observed significant increase in the properties with fiber mixing (Fig. 4a). The lignocellulosic fibers with areca have cellulose, hemicellulose and lignin content that add to the mechanical properties of the composites (Maurya et al. 2017; Kurien et al. 2023). The alkali treatment with 5% NaOH created a barrier formation in the fibers which reduced water absorption properties of natural fibers (Sumesh and Kanthavel 2020; Rajeshkumar 2021). Glass fiber in combination with epoxy resin resulted in a significant improvement in the flexural strength of polymer composites (Ramamoorthy et al. 2015). The alkali-treated fibers at
overall fiber wt% of 20 observed an increase from 38.9 to 52.4 MPa. This increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation (Swolfs et al. 2014; Khan et al. 2021). The treated (5%) natural fiber combinations observed maximum flexural strength of 74.6 MPa, in comparison to untreated natural fiber combination of 60.9 MPa. Fiber/matrix bonding, homogenous distribution of fiber these two factors must be better for enhancing the flexural strength of polymer composites (Sumesh and Kanthavel 2022). The flexural modulus observed significant improvement with alkali treatment and reinforcement incorporation in epoxy-based composites (Mittal et al. 2016). The maximum flexural modulus of 6.73 GPa was observed in alkali treated 25 wt% AF/25 wt% GF combination (Fig. 4b). The flexural strength of epoxy resin was found to be 44.8 MPa, whereas most of the combinations showed better results than that.

Fig. 4. a) Flexural Strength (FS), Flexural Modulus (FM) of Hybrid Natural Fiber Composites

**Impact Testing and Hardness**

The impact strength of epoxy matrix composites did not exhibit a high dependency on different factors in comparison to tensile and flexural strength (Fig. 5a). The impact strength results showed better improvement with the hybrid fiber mixing and alkali treatment with natural fibers (Rajeshkumar 2021; Goutham et al. 2023). The overall fiber incorporation from 20 to 40 wt% observed better properties. Higher fiber incorporation created high fiber debonding, fiber cracks, and similar surface deformations that declined the impact strength of the polymer composites (Sumesh and Kanthavel 2020; Karuppiah et al. 2022). The alkali treated fibers and the untreated fiber combinations observed 3.02 to 4.56 kJ/m² and 2.54 to 3.47 kJ/m² of impact properties, respectively. The hardness properties of epoxy-based composites increased with treatment and fiber incorporation (Fig. 5b). The maximum hardness was observed with 25 wt% AF/25 wt% GF/epoxy combination with alkali treated fibers. Hardness is highly influenced by the quality of bonding of fiber/matrix phase in epoxy-based composites (Ramamoorthy et al. 2015; Sumesh and Kanthavel 2022).
Mechanical Results with Change in Natural Fiber addition and NaOH Treatment

It was observed from the previous step results that the combination 20 wt% AF/20 wt% GF exhibited overall better mechanical properties. This combination was tried with different natural fiber additions of 10, 20, 30, and 40 wt%. The maximum tensile strength
with 41.1 MPa, flexural strength with 70.9 MPa, impact strength of 4.56 KJ/m² was observed with 20 wt% AF addition (Fig 6). Increase in the natural fiber incorporation beyond the optimum level resulted in a decline of the mechanical properties due to poor interfacial adhesion of filler and matrix phase (Rajeshkumar 2021).

The same 20 wt% AF/20 wt% GF combination with different chemical treatment using NaOH ranging from 0, 3, 5, and 8 wt% observed better tensile, flexural, and impact results at 5 wt% NaOH addition (Fig. 7). The surface treatment in natural fiber could act as a smooth carrier for improvement matrix/filler interaction (Sumesh and Kanthavel 2020).

![Fig. 7. a) Tensile Strength (TS), b) Flexural Strength (FS) and c) Impact Strength (IS) of natural fiber hybrid composites with different NaOH treatment](image)

**FTIR Results**

The FTIR results for NaOH treatment in the areca fibers showed increased cellulose content (Fig. 8). The C-H asymmetric deformation and CH₂ symmetric cellulose bending in NaOH treated areca fibers showed a peak at 1370 cm⁻¹ (Sumesh and Kanthavel 2022). This was not visible in untreated areca fibers. The surface treatment provided hydroxyl groups and created polar nature in the areca fibers. The peaks at 3277 and 3302 cm⁻¹ for untreated and treated areca fibers corresponded to stretching vibrations in the natural fibers due to -CH and -OH groups (Todkar and Patil 2019). It can be seen that the peak at 5% NaOH treated natural fibers was properly visible (3302 cm⁻¹) in comparison to non-treated areca fibers (3277 cm⁻¹). The peaks at 1634 and 1642 cm⁻¹ were attributed to bending mode for water absorption in the areca fibers. The peaks at 1022 and 1025 cm⁻¹ were attributed to pyranose vibration in treated and untreated areca fibers (Sumesh and Kanthavel 2022).
Wear Testing

