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Tensile and Impact Properties of Woven Glass Fibers/Epoxy Composites Filled with Short Glass Fibers

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Abstract

Glass fiber/polymer composites are widely utilized in many structural applications because of their high specific strength and stiffness-to-weight ratios. In this study, woven glass fiber/epoxy was hybridized with short glass fibers of different lengths (2, 4, 6, 2+4, 2+6, and 4+6 mm) and contents (3, 6, 9, and 12 wt%) to produce hybrid woven SGF/epoxy composites. Variations in the thickness, fiber volume fraction, density, and void content of the prepared composites were determined. Mechanical tests such as tensile and Charpy impact tests were conducted. Compared to the woven fabric composites without short glass fibers (control samples), the tensile strength increased by approximately 13% at an optimum weight fraction of 3 wt% using short glass fiber lengths of 4 mm. Meanwhile, the incorporation of short glass fibers into the woven glass composites decreased the tensile modulus for all lengths. The maximum enhancement in the impact strength (approximately 14%) was achieved by the hybrid composite samples reinforced with 4 mm of short glass fibers at 3 wt%. This hybrid composite offers 18% and 20% improvements in the specific tensile and impact strengths, respectively. In summary, filling the woven fabric composites with specified short fiber contents and lengths can increase their mechanical performance when resin-rich regions are reinforced with short fibers without forming relatively thick interleaves between the woven fabric plies.

Keywords: Hybrid Composites; Interleaf; Mechanical Properties; Resin-Rich Region; Short Glass Fibers; Woven Glass Fibers

1. Introduction

Owing to the preferrable specific properties of polymeric matrix composites, such as their high stiffness and strength-to-weight ratios, they are widely used in automotive, aerospace, sporting goods, structural components, biomedical devices, and other applications [1]-[3]. Carbon and glass fibers are common reinforcements that have been widely used to enhance the mechanical properties of polymeric matrices. These reinforcements are used in composites in both continuous and discontinuous forms [4]-[6]. Although the best mechanical properties can be obtained when using continuous fiber-reinforced composites (i.e., unidirectional or woven), discontinuous short-fiber composites have been utilized in several fields owing to their appropriate mechanical properties [7],[8]. In the automotive industry, discontinuous fiber-reinforced composites can be used owing to their cost-effectiveness, better formability, and good balanced mechanical properties such as stiffness, strength, and toughness [9]. Composites reinforced with woven fabrics have been widely used in structures that require balanced in-plane mechanical properties and improved impact strengths relative to unidirectional fiber-reinforced composites. However, the mechanical properties of such composites are highly related to the loading direction relative to fabric yarn alignment. Other problems that can arise from utilizing interlaced yarns within woven fabrics are the presence of undulation (crimp) at the yarn crossover regions and matrix-rich regions that are related to them [10]. In woven fabric composites, matrix-rich regions are places where the matrix material is the predominant phase over reinforcement. These regions locally affect the initiation and propagation of internal microcracks within the woven composites, which play a crucial role in the dispersion of composite strength. Spread tow technology [11], nanoparticle-filled matrix [12],[13], and short fiber-filled matrix [14] are some of the available solutions that have been used successfully to reduce the detrimental effects of resin-rich regions and, therefore, to enhance the mechanical properties of woven fabric composites.

