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ORIGINAL ARTICLE

The effect of nano-silica on the mechanical properties of composite polyester/ carbon fibers

R.N. Hwayyin[1,*], S.K. Hussien[2] and A.S. Ameed[1]

[1] Faculty Electromechanical Engineering Department, University of Technology, P. Box (19006), Baghdad, Iraq
[2] Faculty Nanotechnology and Advanced Materials Research Center, University of Technology, P. Box (19006), Baghdad, Iraq

ABSTRACT – This study conducted several tensile tests to determine the effect of 20-30 nm silicon dioxide nanopowder on the mechanical properties of composite material polyester/carbon fiber. Samples were prepared at weight fractions of carbon fibers (i.e. 25, 40, and 55%), with different weights of silica nanoparticles (i.e. 0.16, 0.2, and 0.24%). The experimental results showed that the mechanical properties improved at various ratios as a result of increasing the weight fraction of the carbon fibers and the ratio of the silicon dioxide nanopowder in the composition of the composite samples. The maximum increase by 33.49% resulting from increasing the weight fraction from 25% to 40% at 0.16% silicon dioxide nanopowder. The maximum effect of increasing the weight of the silicon dioxide nanopowder from 0.2 to 0.24 resulted from increasing the stress by 33.53% at weight fraction of 25%. The SEM images of the structure showed the distribution of nanoparticles and crack growth in the region neighboring the fracture after the tensile test at different weight fractions of carbon fibers and nano-silica particles. The improvement in the mechanical properties of this low-cost composite material when using nanomaterials has potential for use in multiple applications, including boat hulls.

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Crack growth

INTRODUCTION

Many studies have agreed on the use of carbon fiber in various applications (i.e. the automotive, aircraft, sports, and construction, the military and in medical tools) because of its high mechanical properties, durability, chemical stability, thermal resistance, and lightweight nature [1-11]. The development of ship and boat hulls has progressed through several stages, with the analysis currently being conducted using ANSYS composite materials as alternative materials for marine steel manhole covers because they weigh and cost less [12]. Researchers have investigated the effect of adding a silica nano-material to a thermoplastic polyester and its effect on the mechanical properties, with a unit of nano-composite material designed and analyzed using solid work software [13]. In this study, the carbon fiber was used as an alternative to aluminum in the structure of a high-speed riverboat used by the Iraqi Navy in shallow water [14] . The use of composite materials in this study takes into account reducing the weight and cost of shipping containers while maintaining structural integrity and durability in steel containers through analysis using ANSYS [15]. The study conducted a torsion analysis of composite rectangular panels reinforced with multi-walled carbon nanomaterial to determine their critical torsion loads [16]. Fiber-reinforced polymer matrix composites have emerged as a major class of structural materials and a suitable alternative to a large number of conventional critical weight material components in the aerospace, automotive, and other industries because of their high strength, weight ratio, and stiffness/weight ratio [17–19].

Nanocomposites have the potential to become the base material in future structures due to their excellent mechanical properties, and superior thermal, electrical, optical, and other properties [20–23]. The latest developments described in this study relate to using advanced composite materials in manufacturing boat and ship hulls [24]. This study investigated the mechanical properties of carbon fiber composite materials in the longitudinal and horizontal direction with epoxy resin in a wet environment [25]. It found improved mechanical, electrical, and thermal properties when employing carbon nanotubes (CNTs) in wet carbon fibers as nano-filling materials [26]. The present study's value present study lies in focusing on improving the mechanical properties by reinforcing the composite materials (i.e. carbon fibers/polyester) that are used in a wide variety of fields when manufacturing boats and other marine structures. The present study aims to improve the mechanical properties of the composite material (i.e. carbon fiber/polyester resin) by adding silicon dioxide nanopowder at different weight fractions and analyzing the microstructure of the regions neighboring the fracture's region.

