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Effects of silica nanoparticles on glass and carbon fiber epoxy composites

Efectos de las nanopartículas de sílice sobre compuestos epoxi de fibra de vidrio y carbono

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ABSTRACT

In a variety of industries, including construction, automotive, marine, and aerospace, hybrid composite materials have great promise as engineering materials. By carefully choosing both the fibers and matrix employed, they enable designers to obtain desired qualities to a significant degree. The qualities of the material may be altered and adapted by adding various fiber types to a common resin matrix. In order to assess their potential for structural applications, the mechanical properties of a glass and carbon fiber epoxy composite reinforced with silica nanoparticles were examined and compared to those of clean epoxy. The samples were created using the vacuum bag process and heat-cured regardless of the laminated material. To guarantee accurate and trustworthy findings, mechanical characteristics including E_1, E_2, G_{12}, and v_{12} were assessed using the tensile test and the relevant ASTM standards. To evaluate substantial variations in the mechanical characteristics of the glassy epoxy and carbon epoxy composites, experimental and numerical modeling will be used. The findings of this study suggest that silica nanoparticles improve the mechanical properties of composite materials. As a result, performance and strength are enhanced when using these reinforced epoxy compounds in structural applications.

Keywords: Reinforced polymer; mechanical properties; hybrid nano silica composites; glass fiber.

RESUMEN

En una variedad de industrias, incluidas la de la construcción, la automotriz, la marina y la aeroespacial, los materiales compuestos híbridos son muy prometedores como materiales de ingeniería. Al elegir cuidadosamente tanto las fibras como la matriz empleada, permiten a los diseñadores obtener las cualidades deseadas en un grado significativo. Las cualidades del material pueden alterarse y adaptarse añadiendo varios tipos de fibras a una matriz de resina común. Para evaluar su potencial para aplicaciones estructurales, se examinaron y compararon las propiedades mecánicas de un compuesto epoxi de fibra de vidrio y carbono reforzado con nanopartículas de sílice con las de un epoxi limpio. Las muestras se crearon mediante el proceso de bolsa al vacío y se curaron con calor independientemente del material laminado. Para garantizar resultados precisos y confiables, se evaluaron las características mecánicas, incluidas E1, E2, G12 y v12, mediante la prueba de tracción y las normas ASTM pertinentes. Para evaluar variaciones sustanciales en las características mecánicas de los compuestos de epoxi vítreo y epoxi de carbono, se utilizarán modelos experimentales y numéricos. Los hallazgos de este estudio sugieren que las nanopartículas de sílice mejoran las propiedades mecánicas de los materiales compuestos. Como resultado, el rendimiento y la resistencia mejoran cuando se utilizan estos compuestos epoxi reforzados en aplicaciones estructurales.

Palabras claves: Polímero reforzado; propiedades mecánicas; compuestos híbridos de nanosílice; fibra de vidrio.

INTRODUCTION

Due to their superior specific properties, composite materials have many advantages over more traditional materials. These advantages include high strength and stiffness-to-weight ratios, enhanced corrosion and environmental resistance, design flexibility, improved fatigue life, and the potential for lower processing, fabrication, and life cycle costs (Aktaş et al., 2009; Mallick, 1993). (Yuan et al., 2019) used ultra-thin unbonded non-woven Short Aramid Fiber (SAF) veils to enhance laminar carbon fiber composites with weak ply interfaces. Carbon fiber-reinforced polymer laminates with several ultra-thin SAF interfacial layers were tested for impact behavior and compressive strength. According to studies, the mechanical properties of epoxy nanocomposites have been shown to significantly improve when nanoparticles are added. These improvements include several qualities, including tensile strength, fracture toughness, impact resistance, hardness, and fatigue characteristics (Burmistrov et al., 2013; Mostovoy et al., 2022; Oun et al., 2022). However, modern research trends also include polymer composites reinforced with various fillers.

In addition to the aforementioned uses, filler-bound composites are useful in the manufacture of sporting goods, home furnishings, and industrial items (Aljeboree et al., 2022; Balsure et al., 2023). As a result, a variety of fillers are added to improve the mechanical and physical attributes of polymer composites. Levy and Papazian looked into the tensile characteristics of SiC whisker-infused aluminum matrix composites.