Recently, the hybridization of woven-short fibers within composites has been investigated to demonstrate the effect of the inclusion of short fibers in woven polymeric composites. The purpose of developing hybrid composites is to simultaneously exploit the possible advantages of their constituents [15]-[19]. Park et al. [20] studied the potential advantages of incorporating short glass fibers (SGFs) into plain-woven glass fabric/PVC composites, and their tensile, interlaminar shear, and flexural strengths were assessed. Different lengths (1–6 mm) and weight ratios (5–30 wt%) of SGFs were used in their study. The findings revealed that in comparison with fabric-reinforced composites without SGFs, the inclusion of these fibers slightly increased the mechanical properties of the hybrid composites at various short fiber lengths and filling weight ratios. It was concluded that the length and content of the SGFs should be carefully selected to maximize the required mechanical properties. Lee et al. [21] extended Park's study [20] to include the effect of incorporating silane-treated SGFs into the woven glass fabric/PVC composites on the mechanical and dynamic mechanical-thermal properties of the hybrid composites. The results showed that the silane coupling treatment increased the adhesion strength between the SGFs and PVC. Accordingly, a greater improvement in the mechanical properties was obtained when compared to composites reinforced with untreated SGFs. Mörl et al. [10] used SGFs with average length slightly greater than 0.14 mm to reinforce the matrix-rich area of the laminated twill E-glass fabric/polyamide composites with concentrations of 5, 10, 15, and 20 wt%. They showed that filling the matrix-rich regions with 10 wt% of SGFs increased the tensile, compressive, and shear moduli by up to 10%, 6%, and 40%, respectively. Maximum improvement in the tensile strength was approximately 7% compared with samples without SGFs at 10 wt%. However, compressive strength showed a decreasing trend for all hybrid composites. The formation of weak interleaves between adjacent woven glass fabrics occurred when the SGFs content exceeded 10 wt%. These interleaves have a low volume fraction of SGFs, which contributes to a reduction in the improved mechanical properties after reaching a plateau. Dasari et al. [22] investigated the effect of the incorporation of SGFs with different lengths (combined of 2 to 5 mm) and weight ratios (0.1 to 0.5 wt%) into the epoxy matrix on the flexural behavior of modified short glass-woven glass hybrid composites. The inclusion of 0.1 wt% of SGFs into the woven/glass composites provided the highest improvement in the flexural strength and modulus of approximately 24% and 7%, respectively. The authors attributed this improvement to the good dispersion and lower agglomeration when adding 0.1 wt% of SGFs within the composites compared to other weight ratios. Dasari et al. [14] extended the work in [22] using short carbon fibers with lengths combined of 2 to 5 mm as a secondary reinforcement within the woven glass fiber/epoxy composites. They assessed the effect of adding different weight ratios (0.1–0.5 wt%) of short carbon fibers to the epoxy matrix on the tensile, flexural, and interlaminar fracture toughness of the hybrid composites. The best filler concentration of short carbon fibers that offered the highest improvement in mechanical properties was 0.1 wt%. The highest improvements in the tensile properties (strength and modulus), flexural properties (strength and modulus), and interlaminar fracture toughness (modes I and II) were about (29%, 21%), (17%, 9%), and (13%, 20%), respectively.

To the best of our knowledge, few studies have focused on investigating the effect of adding short fibers to woven composites to reinforce matrix-rich regions. Most of these studies used thermoplastic polymeric matrix composites. Therefore, further studies are required to comprehensively understand the effects of adding short fibers to thermoset polymeric composites reinforced with woven fabrics and to determine the conditions under which the short fiber length and its concentration would offer maximum improvement in the mechanical properties of the composite. Therefore, this study aimed to hybridize discontinuous glass reinforcements in the form of SGFs with different lengths and weight ratios with E-glass woven fabric/epoxy composites to reduce the detrimental effects of resin-rich regions. Tensile and impact tests were conducted to assess the feasibility of the hybridization process on the mechanical properties of the hybrid woven-SGFs/epoxy composites.

2. Materials and Methods

2.1. Materials

Plain-weave E-glass fabrics and short E-glass fibers of different lengths (2, 4, and 6 mm) were used as the primary and secondary reinforcements (i.e., filler in the matrix), respectively. An epoxy resin (Quickmast 105) was used as the thermosetting matrix phase. The mixing ratio of the epoxy resin to hardener was 4:1 by volume. The properties of the glass fibers and epoxy matrix are listed in Table 1.

Table 1. Properties of the woven E-glass fabric, SGF, and epoxy matrix used in the current work [23], [25].

Property	E-glass fibers	Epoxy resin
Tensile strength (MPa)	3450	≥ 25
Tensile modulus (GPa)	72	3.5
Density (g/cm^3)	2.56	1.1
Areal density (g/m^2)	600±30	-
Count of cloth (end/m)	260	-
Filament diameter (μm)	17	-
Tex	1200	-

2.2. Fabrication of the Composites

In this work, three different SGF lengths (2, 4, and 6 mm) were separately used as secondary reinforcements in the epoxy resin at weight ratios of 3, 6, 9, and 12 wt% relative to the epoxy. In addition, three different short-fiber mixtures (compositions) were used. Each of them contains equal weights of two different fiber lengths (e.g., 2+4 composites contain equal weights of both 2 mm and 4 mm of SGFs). This produces three different mixtures, each having two different short fiber lengths (i.e., 2 mm with 4 mm, 2 mm with 6 mm, and 4 mm with 6 mm). The steps of the fabrication process were as follows:

- The SGFs were placed in an oven at 60 °C for five hours to remove humidity prior to their inclusion in the epoxy as a filler.