The dry sliding wear rate of hybrid natural fiber composites was carried out using pin on disc equipment with constant sliding distance of 500 m, sliding speed of 5 m/sec (Fig. 9a). Already in the authors’ previous experiments, it was confirmed that surface treated fibers had significant improvement in the mechanical properties of the composites (Rajeshkumar 2021). Alkali-treated natural fibers were used in this combination. In the current application, the influence of different loads from 10 N to 20 N was applied with different combinations to find the wear loss of the specimen. The results observed decrease in the wear loss with the increase in wt.% of hybrid fiber incorporation from 20 to 40 wt.%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influenced with applying higher loads (Aslan et al. 2018). The irregularities in distribution of hybrid fiber incorporation at overall wt% of 50 led to the increase in wear loss of epoxy matrix composites. The increase in load from 10 to 20 N created high temperature area across the sample that will increase the wear loss with higher loads (Maurya et al. 2017). The better adhesion of fiber/matrix created a barrier layer that will protect the sample from higher wear rate (Rajeshkumar 2021).

The coefficient of friction (CoF) showed just the opposite of wear loss factor. The frictional rate was highly increasing with increase in hybrid fiber wt% and also with higher loads applied (Fig. 9b). The hybrid fiber combination possesses high hardness with increase in fiber wt% leading to high coefficient of friction (Kumar et al. 2019). Increase in the load created a high pressure with specimen and rotating disc, leading to high friction in the sample (Nanda and Satapathy 2021).
Fig. 9. a) Wear Loss, b) Coefficient of Friction (CoF) of Hybrid Natural Fiber Composites

SEM Analysis

The initial set of SEM analyses was taken before the wear testing of natural fiber samples (Fig 10). The images showed rough surfaces in the NaOH-treated natural fiber composites (Fig 10b) in comparison to untreated areca fiber combination. This roughness could have enhanced the compatibility of natural fiber/epoxy resin matrix (Rajeshkumar 2021). It is also visible that glass fiber, areca fiber at 20 wt% with the 5% NaOH treatment exhibited better interaction with fiber and resin. This contributed to the properties of polymer composites by adding to stress transferring capacity (Fig 10d) compared to untreated natural fiber with same fiber addition (Fig 10c).

The next set of combination SEM images were taken after wear testing. Figure 11 a) shows that untreated 10 wt% AF/10 wt% GF observed higher fiber breakages and matrix cracks in comparison to NaOH treated natural fibers (11 b). The same percentages of decline in the wear resistance of natural fiber epoxy-based composites were observed (Goutham et al. 2023; Ariveand et al. 2024). The combination with 20 wt% AF/20 wt% GF exhibited greater distribution of fibers in the matrix with better fiber/resin compatibility in NaOH treated natural fibers 11d than untreated fibers 11c. The sample with 25 wt.% AF/25 wt% GF (Fig. 12a, b) showed slight irregularities in the fiber distribution that declined the mechanical properties. The results were shown in Table 2, with almost 40% of SiO$_2$, which can be attributed to the presence of glass fibers. Other compounds including Al$_2$O$_3$, Fe$_2$O$_3$, CaO, and TiO$_2$ were in low amount and were attributed to components of the natural fibers. The other content with almost 50% was epoxy resin. Similar results with SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, CaO, TiO$_2$ were shown with natural fiber epoxy-based composites (Kornejenko et al. 2022).

Table 2. The XRF Results for 25 wt.% AF/25 wt.% GF/Epoxy Combination

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>39.5</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>4.13</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>1.2</td>
</tr>
<tr>
<td>CaO</td>
<td>1.1</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.5</td>
</tr>
<tr>
<td>MgO</td>
<td>0.6</td>
</tr>
<tr>
<td>Element</td>
<td>Percentage</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.3</td>
</tr>
<tr>
<td>S0₃</td>
<td>0.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.1</td>
</tr>
<tr>
<td>Cl</td>
<td>0.7</td>
</tr>
<tr>
<td>MnO</td>
<td>0.4</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.2</td>
</tr>
<tr>
<td>Others</td>
<td>50.07</td>
</tr>
</tbody>
</table>

**Fig. 10.** SEM images before wear testing for a) untreated 10 wt% AF/10 wt% GF combination, b) 5% NaOH treated 10 wt% AF/10 wt% GF combination, c) untreated 20 wt% AF/20 wt% GF combination and d) 5% NaOH treated 20 wt% AF/20 wt% GF combination
Fig. 11. SEM Images after wear testing for a) untreated 10 wt% AF/10 wt% GF combination, b) 5% NaOH treated 10 wt% AF/10 wt% GF combination, c) untreated 20 wt% AF/20 wt% GF combination, and d) 5% NaOH treated 20 wt% AF/20 wt% GF combination, all at 15 N load.