The findings of the experiment were contrasted with those of the finite element model. The analytical findings were found to closely match the experimental values. Notably, when the SiC filler content rose throughout their experiment, they saw a decrease in Young's modulus (Levy & Papazian, 1990). In addition, it has been shown that adding nanofillers such as nanoclay, carbon nanotubes, titanium dioxide (TiO_2), and silica dioxide (SiO2) to the polymer matrix improves a number of characteristics. These include enhanced load-bearing capacity, fire resistance, fracture toughness by delaying the onset and progression of cracks, greater wear resistance, better thermal characteristics, and a reduction in the coefficient of friction (Demirci et al., 2017; Nazarenko et al., 2016). Due to their large specific surface area, outstanding mechanical capabilities, cost-effectiveness, and strong bonding ability with the polymer matrix, silica (SiO_2) nanoparticles have become one of these nanofillers that has seen substantial growth (Brunner et al., 2006; Han & Cho, 2006; Tzetzis et al., 2013). Tjong (Tjong, 2006) gave a summary of current developments in polymer nanocomposites reinforced with layered silicates, ceramic nanoparticles, and carbon nanotubes (CNT) in terms of manufacturing, structure, and mechanical characteristics. The parts that follow will go into further detail on this subject. (Agag et al., 2001) examined the thermal expansion coefficient of BPDA/PDA polyimide film and found that the value dropped when clay was added. (Crosby & Lee, 2007) examined the impact of nanoscale factors on the mechanical properties of polymer nanocomposites. The interfacial area, nanoscale filler, and polymer matrix, which together make up these composites' three main constituents, were also covered. SiO_2 nanoparticles are highly desirable due to their favorable characteristics, including low cost, non-toxicity, biocompatibility, and excellent thermal resistance.

Moreover, SiO_2 nanoparticles exhibit remarkable mechanical reinforcing capabilities. However, the high hydrophilicity of the nanostructured SiO_2 surface poses a significant challenge, as it tends to induce agglomeration and poor dispersion of the nanoparticles within the polymer matrix. Consequently, one of the primary obstacles to the fabrication of polymer/SiO_2 nanocomposites lies in the development of effective strategies to control the dispersion of nanoparticles within the polymeric hosts (Landowski et al., 2014; Wang et al., 2013). (Hosur et al., 2007) studied the impact behavior of carbon/epoxy composites with nano clay admixture. They discovered that integrating nano clay into the composites reduced impact damage.

This decrease was attributable to the nanophase laminates' greater rigidity and resistance to damage propagation. (Reis et al., 2012, 2013, 2014) studied glass and Kevlar/epoxy composites and found that adding nano clay enhanced impact loads, decreased displacements, improved elastic recovery, and increased maximum residual tensile strength. These results suggested that nano clay outperformed the other nanofillers investigated in terms of improving the impact and mechanical characteristics of composite materials. Furthermore, an evaluation of several nanofillers in Kevlar/vinyl ester composites, including carbon nanotubes, nano clay, aluminum oxide, and silicon carbide, found that nano clay fillers generated the most substantial increases in impact and mechanical characteristics. The ideal proportion of nano clay was discovered to be 4.3 wt.% (Moustafa et al., 2014). The aim of this research is to assess the potential of silica nanoparticle-reinforced glass and carbon fiber epoxy composites for structural applications. The research compares these composites' mechanical properties to those of plain epoxy. The study's conclusions show that silica nanoparticles improve the composite materials' mechanical properties, enhancing their performance and strength in structural applications.

1. MATERIALS AND METHODS

2.1. Materials

Composite materials are made up of two or more components, such as carbon fibers and low-modulus, high-elongation glass fibers. This combination lowers production costs while simultaneously improving the compound's ability to withstand damage and imparting outstanding performance features. All materials used in this study are listed in Table 1.