- The required weight ratio of the SGFs relative to the epoxy resin was incorporated into the epoxy resin and mixed well using a magnetic stirrer at 200 rpm for 30 min.
- A hand layup procedure was used to manufacture composite sheets with 200 mm × 300 mm dimensions. Eight layers of woven E-glass fabric were used as the primary reinforcements for each composite.
- During the curing process, the composite constituents were subjected to a constant pressure of 10 kPa at a room temperature of 38±2 °C.
- After 24 hours, the composite sheets were removed from the mold. Therefore, 25 different composite sheets (woven glass/epoxy composites with and without SGFs) were fabricated.
- A band saw machine was used to cut the composite samples according to the dimensions recommended by testing standards.

The percentage of the fiber volume fraction of hybrid composites was calculated using equation (1) as per [25].

$$V_f\% = \left(\frac{\frac{W_{sho}}{\rho_{sho}} + \frac{W_{wov}}{\rho_{wov}}}{\frac{W_c}{\rho_c}}\right) \times 100 \quad (1)$$

where:

V_f = composite fiber volume fraction, W_{sho} = weight of SGFs, W_{wov} = weight of woven glass fabrics, ρ_{sho} = density of SGFs, ρ_{wov} = density of woven glass fiber, W_c = composite's weight, and ρ_c = actual composite's density.

The fabricated composites along with their descriptions are listed in Table 2.

2.3. Microscopic Examination

The specimens from the composite sheets were polished using a fine emery cloth to achieve a smooth surface. The resin-rich regions and distribution of the SGFs in the composites were examined using a light microscope (DH Scientific, D 50374, Germany).

2.4. Density and Void Content of Composites

The densities (ρ_c) of the composite samples were measured according to the ASTM D792 standard [26]. The composite samples were weighed separately in air and distilled water (suspended specimens). The water temperature was maintained at 23±0.2 °C. A laboratory digital balance with an accuracy of ± 0.001 g was used to measure the weight. The density of the composite (ρ_c) was calculated as follows [26]:

$$\rho_c = \frac{W_a}{W_b} \times 0.9975 \quad (2)$$

where:

W_a = specimen weight in air, W_b = specimen weight in water, and 0.9975 g/cm³ is the density of water at 23°C.

The void content in the composites was analyzed according to ASTM D2734 [27] as per (3):

Table 2. Description of fabricated composites.

Designation	Used SGFs (Length mm, weight fraction%)	SGFs weight ratio in the composites (wt%)
Control	-	0
2	(2,100)	3
2	(2,100)	6
2	(2,100)	9
2	(2,100)	12
4	(4,100)	3
4	(4,100)	6
4	(4,100)	9
4	(4,100)	12
6	(6,100)	3
6	(6,100)	6
6	(6,100)	9
6	(6,100)	12
2+4	(2,50) + (4,50)	3
2+4	(2,50) + (4,50)	6
2+4	(2,50) + (4,50)	9
2+4	(2,50) + (4,50)	12
2+6	(2,50) + (6,50)	3
2+6	(2,50) + (6,50)	6
2+6	(2,50) + (6,50)	9
2+6	(2,50) + (6,50)	12
4+6	(4,50) + (6,50)	3
4+6	(4,50) + (6,50)	6
4+6	(4,50) + (6,50)	9
4+6	(4,50) + (6,50)	12

$$V = 100 - \rho_c\left(\frac{R}{D} + \frac{r}{d}\right) \quad (3)$$

V = void content %,
R = percentage weight ratio of the resin in the composite,
r = percentage weight ratio of the fiber in the composite,
D = resin density, and
d = fiber density.

