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IMPROVING THE MECHANICAL PROPERTIES OF CARBON-EPOXY AND GLASS-EPOXY COMPOSITES BY INCORPORATING SILICA NANOPARTICLES

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ABSTRACT

Hybrid composite materials possess significant potential as engineering materials across various application sectors such as construction, automotive, marine, and aerospace. They provide designers with the ability to achieve desired properties to a considerable extent by carefully selecting both the fibers and matrix used. By incorporating different types of fibers into a common resin matrix, the material's properties can be customized and tailored accordingly. In this study, the mechanical properties of glass and carbon fiber epoxy composites that were strengthened with silica nanoparticles were looked at and compared to those of plain epoxy to figure out how well they could be used in structural applications. Regardless of the laminated material, the samples were manufactured using the vacuum bag method and heat-cured. Mechanical properties such as E_1, E_2, G_{12}, and ν_{12} were determined using the tensile test and the relevant ASTM standards to ensure accurate and reliable results. Experimental and numerical modeling will be employed to assess significant differences between the glassy epoxy and carbon epoxy composites in terms of their mechanical properties. The results of this study show that adding 2% wt of SiO_2 nanoparticles to composite materials improves their mechanical properties. The tensile strength of the glass composite went up by 5.74 percent, and the tensile strength of the carbon composite went up by 13.51 percent.

KEYWORDS: Glass fiber-reinforced polymer; Mechanical properties; Hybrid nano-composites; Carbon fiber.

1. INTRODUCTION

The main justification for replacing traditional metal with fiber reinforced polymer laminated composite (FRP) in structural applications like aerospace, automobiles, and turbine blades is the combination of high specific strength (strength to density ratio) and high specific stiffness (modulus to density ratio) coupled with lightweight and improvements in corrosion, wear, and fatigue resistance. Carbon and glass fibers are the most often utilized materials in industrial applications. Due to its low strain-to-failure, carbon fiber is not suited for use in structural components alone despite having high strength and modulus. Glass fiber was added to carbon to make up for its drawbacks, since carbon has low strength and modulus but high strain to failure.

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Due to their superior specific properties, conventional materials. High strength and stiffness-to-weight ratios, increased corrosion and environmental resistance, design flexibility, higher fatigue life, and the possibility of cheaper processing, manufacturing, and life cycle costs are among the benefits. (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

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 (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 and Lee

Composite materials offer several benefits over 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 nano clay, carbon nanotubes, titanium dioxide (TiO_2), and silica dioxide (SiO_2) 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,

(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).

Despite extensive study on this subject, there is definitely a research gap addressing the influence of nanoparticle presence on the mechanical characteristics of composite materials. As a result, the purpose of this research is to determine the influence of incorporating 2 wt% SiO2 nanoparticles into the epoxy matrix on tensile strength and mechanical parameters (modulus of elasticity, modulus of rigidity, and Poison ratio).

2. 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 2, 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 proper penetration between the fibers, and then the curing process takes place for 15 hours after the tubes are hermetically sealed. The carbon sheets were constructed in the same way as the glass layers described above, which were hand-laid together 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.

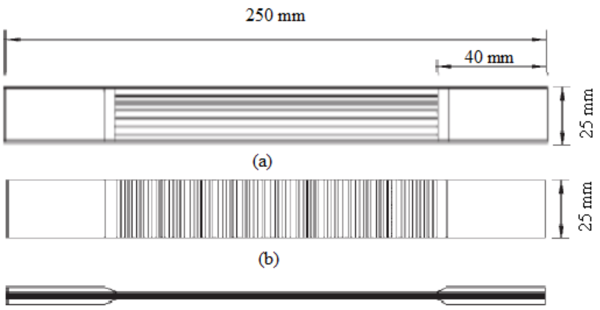


Fig.(1):- Dimension of the specimens (a) for longitudinal (E1 and ν12) (b) foe transverse (E2 and G12)

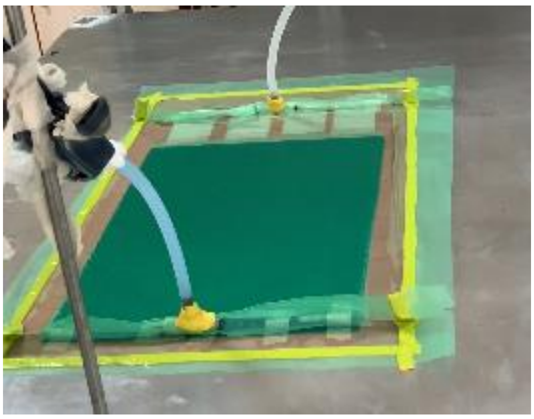


Fig.(2):- Vacuum bagging technique

Fig.(3):- Probe sonicator

2.3 Preparation of test specimens.

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).