Table 1. Specifications of the materials used to manufacture laminates

Glass fiber reinforcement	unidirectional (Glass Fabric Unidirectional-300 gr/sqm)
Carbon fiber reinforcement	unidirectional (Carbon Fabric Unidirectional-300 gr/sqm Thermofixed)
Matrix (liquid)	Epoxy resin MGS (LR 285)
Hardener (liquid)	MGS (LH 287)
(Silicon Dioxide) Nanoparticles	15-35nm, Purity 99.5+%, amorphous
Fiber’s volume fractions	0.4

2.2. Manufacturing composites

Glass fibers, carbon fibers, and resins were combined in samples of composite materials at a volume proportion of 50%. To calculate the mechanical properties of each carbon plate and glass plate with resin and with the resin added with 2% SiO_2 nano-silica particles as shown in Figure 1, there are many different ways to make composites, and each approach has pros and cons that are appropriate for certain uses. Regardless of the kind of laminated material utilized in this investigation, processing samples was done using a vacuum bag approach. Samples underwent a 15-hour curing process at 80 °C. This technique allowed for the creation of samples with a range of forms, sizes, and dimensions since it delivered consistent clamping pressure that was equally distributed throughout the whole surface. With a bubble-free rate of almost 99%, vacuum bag technology offers a high level of quality with less bubble formation. The eight layers of glass were manually stacked in the correct order $[0]_8$ for the manufacturing of the laminate, and a veneer layer was added on top to avoid adhering to the leaky grid. The resin intake and outflow pipes, as well as the vacuum bag, are all securely fastened. The vacuum device was then turned on, and the pressure gauge was watched until it hit 760 mmHg, which signifies total vacuum. After then, the system was shut down, and a 30-minute waiting time was recorded to ensure there was no vacuum bag leak. The resin is added to the vacuum bag after the core temperature reaches 80°C, ensuring appropriate penetration between the fibers. Figure 2 illustrates the 15-hour curing process after the tubes were hermetically sealed. The carbon sheets were created in the same way as the aforementioned glass layers, which were manually stacked in the exact order $[0]_8$. A SONICS (Ultrasonic Nanoparticle Dispersion) device was employed to obtain a uniform dispersion of nanoparticles inside the resin in the case of slides containing SiO_2 nanoparticles, as illustrated in Figure 3. The precise mixing of the nanoparticles and resin is made possible by this unique apparatus.

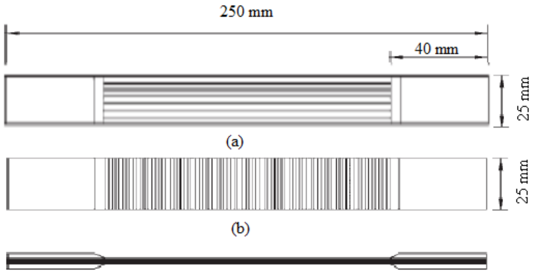


Figure 1. Dimension of the specimens (a) for longitudinal (E_1 and ν_{12}); (b) foe transverse (E_2 and G_{12})

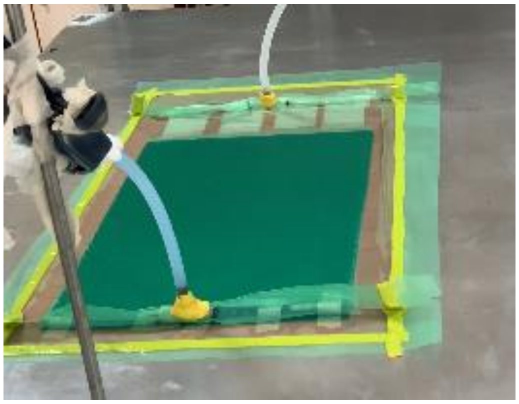


Figure 2. Vacuum bagging technique

Figure 3. Probe sonicator

2.3. Determination of mechanical properties

For different ASTM mechanical tests, specimens of the right sizes were cut from the composite plates using the DIAMANT RUBI cutter, as shown in Figure 4. As illustrated in Figure 5, tensile test specimens with the dimensions 250 mm in length, 25 mm in width, and 2 mm in thickness were produced using ASTM D3039 (ASTM International, 2020).