2.5. Tensile Test

Tensile tests were conducted using a universal tester machine (200KN-WDW-200E) with a crosshead speed of 2 mm/min. Composite specimens with dimensions of 25 mm × 250 mm as shown in Fig. 1. were prepared in accordance with the ASTM D3039 standard [28]. Three specimens were tested for each grouped composite, and the average readings were recorded. This means the overall number of specimens required for tensile tests was 75 specimens.

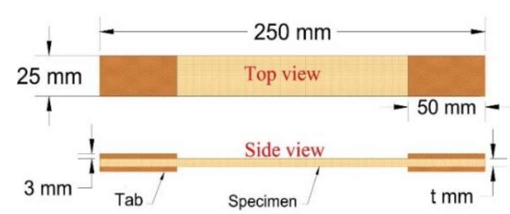

Figure 1. The geometry of the specimen for tensile tests.

2.6. Impact Test

The absorbed energy was measured for the composite samples in accordance with the ISO 179 standard [29] using Charpy's model. The impactor weighed 2.05 kg at an impact speed of 3.8 m/s. Unnotched composite specimens with dimensions of 55 mm × 10 mm were prepared as shown in Fig. 2. The absorbed energy for each sample was divided by its sectional area to obtain the impact strength. The average of three samples was considered. This means the overall number of specimens required for impact tests was 75 specimens.

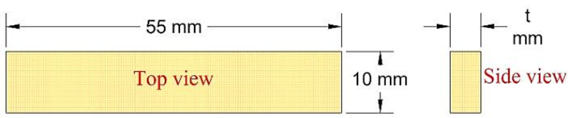

Figure 2. Geometry of the specimen for impact tests

3. Results and Discussion

Fig. 3 shows microscopic images of woven fiber/epoxy and hybrid woven-SGF/epoxy composites using SGFs with a length of 2 mm at various filling weight ratios. The distribution of SGFs was observed between the interlacing yarn sides, and interleaves were formed even when using a 3 wt% content. The addition of SGFs to the woven/epoxy composites increased the composite thickness. Increasing the inclusion of SGFs in the composites increased the overall thickness of the hybrid composite, which is in agreement with Park's results [20]. The variations in the thicknesses of the different composite sheets with the inclusion of SGFs at different weight ratios and lengths are shown in Fig. 4. In the case of using 2 mm length of SGFs and 3 wt%, the thickness of the composite increased from 3.76 mm to 4.05 mm and continued to increase until it reached to 5.1 mm at 12 wt%. In addition, increasing the length of the SGFs led to a greater increase in thickness for the same wt%. This behavior was attributed to the displacement of the SGFs within the uncured epoxy resin after pouring them between the woven fabrics. This displacement decreased with an increase in the length of the short fibers owing to the higher resistance (i.e., drag force) by the viscous epoxy liquid, in addition to increasing the entanglement between the short fibers [30]. Therefore, moving the SGFs into matrix-rich regions was restricted to a lower number of short fibers as their length increased. On the other hand, the overall fiber volume fraction (i.e., woven and SGFs) decreased regularly with increasing percentage content of short fibers, as shown in Fig. 5. The presence of interleaves contributes to the decrease in the overall fiber volume fraction, as they have a very low spatial volume fraction of SGFs. Fig. 6 shows the effect of the incorporation of SGFs on the density of the composites. Although glass fibers have a density greater than that of the epoxy matrix, the addition of SGFs to the woven glass/epoxy composites led to a reduction in the density of the hybrid composites. This result appears positive in the first insight; however, it was accompanied by a reduction in the overall fiber volume fraction of the composites. Additionally, the formation of voids contributed to the reduction in the composite density with an increase in the weight ratio of the SGFs. These empty pores are third-phase pockets within the fiber-reinforced composites that negatively affect their mechanical properties. The formation of these voids increased as the length and content of the short fibers increased, as shown in Fig. 7. Voids were presented at the short fiber ends and along its sides. Increasing the content and length of the SGFs within the viscous epoxy resin would increase the possibility of forming these defects as the small air/gaseous bubbles were entrapped between the entangled SGFs.

