Analysis of mechanical and water absorption properties of hybrid composites reinforced with micron-size bamboo fibers and ceramic particles

Abstract: Bamboo and its hybrid composites were made using the hand lay-up method to evaluate the change in mechanical and physical properties that occurred through filler addition. Density measurements and tensile test results showed an increment in values when a certain percentage of silicon carbide (SiC) was added. As the SiC percentage grows from 0 to 6%, the density of the hybrid composite increases from 1.15 to 1.36 gm/cc whereas tensile strength increases from 37 MPa to 42 MPa when 4 wt% SiC is added in 20 wt% of the bamboo composite. The scanning electron microscopy (SEM) analysis of tensile fractured samples further supported the improvement in tensile characteristics. To examine the impact and hardness characteristics, composites were subjected to the Charpy impact test and hardness test. 4 wt% of SiC addition in 20 wt% of the bamboo composite decreased the impact strength from 28.79 to 27.43 (×10⁻³ kJ/m²) and increased the hardness from 44 to 55 Hv. The composites' water absorption behavior demonstrated that the addition of filler lifts the composite’s resistance to absorbing water, preserving the composites’ dimensional firmness and mechanical qualities.

Keywords: natural fiber; bamboo; polymer composites; mechanical properties; filler; water absorption

1 Introduction

Because of their environmental friendliness, biodegradability, and high strength, natural fiber-reinforced composites (NFCs) are receiving a lot of attention (Karim et al. 2020; Zhao et al. 2022). Due to the requirements for high strength and economically better composites, substitutes of conventional materials have always been proposed to serve the same purpose (Jagadish and Bhowmik 2021). The mechanical performance of NFCs is extremely significant and to escalate it, various efforts have been put in. Improvement in mechanical properties is dependent on numerous factors which include the fiber volume, filler content, fiber/matrix adhesion, and fiber type (Hassan et al. 2020; Prabhakar et al. 2022; Ramzan et al. 2020). Besides, homogenous dispersion of the fibers and added filler are important parameters that need to be continuously regulated during mixing. Agglomeration due to poor dispersion might reduce the composite’s overall strength (Cruz-Riaño et al. 2021). Poor uniformity can also lead to the composite failing catastrophically (Dasore et al. 2022). Therefore, a uniform distribution of fibers and filler is very much needed for mechanical strength enhancement (Abdul Karim et al. 2022). Fiber content/volume inside the composite also plays a strength-determining role in increasing mechanical strength (Nurazzi et al. 2022). In general, mechanical strength is upgraded by enhancing the fiber content until a particular point. However, composite strength starts to decline as fiber content reaches a certain level (Tahir et al. 2022).

Schneider et al. (Karmaker and Shneider 1996) investigated the mechanical performance of jute and kenaf composites and concluded that jute fibers give higher strength to the propylene than kenaf fibers. Srivastav et al. (2016) examined the mechanical performance of a jute/glass hybrid composite. According to their findings, the mechanical characteristics of the composite are significantly influenced by the loading rate. A comparison between wood-based composites and jute composites made by Munikenche Gowda et al. (1999) showed better strength characteristics in jute composites than in wood composites. Okubo et al. (2004) inspected the strength of bamboo composites and their
dependence on fiber loading whereas Ismail et al. (Ismail et al. 2002) investigated how bonding agents affected the bamboo composite’s mechanical response. The addition of bonding agents improves the interfacial bond increasing tensile strength (Nelson and Riddle 2022).

The addition of filler in polymer composites can be done because of several reasons such as density control, improved hardness, increase in strength, and enhancement in wear resistance (Gupta 2022). Different kinds of fillers can be used e.g. silicon carbide (SiC), silica, charcoal, etc. Yamamoto et al. (2003) investigated how silica addition affected the mechanical characteristics of polymer composites. Furthermore, the shape and size of silica can also influence the character of the composite. Patnaik et al. (2009) inspected the change in the mechanical performance of the composite with a change in filler content. Different filler contents have different effects on composite properties, depending on the compatibility and interaction mechanisms between the filler and the other reinforcement and matrix. The combination of silicon carbide and bamboo in an epoxy composite offers a multitude of application possibilities. It can be utilized in the construction of lightweight yet strong structural components for aerospace, automotive, and civil engineering projects. The composite’s versatility extends to sporting goods, marine applications, and the aerospace industry. Additionally, it shows promise in renewable energy and consumer product sectors, highlighting its wide range of potential applications (Hasan et al. 2023a).