Figure 4. DIAMANT RUBI cutter

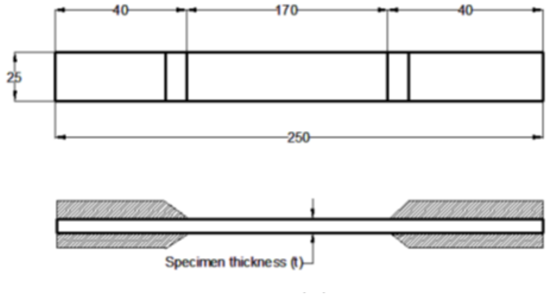


Figure 5. Specimens test for tensile test ASTM D3039

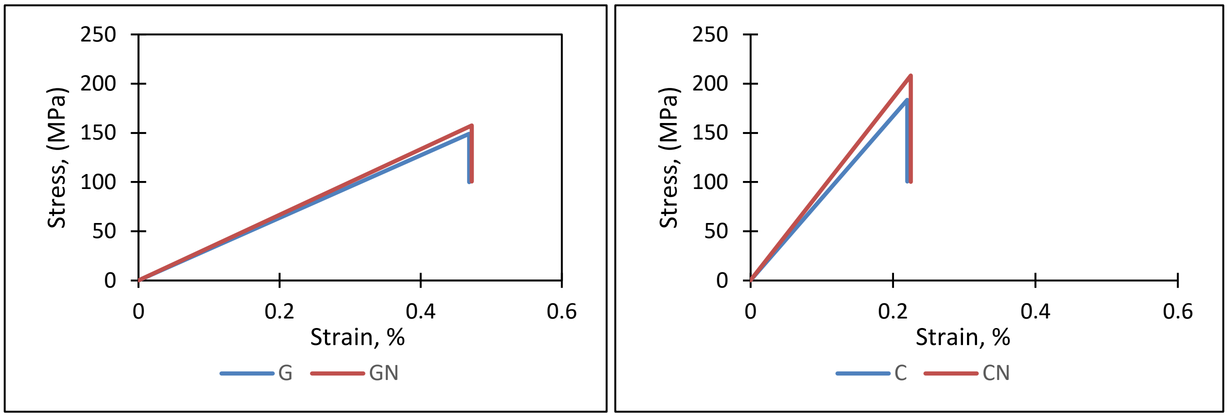
2.4. Determination of the Tensile Properties

Eight oriented composite plates were used to test the mechanical properties of a unidirectional glass/epoxy composite and a carbon/epoxy composite under static loading conditions. The preparation of the test samples followed ASTM guidelines. A Shimadzu-AGIS Tensile Testing Machine with a 100 kN load capacity was used for all mechanical testing, with a constant displacement rate of 1 mm/min.

Using longitudinal $[0^o]_8$ unidirectional composite specimens, the longitudinal Young's modulus (E_1), Poisson's ratio (ν_{12}), and longitudinal tensile strength (X_t) were calculated in accordance with ASTM D3039 (ASTM International, 2020). Referring to Figure 1-a, these specimens were 250 mm long and 25 mm wide. Using transverse $[90^o]_8$ unidirectional specimens, the transverse Young's modulus (E_2) and transverse tensile strength (Y_t) were measured. These specimens measured 250 mm in length and 25 mm in breadth (see Figure 1-b).

The tensile specimens were beveled glass/epoxy tabs that were adhered to straight-sided coupons with a constant cross-section. The specimens were exposed to axial loading until failure occurred in order to ascertain the tensile characteristics of the unidirectional glass/epoxy composite and the unidirectional carbon/epoxy composite as shown in figure 6. A strain gage was used to measure the strain at both longitudinal and transverse angles. As a result, precise values for E_1, E_2, and ν_{12} could be discovered. By dividing the failure load by the cross-sectional area of the longitudinal and transverse specimens, respectively, the tensile strengths of the unidirectional composite plates, X_t and Y_t, were calculated. composite specimens can be found by two main steps. First, Ex modulus of the specimens is obtained by video extensometer. And then G_{12} is calculated by using the following equation (Hancox, 1996).

$$G_{12} = \frac{1}{\left(\frac{4}{E_x} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\nu_{12}}{E_1}\right)}$$



(a) (b)

Figure 6. Tensile stress-strain plot of (a) glass/epoxy (b) carbon/epoxy

2.5. Numerical model

The finite element (FE) models were essential for simulating the stress and strain behavior of the composite panels. It was possible to obtain insight into the structural performance of the panels under various loading conditions by utilizing these models. The numerical modeling process utilized in this study was consistent with the methodology used to investigate the behavior of neat epoxy composite materials and hybrid composite materials containing silica nanoparticles.