Fig.(4):- DIAMANT RUBI cutter

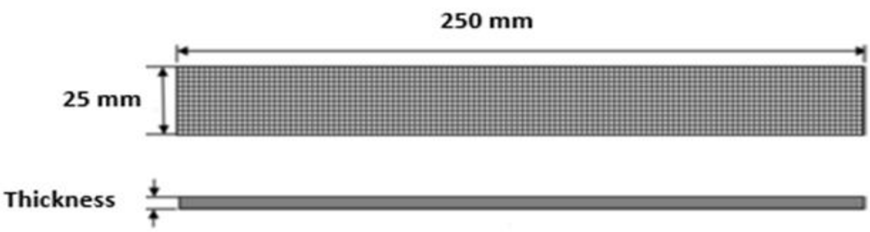


Fig.(5):- Specimens test for tensile test ASTM D3039

2.4 Determination of the Tensile Properties

Under static loading conditions, eight oriented composite plates were utilized to evaluate the mechanical properties of a unidirectional glass/epoxy composite and a carbon/epoxy composite. 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 2 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. 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. The tensile strengths, X_t and Y_t, of the unidirectional composite plates were calculated by dividing the failure load by the cross-sectional area of the longitudinal and transverse specimens, respectively. The discovery of composite specimens involves two primary stages. First, the specimen's Ex modulus is determined using a video extensometer. Then G_{12} is computed by employing Equation 1. (Hancox, 1996).

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

The density was calculated using the AS 220.R2 PLUS Analytical Balance › Radwag Balances and Scales device shown in figure 6, where the weight of the sample in the air can be calculated, and then the weight of the same sample in the water, after which the device calculates the density automatically.

Fig.(6):- AS 220.R2 PLUS Analytical Balance › Radwag Balances and Scales device

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 7, 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.

Table (2):- Glass and carbon fiber mechanical characteristics

Sample	Material	E_1 Gpa	E_2 Gpa	G_{12} Gpa	v_{12}	Density g/cm^3
G [08]	Pure Glass/Epoxy	31.80	10.95	4.27	0.21	1.6576
GN [08]	Pure Glass/Epoxy with nanoparticles	33.36	13.41	4.48	0.26	1.8413
C [08]	Pure Carbon/Epoxy	99.44	6.27	4.03	0.24	1.4838
CN [08]	Pure Carbon/ Epoxy with nanoparticles	101.60	6.41	4.12	0.30	1.5056

*G: Glass laminate, GN: Glass laminate with silica nanoparticles, C: Carbon laminate, CN: Carbon laminate with silica nanoparticles, [08] eight layers of unidirectional fibers with zero angle of stacking sequence.

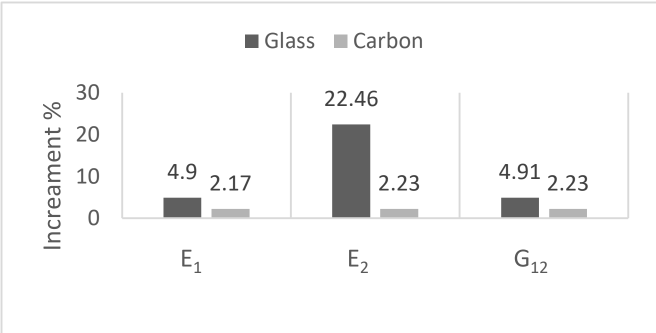
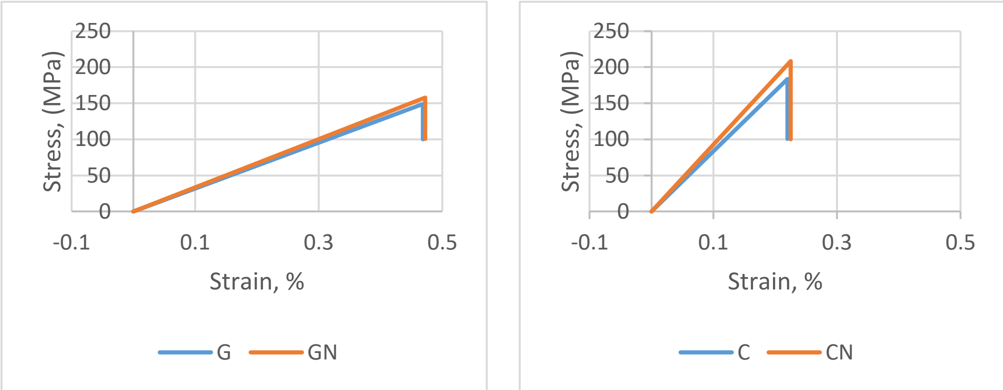