Various studies have been published indicating the importance of natural fibers and filler contents (Arockiam et al. 2022; Hariprasad et al. 2022; Mishra et al. 2022), but very less research has been done on fiber and filler size dependence in bamboo fiber reinforced polymer composite. The physical and mechanical properties of composites can be altered by changing the fiber and filler sizes. As a result, rather than increasing the fiber content, the strength can be boosted further by using the most suitable fiber and filler size. The present research has aimed to study the mechanical, physical, and water absorption characteristics of a hybrid composite reinforced with micron-size bamboo and silicon carbide in an Araldite (5052) epoxy matrix. The obtained results will further open new areas where bamboo/SiC epoxy composites can be used.

2 Experimental

2.1 Materials and methods

The bamboo species Bambusa arundinacea was sourced from a local market in Topi, Pakistan, whereas Nobel Trading Company in Pakistan supplied the Araldite epoxy (Molecular Weight: 392.9 g/mol) and hardener (Molecular Weight: 166.17 g/mol). SiC (200 mesh size) is used for preparing the hybrid composite and was bought from Sigma Aldrich, USA. To obtain the bamboo fibers (length ∼250 μm, diameter ∼25 μm), the bamboo strips were divided into tiny, 2 cm long, 1 cm wide pieces and grounded into small bamboo fibers of micrometer in size. Grounded fibers were then subjected to sieve analysis (911MPELMS Sieving Machine) where fibers were separated based on their diameters. Fibers of some specific size are then used for composite preparation. Composites with variable fiber (0, 10, 20, and 30 wt%) and SiC (0, 2, 4, and 6 wt%) content were made by homogeneously mixing the reinforcement in an epoxy matrix using an overhead stirrer. The epoxy and reinforcement mixture were stirred for 30 min followed by degassing of the mixture in a desiccator to remove the entrapped air. The uniformly stirred and degassed mixture was then cast into a steel mold and left to cure for 24 h at room temperature. Figure 1 shows the composite fabrication method. This study aims to improve the performance of bamboo composite by adding SiC as a filler, therefore, bamboo content inside the composite was first optimized followed by filler content optimization to further enhance the properties of the composite. The addition of SiC changes the colour of the composite and individual filler particles cannot be seen in the polymer composite.

2.2 Characterization

Tensile characteristics of bamboo composites and bamboo/SiC hybrid composites were investigated by using a 30 kN load on a tensile testing
machine (INSTRON 5567-USA) by following the ASTM D3039 standard. A sample size of 250 × 25 × 5 mm was used for testing. To understand the failure mechanism of the fractured samples, a scanning electron microscope (SEM) (Philips – XL 30 – The Netherlands) was used. Archimedes’ principle following the ASTM D792 standard was employed to analyze the density of the composites.

The Charpy impact test was used to assess the composite’s capacity to absorb energy. Samples of size 125 × 12.7 × 10 mm were prepared following the ASTM D6110-10 standard and were tested on a SHIMADZU impact testing machine. Micro-hardness testing on composite materials is done using a Leitz micro-hardness tester. Under the weight of 20 N, a diamond indenter with a square base is pressed onto the sample. As the composite contains bamboo reinforcement which has a hydrophilic character and can absorb water easily, water absorption resistance of the composites was analyzed using ASTM D570-98 standard. Composite samples were weighed and immersed in water for various durations (24–240 h). Samples were taken out and weighed again to evaluate the water absorption behavior of the composite samples.