Utilizing the ANSYS software with the ACP module(Kanani, 2020), the FE models were created. This software program provides sophisticated simulation and analysis capabilities for structural systems. The FE models contained a total of 5525 elements and 22964 nodes, providing a comprehensive representation of the geometry and behavior of the composite panels.

These elements accurately represented each plate within the composite panels, enabling a precise analysis of their mechanical response as shown in Figure 7.

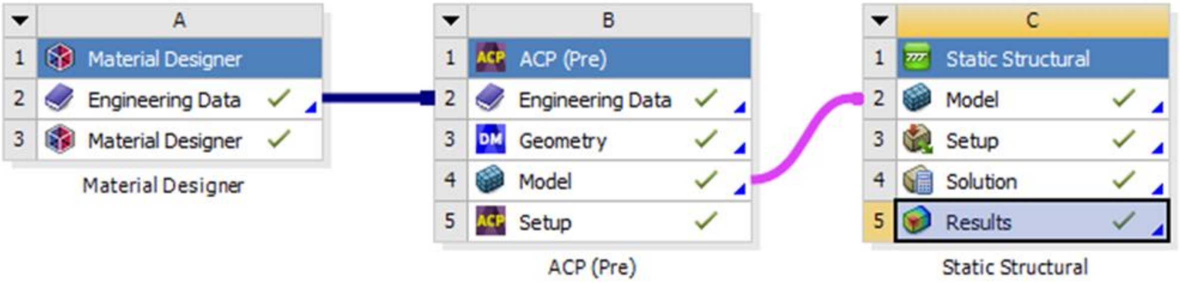
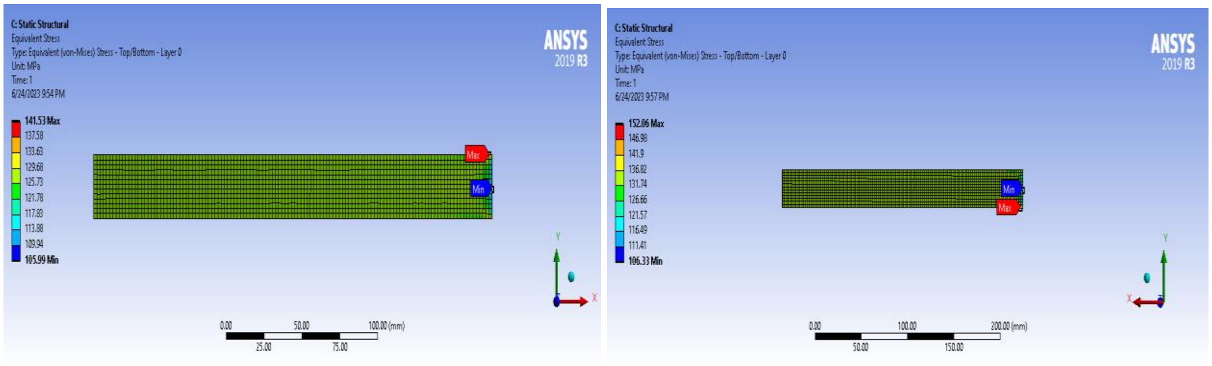


Figure 7. modelling laminates in ANSYS(Workbench)