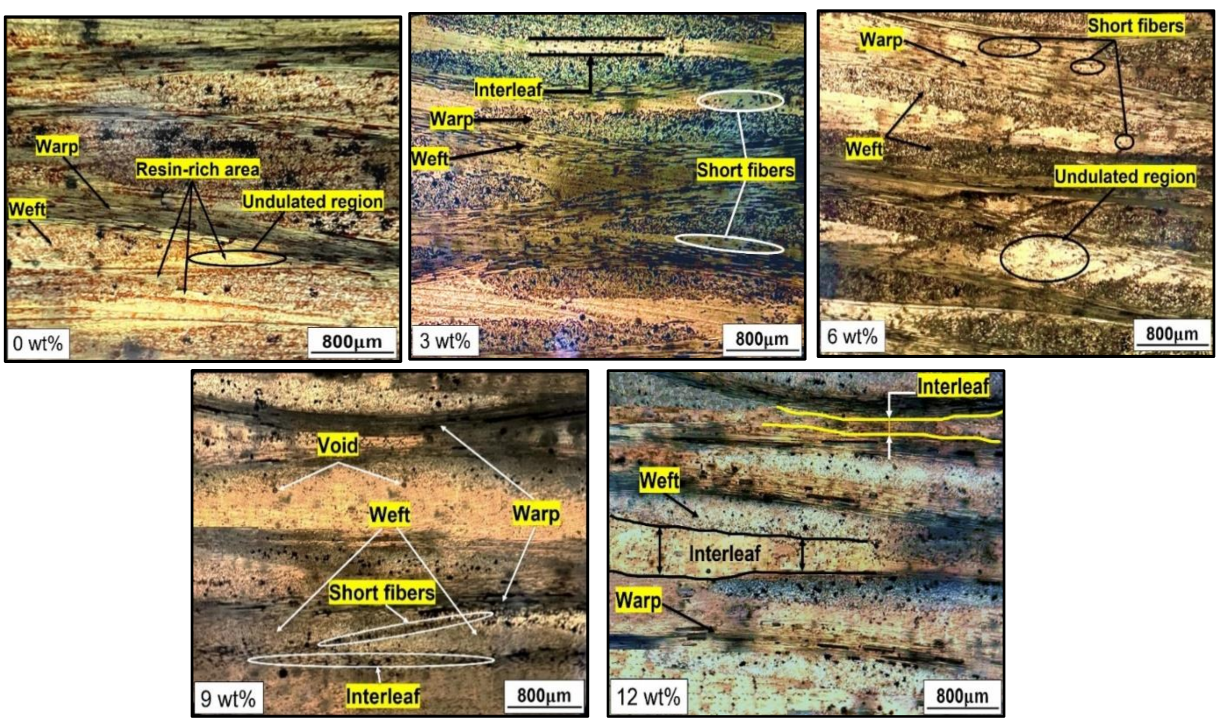

Figure 3. Microscopic images of composites reinforced with 2 mm of SGFs at different weight ratios

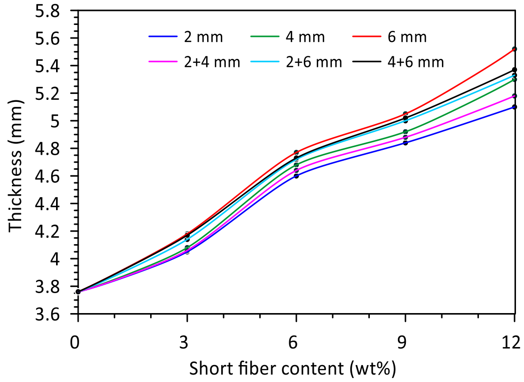

Figure 4. Effect of SGFs length and their content on the composite thickness.