### 3 Results and discussion

#### 3.1 Physical and tensile properties of composites

Density measurements were performed through Archimedes’ principle to analyze the effect of SiC filler on composites’ properties. The theoretical and experimental density values of the composites are shown in Tables 1 and 2. Density measurements clearly show that the presence of voids during the manufacturing of the composites led to theoretical density values that were greater than experimental density values. Due to insufficient adhesion between the reinforcement and matrix, the void percentage rises with the fiber percentage. A rise in fiber content slightly decreases the composite’s density whereas the filler addition produces a prominent increase in density. A high density of the composites showed that fibers and filler are closely packed and few spaces are present among the two components whereas low-density composites have more spaces. The composite reinforced with 30% bamboo fibers has an excess of fibers and a low matrix content, resulting in void formation since the matrix is insufficient to evenly distribute the fibers. This causes a decrease in density at 30 wt% of fiber loading (Nanda and Satapathy 2017). A close-pack composite structure may also enhance the mechanical characteristics of the composite.

Based on earlier research (Abdul Karim et al. 2020), the composite strength begins to decline as the fiber content increases from 20 to 30 wt%; thus, fiber loadings of 10, 20, and 30 wt% were chosen for examination. Because the fibers are micrometers in size and have a large surface area, the goal is to create high-strength composites with the least amount of filler. As a result, SiC compositions of 2, 4, and 6 wt% are used for analysis. The mechanical properties of the composites are significantly influenced by the amount of bamboo fiber present. The tensile strength and modulus of the composites both rise with an increase in fiber content as shown in Figure 2. When an epoxy matrix is reinforced with only 10 wt% of bamboo fibers, a slight increase in tensile strength and modulus was observed which is due to low fiber content, but as the fiber content reaches 20 wt% the composite showed the highest values of strength and modulus. Better strength properties at 20 wt% are attributed to the homogeneous distribution of fibers within the matrix, which aids the stress mechanism between fibers and matrix. A noticeable decline in mechanical characteristics was seen as the fiber content was raised further, up to 30 wt%. This was due to the fibers’ poor dispersion within the matrix, which affected the stress transfer mechanism. Poor dispersion is due to the high content of fibers, as the matrix is not sufficient to cover up all the fibers thus disturbing the mechanical characteristics. High fiber content leads to poor dispersion and hence affects the mechanical strength negatively. Created defects such as voids act as crack initiation sites leading to composite failure at a low-stress level.

Reinforcing epoxy with 20 wt% bamboo fibers gives the highest strength to the composite, therefore, 20 wt%
was chosen to examine the impact of filler addition on mechanical characteristics. As seen in Table 2, SiC addition increases the density of the composite which means void content reduces composite. A decrease in void fraction enhances the mechanical strength of the composite. As discussed before, three percentages of SiC were chosen to find the most suitable composition of a hybrid composite. Figure 3 also displays the hybrid composites’ tensile strength and modulus data. The highest value of strength and modulus was obtained for a composite reinforced with 4 wt% of SiC filler. High strength in filled composites is due to uniform transmittance of stress by the epoxy to other reinforcements i.e. bamboo and SiC. Enhancement in tensile strength was also caused by the cross-linking that occurs between SiC and bamboo fibers. With a further increase of filler content to 6 wt% stress transmission and cross-linking are affected leading to a decrement in tensile strength. One of the reasons for the improvement in strength is the good dispersion of filler throughout the bamboo fibers and matrix. 4 wt% SiC is sufficient to fill any gaps left by the addition of bamboo fibers (Biswas 2012; N 2018). The addition of filler to voids increases the strength of the hybrid material. In the case of a 6% hybrid composite, the filler is in excess, creating inadequate dispersion among the matrix and reinforcement, resulting in a loss in strength.
The fractured surface of the 20 wt% of bamboo fibers composite and a composite reinforced with 20 wt% of bamboo and of a 4 wt% of SiC were also observed in SEM. The analysis shows that the fractured surface of the composite reinforced with 20 wt% bamboo has a ductile appearance whereas the hybrid of bamboo and SiC showed brittle nature, as seen in Figure 4. Figure 4 (a) demonstrates the reinforcement-matrix interaction, fiber pull-out, and fiber breakage of the bamboo fibers. At 20 wt% of bamboo fibers, good interfacial bonding improves the strength attributes of the composites. Similarly, in Figure 4 (b), a good interfacial bond between the fiber, SiC, and matrix can be seen, resulting in bamboo fiber breakage (Jawaid et al. 2022). The results indicated that epoxy in the presence of bamboo had a ductile character which can be confirmed by the presence of pulled-out fibers on the fractured surface. Fiber pull-out implies a weak interfacial bond and causes crack deflection thus changing the crack direction and fiber debonding. Debonding of the fibers is caused by the matrix detachment from the fibers which leads to composite failure (Hasan et al. 2023c). By ceramic filler addition, the composite turned into a brittle material as can be seen by the presence of brittle zones on the fractured surface. The addition of filler also improves the interfacial bonding between the fibers and matrix, thus increasing the tensile strength. Ductile and brittle behavior can be further related to hardness, i.e. filler addition also increases the hardness of the composites. It is vital to note that raising the SiC content above 4% reduces mechanical strength due to void formation, as seen in Figure 4 (c).