One end of the plate imitated a constrained boundary condition by being fixed in all dimensions, while the other end was displaced along the longitudinal axis. This configuration was determined based on experimental results. The figures (8, 9) showed the stress behavior for each composite of glass and carbon with and without adding silica nanoparticles. Table 3 shows the comparison between the experimental results and the simulation results using the finite element method.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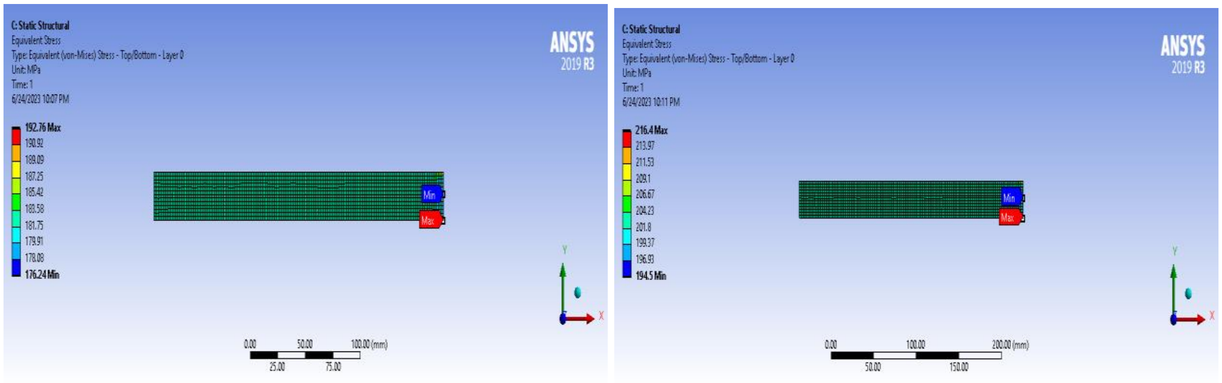
(a) (b)

Figure 8. Numerical analysis results Stress (MPa) (a) Pure glass\epoxy, (b) glass\epoxy with adding 2% SiO_2 nanoparticles.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(a) (b)

Figure 9. Numerical analysis results Stress (MPa) (a) Pure carbon\epoxy, (b) carbon\epoxy with adding 2% SiO2 nanoparticles

2. RESULTS AND DISCUSSION

The effects of SiO_2 nano-silica integration on the mechanical properties of laminates made of glass and carbon materials are shown in Table 2. As shown in Figure 10, there are differences between the two laminate types. In comparison to glass-based laminates, they have an increase in the longitudinal, transverse, and shear moduli of about 4.9%, 22.5%, and 4.9%, respectively. while carbon-based laminates have an increase in the longitudinal, transverse, and shear moduli of about 2.2%, 2.1%, and 2.2%, respectively. According to these results, the structural arrangement that is found in glass laminates leads to increased mechanical properties, perhaps because of improved structural condensation. A comparison of these plots indicates the influence of SiO_2 nanoparticle addition on mechanical characteristics enhancement, which is due to the nanoparticles' large surface area and capacity to establish strong chemical interactions with the resin and fibers. The addition of SiO_2 nanoparticles strengthens the interfacial interaction between fibers and resin. This enhanced bonding prevents fracture propagation inside the composite material, increasing its tensile strength, toughness, and stiffness. Furthermore, SiO_2 nanoparticles act as fillers, strengthening the structure of the composite material and improving load transmission between the fibers, hence boosting strength and stiffness. The homogeneous distribution of SiO_2 nanoparticles in the resin matrix reduced void and defect formation, further improving mechanical characteristics.

Table 2. Glass and carbon fiber mechanical characteristics

Sample	Material	E1 Gpa	E2 Gpa	G12 Gpa	ν12	Density g/cm3
G[0o]8	Pure Epoxy/Glass	31.80	10.95	4.27	0.21	1.6576
GN[0o]8	Epoxy/Glass with SiO_2 nanoparticles	33.36	13.41	4.48	0.26	1.8413
C[0o]8	Pure Epoxy/Carbon	99.44	6.27	4.03	0.24	1.4838
CN[0o]8	Epoxy/Carbon with SiO_2 nanoparticles	101.60	6.41	4.12	0.30	1.5056