Fig.(7):- Increment percentage of mechanical properties by adding 2 wt % of silica nan Oparticles

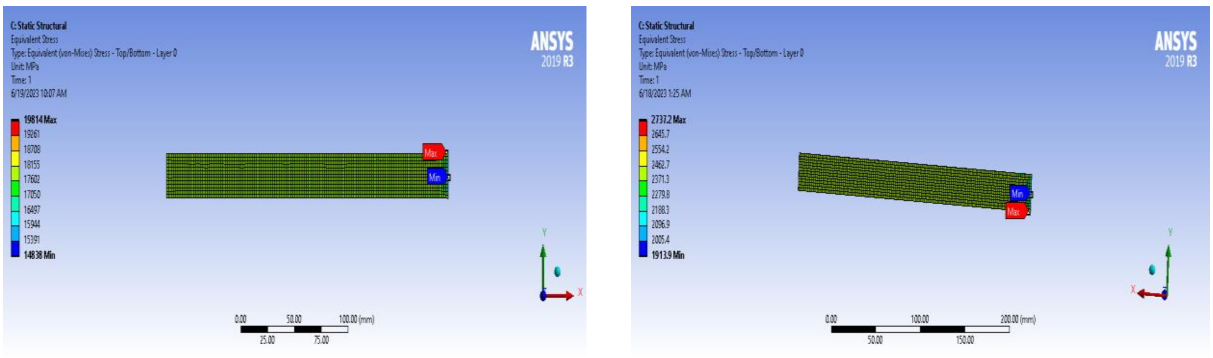
The experiment found that adding silica nanoparticles to the composite materials significantly increased the tensile strength at the point of failure. The collective resistance provided by the mixture of glass fibers and hybrid epoxy as well as carbon fibers and hybrid epoxy is affected by their intrinsic properties, orientation, and volume fraction (Caminero et al., 2019). The epoxy matrix is essential for the composite's ability to withstand stress. Figure 8 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.



(a) (b)

Fig.(8):- Tensile stress-strain plot of (a) glass/epoxy (b) carbon/epoxy

The finite element (FE) models were essential for simulating the stress and strain behaviour 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 modelling process utilized in this study was consistent with the methodology used to investigate the behaviour of neat epoxy composite materials and hybrid composite materials containing silica nanoparticles. Utilizing the ANSYS software with the ACP module, 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 behaviour of the composite panels. These elements accurately represented each plate within the composite panels, enabling a precise analysis of their mechanical response. 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 figure 9 and figure 10 showed the stress behaviour for each composite of glass and carbon with and without adding silica nanoparticles.



(a) (b)

Fig.(9):- Numerical analysis results tensile stress (MPa) (a) pure glass\epoxy, (b) glass\epoxy with adding 2% SiO2 nanoparticles

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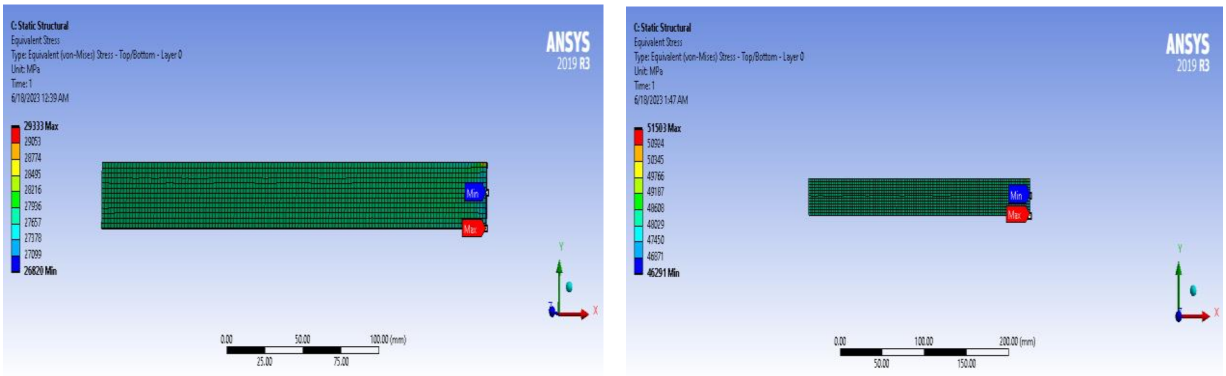

(a) (b)

Fig.(10):- Numerical analysis results tensile stress (MPa) (a) pure carbon\epoxy, (b) carbon\epoxy with adding 2% SiO2 nanoparticles

4. 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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