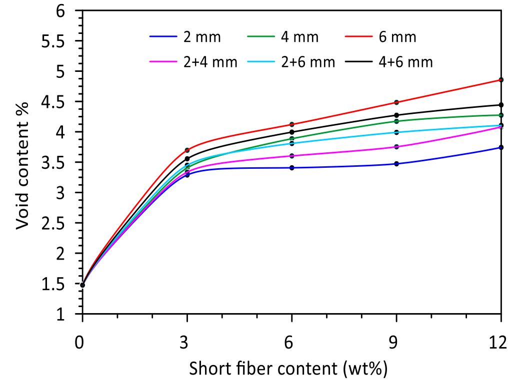

Figure 7. Effect of SGFs length and their content on the composite void content

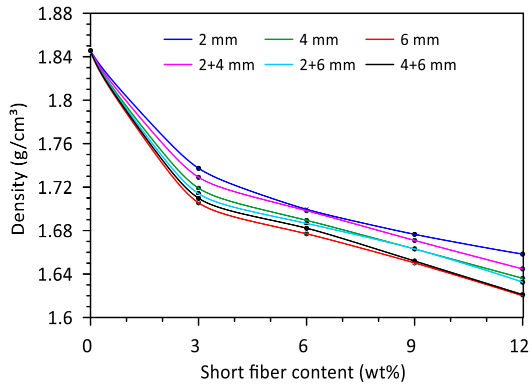

Figure 5. Effect of SGFs length and their content on the overall fiber volume fraction of the composite

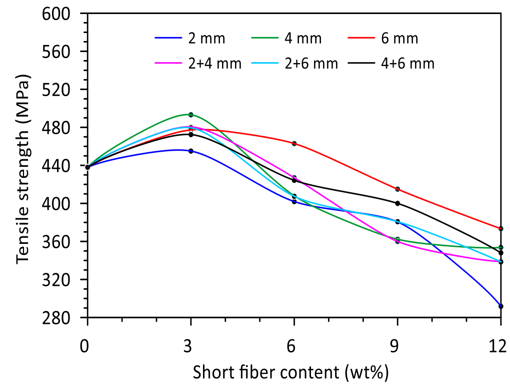

Figure 8. Effect of SGFs length and their content on the composite tensile strength.

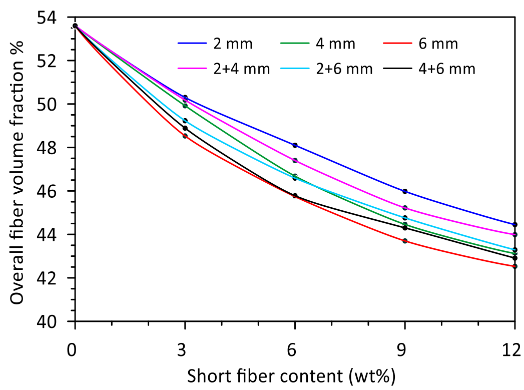

Figure 6. Effect of SGFs length and their content on the composite density

Fig. 8 shows the relationship between the tensile strength and SGFs content (wt%) for different short fiber lengths. The results indicated that the tensile strength of the woven-short fiber hybrid composites improved with the addition of a certain amount of SGFs and then decreased at higher short fiber contents. At a fiber content of 3 wt%, the highest values were obtained for all hybrid composites.

The maximum improvement in the tensile strength (approximately 13%) was found for composite samples filled with 4 mm of SGFs at 3 wt% compared to the reference samples (i.e., woven glass fabric/epoxy composites).

In addition, this hybrid composite exhibited a maximum improvement in the specific tensile strength of approximately 18% relative to the control samples. The specific property was obtained by dividing the property of the composite by its density. A similar trend was observed for samples filled with other SGF lengths. For composites reinforced with woven fabrics, only the epoxy matrix filled the undulated regions of the plain-woven composites. The addition of short fibers with an optimal percentage and length into the composite tends to improve the tensile strength by filling the undulated region with short fibers and improving the interfacial bonding between the fibers within the woven yarns and epoxy matrix. Another advantage that could be obtained by incorporating short fibers between the fabrics is layer bridging [31]. The bridging of adjacent fabric layers effectively prevented crack propagation; therefore, the tensile strength increased. It is noteworthy that hybridizing short fibers with woven fabrics affects the hybrid composite performance in two opposite ways. The first is to reinforce the resin-rich regions in the interlaced yarns (i.e., a positive effect). The second trend is the increase in the composite thickness owing to the formation of weak interleaf layers (i.e., detrimental effects). The inclusion of low SGF content led to the lowest change in the composite thickness and the highest fiber volume fraction as compared with higher samples filled with higher filler contents. When the short-fiber content increased, thicker interleaves formed between the woven glass fabric layers. Increasing the void content with increasing weight fraction of the SGFs is another reason for the deterioration of the tensile strength of the hybrid composites. These voids increase the localized stress concentrations. Subsequently, the ability of the material to withstand external tensile loading was reduced.