Figure 5 compares the prepared hybrid bamboo/SiC composites to the literature and demonstrates a considerable difference in tensile strength. Biswas (2012) examined the mechanical performance of bamboo short fiber epoxy (LY 556) composites with a varied fiber content of 0, 5, 30, and 45 wt%. Among all composites manufactured, 45 wt% composites had the maximum tensile strength of 10.48 MPa. The hybrid composites are then prepared with SiC particles measuring 80 μm in size using 45 wt% bamboo and 0, 5, 10, and 15 wt% of SiC. The hybrid composite with 10 wt% SiC reinforcement had the maximum tensile strength of

Figure 4: SEM of composite reinforced with 20 wt% of bamboo fiber (a) 0 %, (b) 4 %, and (c) 6 % SiC.
13.44 MPa. When the Biswas (2012) research is compared to the current research, it is clear that the size of the fiber and filler has a significant impact on the tensile strength of the composite, i.e., employing bamboo (250 μm long and 25 μm in diameter) and 200 mesh size SiC in Araldite (5052) epoxy can significantly boost the strength of the composite.

3.2 Energy absorption and hardness of composites

The impact energy of the composite is related to its ability to resist fracture when high-speed stress is applied whereas impact properties indicate the overall toughness of the composite. Composites reinforced with natural fibers are usually employed for structural applications. Therefore, impact energy characteristics are of significant concern (Kumar et al. 2022). Impact energy or fracture toughness depends strongly on reinforcement content and interfacial bonding. Figure 6 shows the impact energy absorption ability of bamboo and its hybrid composites. The impact strength of the composite improves as the bamboo fiber percentage increases. In bamboo composites, impact strength can be affected by crack bridging, friction between the matrix and reinforcement, and wetting characteristics of the two components. For short fiber composites, pull-out fibers during fracture also help in high energy absorption. Fiber pull-out is more prominent in composites with weak...
interfacial bonds. That is why the composite reinforced with bamboo has absorbed more energy than the hybrid composite reinforced with bamboo and SiC (Dassios 2007). SiC in the hybrid composite holds the fibers tightly and restricts fiber pull-out resulting in low energy absorption (Wang et al. 2015). A reverse trend was observed in the hybrid composite where increased filler loading decreases the impact strength. Reduction in impact properties at high filler content may also be due to micro spaces created during composite manufacturing that act as crack initiation sites.