The SEM analysis after wear clearly showed the importance of hybrid fiber combination in enhancing the wear applications of the polymer composites. Figure 11a of D2 Treated 25 wt% AF/25 wt% observed high wear loss in the combination due to poor distribution of fiber causing fiber debonding and fiber breakages with lesser wear resistance. Figure 11b of D1 with Treated 25 wt% AF/25 wt% observed better wear resistance due to higher fiber incorporation with better fiber/matrix bonding.

Fig. 12. SEM Images after wear testing for a) untreated 25 wt% AF/25 wt% GF combination and b) 5% NaOH treated 25 wt% AF/25 wt% GF combination at 10 N load.

CONCLUSIONS

1. The tensile strength of areca fiber /glass fiber/ epoxy resin combination observed significant improvement in the strength with hybrid fiber incorporation and alkali treatment. The combination of areca fiber (10 wt%)/glass fibers (10 wt%) observed 23.8 MPa of tensile properties compared to untreated fibers with 15.5 MPa.

2. The areca fiber (20 wt%)/glass fibers (20 wt%) with 5% alkali treatment exhibited maximum tensile strength up to 62.6% in comparison to untreated fiber combination with 10 wt%. Tensile modulus was enhanced with the increase in hybrid fiber incorporation of areca and glass fibers with overall wt% up to 50.

3. The alkali treated fibers at overall fiber wt% of 20 exhibited an increase in flexural strength from 38.9 to 52.4 MPa. This increase in flexural strength with alkali treatment was observed from 20 to 50 wt% hybrid fiber incorporation.

4. Fiber/matrix bonding, in combination with homogenous distribution of fiber enhanced the flexural strength of polymer composites. The maximum flexural modulus of 6.73 GPa was observed in alkali treated 25 wt% AF/25 wt% GF.

5. The increase in wear resistance was shown with the increase in wt% of hybrid fiber incorporation from 20 to 40 wt%. The interfacial adhesion of fiber with matrix created a pressure absorbing zone that was positively influence with applying higher loads.

6. The irregularities in distribution of hybrid fiber incorporation at overall wt% of 50 leads to the increase in wear loss of epoxy matrix composites. The increase in load from 10 to 20 N created a high temperature area across the sample that will increase the wear loss with higher loads. The better adhesion of fiber/matrix created a barrier layer that will protect the sample from higher wear rate.

7. The frictional rate is increasing with increase in hybrid fiber wt% and also with higher loads applied. The hybrid fiber combination possesses high hardness with increase in fiber wt% leading to high coefficient of friction. Increase in the load created a high pressure with specimen and rotating disc leading to high friction in the sample.

8. The initial set of SEM analysis taken before the wear testing of natural fiber samples showed rough surfaces in the NaOH-treated natural fiber composites in comparison to untreated areca fiber combination. This roughness could have enhanced the compatibility of natural fiber/epoxy resin matrix. It is also visible that glass fiber, areca fiber at 20 wt% with the 5% NaOH treatment achieved better interaction with fiber and resin. This added to the properties of polymer composites by adding to stress transferring capacity comparing to untreated natural fiber with same fiber addition.

9. The SEM analysis after wear clearly showed the importance of hybrid fiber combination in enhancing the wear applications of the polymer composites. The treated 10 wt% AF+10 wt% GF observed high wear loss in the combination due to poor distribution of fiber, causing fiber debonding, fiber breakages with lesser wear resistance. The treated 20 wt% AF+20 wt% GF with 40 wt% of overall hybrid fiber incorporation achieved better results due to improved adhesion of fiber with matrix phase.
ACKNOWLEDGMENTS

The authors would like to acknowledge the support of Prince Sultan University, Riyadh for paying the Article Processing Charge (APC) of this publication.

Data Availability Statement

Data is available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES CITED


applications,” *Tribology International* 122, 143-150. DOI: 10.1016/j.triplanet.2018.02.030


Sciences 23(4), article 2023. DOI: 10.3390/ijms23042023


Palanisamy, S., Kalimuthu, M., Santulli, C., Palaniappan, M., Nagarajan, R., and
Fragassa, C. (2023b). “Tailoring epoxy composites with Acacia caesia bark fibers: Evaluating the effects of fiber amount and length on material characteristics,” *Fibers* 11(7), article 63. DOI: 10.3390/fib11070063


Sivasubramanian, P., Kalimuthu, M., Palaniappan, M., Alavudeen, A., Rajini, N., and