The effect of adding SGFs to the woven glass/epoxy composites with different lengths and contents on the tensile modulus of the hybrid composites is shown in Fig. 9. The control samples had the highest tensile modulus among the hybrid composite samples that contained SGFs. The degradation of the tensile modulus of the hybrid composites could be related to the formation of interleaf layers. These weak layers comprise short fibers with uneven distribution and random alignment within the epoxy matrix, which reduces their ability to regularly transfer the load from the matrix to the reinforcing fibers. Therefore, a lower tensile stress is required to strain hybrid composites.

The fractured tensile samples are shown in Fig. 10. Delamination between the woven plies close to the fractured surface and fiber pull-out was observed. Because the shortest length of the used SGFs is larger than the critical fiber length, short fibers directed in the loading direction would break rather than be pulled out [32], [33]. Misaligned fibers that are directed randomly within the matrix relative to the loading direction are exposed to peeling stress at the fiber-matrix interface. Subsequently, fiber-matrix debonding and fiber pull-out from the matrix occur with an increase in the tensile load to a level higher than the composite ultimate strength [32].

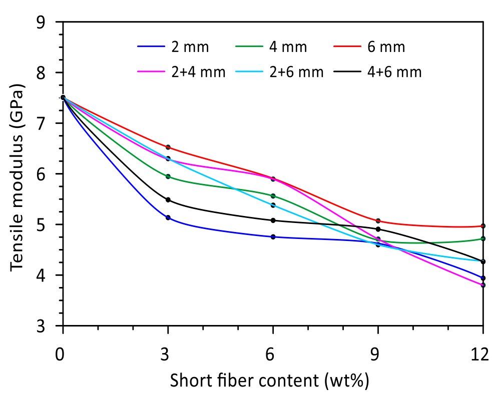

Figure 9. Effect of SGFs length and their content on the composite tensile modulus

Fig. 11 shows that the best performance against impact loading was achieved when the SGFs length was 4 mm at a content equal to 3 wt%. This hybrid composite provided improvements in the impact strength and specific impact strength of approximately 14% and 20%, respectively, compared to the control sample counterparts.

Similar behavior was observed for the fiber length of 2+4 mm at the same fiber content but with lower improvement owing to using a lower number of 4 mm lengths in the mixture of 2+4 mm at the same wt%. Bridging between adjacent woven plies provided by short fibers plays an important role in absorbing the impact energy by obstructing the delamination of plies owing to midspan impact loading. In addition, increasing the fiber length and content resulted in higher interleaf thickness and void content, leading to a loss of the advantages obtained at 3 wt%.

Figure 10. Images of specimens after tensile tests

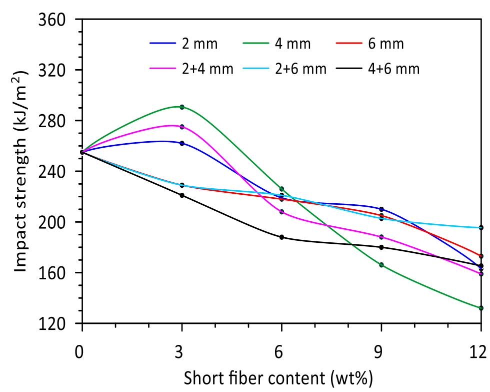

Figure 11. Effect of SGFs length and their content on the Composite Impact Strength

Fig. 12 shows the composite samples prepared in this study after the impact event. The dominant failure modes in most of the tested specimens were plies delamination, fiber debonding, and fiber breakage. Fig. 13 shows the percentage changes in the mechanical properties (tensile and impact) of hybrid short-woven glass/epoxy relative to woven glass/epoxy composites (control samples). The maximum enhancement in the tensile and impact strengths increased by approximately 13% and 14% at an optimum weight fraction of 3 wt% using short glass fiber lengths of 4 mm. Meanwhile, incorporating SGFs into the woven glass composites decreased the tensile modulus for all used lengths.

4. Conclusions and Future Works

This study investigated the tensile and impact properties of woven glass fiber fabric/epoxy composites filled with SGFs of various lengths and contents.