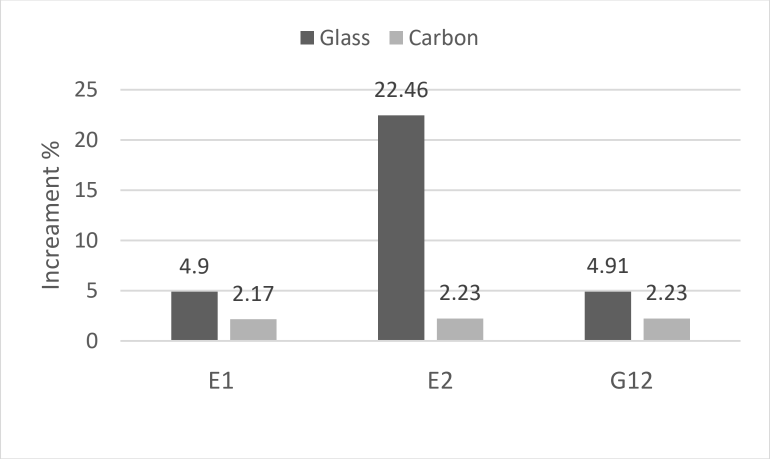

Figure 10. Increment percentage of mechanical properties by adding 2 wt.% of silica nanoparticles

The experiment found that adding silica nanoparticles to the composite materials significantly increased the tensile strength at the point of failure. The collective resistance provided by the mixture of glass fibers and hybrid epoxy as well as carbon fibers and hybrid epoxy is affected by their intrinsic properties, orientation, and volume fraction (Caminero et al., 2019). The epoxy matrix is essential for the composite's ability to withstand stress. Figure 6 shows the effects of adding 2% SiO_2 nanoparticles to the epoxy, which significantly increased the tensile strength of the glass composite by 5.74% and the tensile strength of the carbon composite by 13.51%. A comparison of these plots indicates the influence of SiO_2 nanoparticle addition on mechanical characteristics enhancement, which is due to the nanoparticles' large surface area and capacity to establish strong chemical interactions with the resin and fibers. The addition of SiO_2 nanoparticles strengthens the interfacial interaction between fibers and resin. This enhanced bonding prevents fracture propagation inside the composite material, increasing its tensile strength, toughness, and stiffness. Furthermore, SiO_2 nanoparticles act as fillers, strengthening the structure of the composite material and improving load transmission between the fibers, hence boosting strength and stiffness. The homogeneous distribution of SiO_2 nanoparticles in the resin matrix reduced void and defect formation, further improving mechanical characteristics.

Table 3. Comparison mechanical properties between glass and carbon fibers

	Stress MPa		Correlation	Strain %		Correlation
Sample	Experimental	Numerical		Experimental	Numerical	
G $[0^o]_8$	149.0263	141.53	95%	0.4686	0.49	96%
GN$[0^o]_8$	158.54	152.06	96%	0.47234	0.501	95%
C $[0^o]_8$	183.497	192.76	95%	0.2201	0.23	95%
CN$[0^o]_8$	208.2915	216.4	96%	0.2250	0.234	96%

*G: Glass laminate, GN: Glass laminate with silica nanoparticles, C: Carbon laminate, CN: Carbon laminate with silica nanoparticles,

Understanding material behavior requires strong stress-strain correlation in experimental and numerical investigations. Experimental analysis provides real-world data, while numerical simulations allow for scenario exploration. By comparing and assessing the connection between stress and strain derived from both techniques as shown in table 3, they gained confidence in the accuracy and validity of both experimental and numerical methodologies, improving material response prediction under varied loading situations.

3. CONCLUSION

In this study, two sets of laminates were fabricated: one composed of glass layers and the other of carbon layers, each containing eight layers oriented at 0° unidirectional. Almost-static tensile tests with the same stacking order were used to look at the mechanical response of both laminate groups. The impact of SiO_2 nanoparticles incorporation on the mechanical properties was assessed. This corresponds to an increment in strength, strain, and modulus of 5.7%, 0.8%, and 4.9%, respectively, for the glass laminate with SiO_2 nanoparticles in comparison to its counterpart without nanoparticles. Similarly, the carbon laminate with SiO_2 nanoparticles experienced increases in strength, strain, and modulus of 13.7%, 2.24%, and 2.17%, respectively, when compared to the carbon laminate without nanoparticles.

From the above, it can be concluded that the glass and carbon fiber epoxy composites reinforced with silica nanoparticles may be useful in construction, automotive, marine, and aerospace. This sector can build and optimize sophisticated hybrid composites for engineering applications. As well, designers may customize hybrid composite materials by choosing fibers and matrix components. Different fibers in a resin matrix may alter material properties.

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