Figure 7 shows the relationship between hardness and reinforcement content in the composites. As the epoxy polymer is much softer than the bamboo fibers and SiC, an increase in reinforcement loading will enhance the hardness of the composite (Chidhananda et al. 2021). In bamboo composites, an increase in fiber loading significantly increases the hardness because of the higher hardness of bamboo fibers than epoxy. That’s why the composite with a higher content of bamboo showed a high hardness value (Webo et al. 2018). Similarly, for the hybrid composite, enhancement in hardness is linked with the increase of filler content. The hardness of SiC is much higher than that of bamboo and epoxy, which is why filler addition further increases the hardness of the composite. When evaluating the wear characteristics of the composite, the hardness of the composite plays a vital role.

### 3.3 Water absorption characteristics of composites

The properties of the natural fiber composites are negatively impacted by water absorption. It not only affects the dimensional stability of the composites but also changes their mechanical characteristics (Kushwaha and Kumar 2009). Figure 8 shows the water absorption of the prepared composites and its dependence on bamboo fiber content and filler loading. Bamboo fiber is cellulosic with hydroxyl groups (Hasan et al. 2023b; Judawisastra et al. 2017). Hydroxyl groups make the fibers hydrophilic having the ability to absorb water resulting in a weight increase. Regarding this fact, cellulosic content in a composite plays a vital role in water absorption and a composite with higher content of cellulosic fibers absorbs more water than a composite with less fiber content. The curves also indicate that the percentage of water absorbed is rapid in the initial stages and becomes constant after a certain interval. This is known as the saturation point, and no additional rise in water absorption was recorded after this threshold.

SiC addition affects the water absorption properties significantly. Obtained results showed that filler addition increases the composite’s resistance toward water absorption and with an increase in filler loading water absorption decreases. The addition of SiC to the 20 % bamboo composite increases the composite’s resistance to water absorption. This decrease could be attributed to the fact that the used SiC particles are hydrophobic in nature (Socha et al. 2002). In addition, the gaps that exist in unfilled composites that contribute to moisture gain are filled with filler particles, resulting in a reduction in moisture absorption in hybrid composites. Less water absorption is associated with the high density of the hybrid composite, i.e. a composite with less void content has a higher density, whereas a composite with a large number of voids has a lower density (Hariyadi and Tamai 2015). Therefore, SiC filler is a suitable candidate for increasing the barrier properties of the bamboo composite. Filler addition creates tortuous pathways resulting in less water absorption (Thwe and Liao 2002). As discussed earlier, SiC also helps in making a strong interfacial bond between the fibers and matrix, therefore, strong bonding also resists the...
movement of water molecules toward the fibers (Espert et al. 2004). The hybrid composite reinforced with 20 wt% bamboo and 6 wt% SiC showed the lowest water absorption.

As mentioned earlier, water absorption in natural fiber composites occurs when water penetrates the interface, saturating the natural fibers and filling the pores, resulting in fiber swelling. However, only fibers with a weakened interface are susceptible to swelling. Although there is a chance that swelling might increase the thickness of the sample, the presence of SiC in the composite enhances its hardness. The exceptional hardness and strength of the composite effectively restrict overall swelling. The composite with SiC reinforcement has a reduced susceptibility to water absorption and swelling compared to natural fiber composites without SiC. Hence, the absence of significant swelling was noted.

4 Conclusions

To analyse the physical and mechanical characteristics, we prepared micron-size bamboo-reinforced epoxy composites and hybrid composites of bamboo and SiC. Density measurements revealed that adding 4 wt% of SiC to 20 wt% of the bamboo composite increased the density from 1.15 to 1.28 gm/cc. The tensile characteristics of the composites exhibited a significant improvement with increasing fiber loading and filler quantity up to a specific limit. With the addition of 4 wt% of SiC to 20 wt% bamboo composites, there was an observed increase of 13.8 and 20 % in tensile strength and modulus, respectively. SEM analysis of the fractured surface revealed different fracture types, including ductile and brittle fractures, along with various defects. Impact energy absorption test results indicated a decrease of 4.95 % in energy absorption with filler addition, while the hardness test showed an increase of 25 % when 4 wt% of SiC was added. Furthermore, the water absorption resistance of the composite was negatively affected by the addition of fillers, with higher filler content leading to increased resistance to water absorption.

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