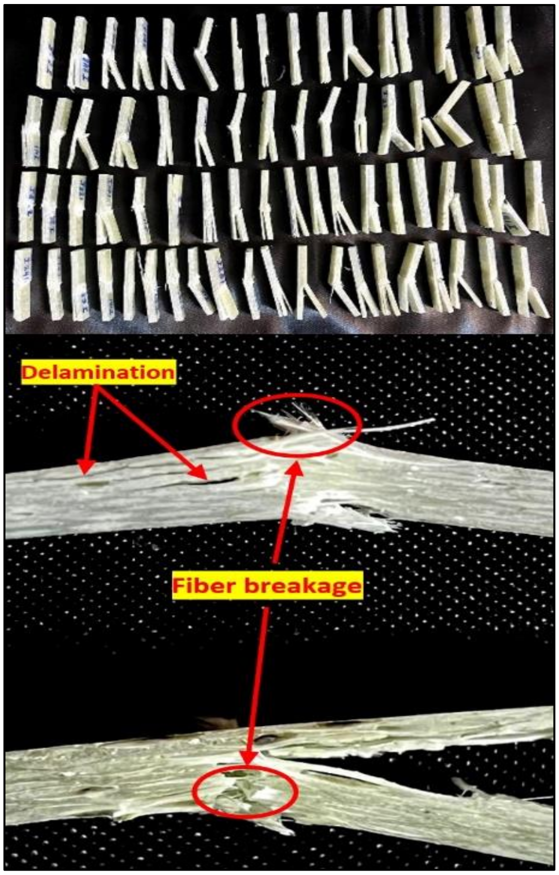

Figure 12. Failure modes of specimens after impact tests

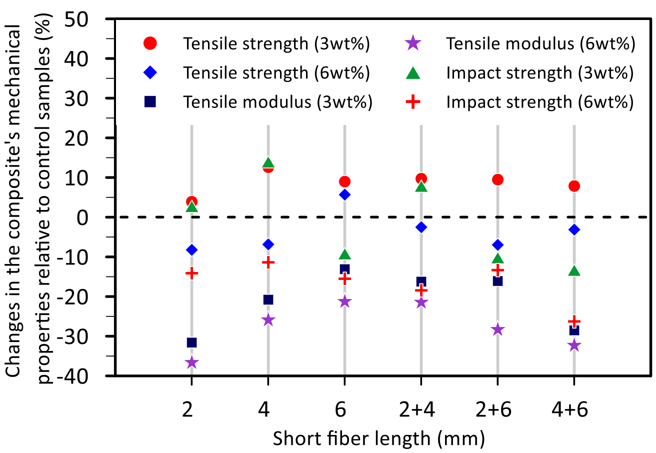

Figure 13. Percentage variation of tensile and impact properties for hybrid short-woven glass/epoxy relative to woven glass/epoxy composites.

The study showed that the inclusion of SGFs in woven glass composites increased their thicknesses owing to the formation of interleaves between the plies. This led to a decrease in the fiber volume fraction of the hybrid composites and an increase in the void content. Adding SGFs with a length of 4 mm at 3 wt% content to the woven glass fabric/epoxy composites offered the highest improvement in the tensile and impact strengths of approximately 13% and 14% respectively, compared with the control samples. A greater improvement was obtained when these properties were related to the composite densities (18% for the specific tensile strength and 20% for the specific impact strength). With respect to the tensile modulus, the results showed a gradual decline in the composite stiffness as the length and content of the SGFs increased. The short fiber length and its weight ratio should be carefully selected to reinforce the resin-rich regions with minimal interleaf formation.

The future work will focus on using weight fractions of SGFs less than 3 wt% with small incremental steps to inspect the potential improvement in the hybrid composites' mechanical properties at lower SGF addition content. In addition, coupling agent treatment will be utilized for the SGFs to increase their adhesion strength with the epoxy matrix and examine its effects on the composite's mechanical properties and vibration characteristics.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Nawras H. Mostafa proposed the research problem and its aim in this research. Haider S. Ward conducted the laboratory experiment, analyzed the data, and wrote the paper. Nawras H. Mostafa supervised the findings of this work while both authors discussed the results and contributed to the final manuscript

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