METHODOLOGY

The mechanical properties of composites consisting of two or more materials are to be determined through experimental and laboratory tests based on the percentages of the weight of the constituent materials represented by the weight fraction. The determination of the volume fraction also contributes to describing the mechanical features of the composite material. Mathematical calculations based on empirical tests provide accurate data on the properties of each

*CORRESPONDING AUTHOR | R. N. Hwayyin | ✉ 10596@uotechnology.edu.iq

composite material. The weight of the resin is the difference between the composite sample and the weights of the fibers [27]:

$$w_{m=}w_c - w_f \tag{1}$$

where, W_m is the weight of the matrix (polyester) (g), W_c is the weight of the composite specimens (g), and W_f is the Weight of fiber (metal mesh), (g). when the specimens consist of three composite materials, the equation is expressed as follows:

$$w_m = w_c - w_f - w_{Nano} \tag{2}$$

where W_{Nano} is the weight of the nano-silica powder, (g). The volume of the fibers (i.e., carbon fiber) in the composite is found by Eq. (3):

$$V_f = \frac{W_f}{\rho_f} \tag{3}$$

The volume ratio of the fiber (i.e., carbon fiber) to matrix (polyester resin) of the composite material which inserted in the specimens can be found using Eq. (4):

$$\frac{V_f}{V_m} = \left(\frac{W_f}{W_m}\right) * \left(\frac{\rho_f}{\rho_m}\right) \tag{4}$$

where V_f is the volume fraction of the fiber (cm^3), V_m is the volume fraction of the matrix (cm^3), V_{Nano} is the volume fraction of the nano-silica powder (cm^3), ρ_f is the density of fiber, (g/cm^3), ρ_m is the density of matrix (g/cm^3), and ρ_{Nano} is the density of nano-silica powder (g/cm^3). The density of composite material can be found using the following:

$$\rho_c = \rho_f.V_f + \rho_m.V_m + \rho_{Nano}.V_{Nano} \tag{5}$$

MATERIAL AND METHODS

Materials

To reduce the production cost of the composite material, this study adopted polyester resin produced by Saudi Industrial resins Ltd. (code number SIROPOL-8341, Saudi Arabia) instead of epoxy or vinyl ester as a matrix for the composite material. The properties of the polyester in the composite materials shown in Table 1 [28] were tested and reinforced with 200 gm plain weave carbon fibers produced by MB Fibreglass (United Kingdom, mbfg.co.uk) at three weight fractions (i.e., 25, 40, and 55%), whose properties are shown in Table 2. The silicon dioxide nanopowder (20-30nm), whose specifications are shown in Table 3 (according to Hongwu Inter National Group Ltd.-China), were added in various weights (i.e., 0.16, 0.2 and 0.24%).

Table 1. Mechanical properties of the polyester resin

Value	Properties
1.22	Specific density (at 20 C°)
68 N/mm^2	Tensile stress at break
2.2 %	Elongation
3600 N/mm^2	Modulus of elasticity
1 to 1.3 g/cm^3 [25°C (77°F)]	Density (ρ)
47	Barcol Hardness

Table 2. Specifications of the carbon fiber mat

Characteristic	Nominal
Mass per unit area (g/m^2)	200
Weave	Plain
Width (mm)	1000/2000
Thickness	0.16

Table 3. Specifications of the silicon dioxide nanopowder

Silicon Dioxide Nanopowder (20-30 nm) Amorphous-Fume (Hydrophobic)	
Code	M606
Form	Powder
Purity	99.8%
Color	White
Odor	Odorless
Melting point	1610-1728° C
Boiling point range	2230
Density:	At 20° C 2.77-2.66 g/cm^3
Water	Insoluble
Case no.	7631-86-9

Methods

A number of samples of tensile tests were prepared from polyester resin reinforced with carbon fiber and nano silica using the sample dimensions of the standard (ASTM D3039) [29] to determine the mechanical properties of the composite materials. The composite materials were prepared from the polyester Siropol-8341, plain weave carbon fiber, and nano silica powder. The carbon fibers were cut according to the dimensions of the acrylic mold and the mixing process between the polyester and nanoparticles was carried out using an ultrasonic processor (UP200Ht, Hielscher Ultrasonics GmbH, Germany) shown in Figure 1. The casting process to mix the polyester with the nanoparticles was conducted in stages to be in between the layers of carbon fibers that were added successively after each addition of the mixture of polyester and nano silica powder. The acrylic die was crafted using a CNC milling machine (Germany) consisting of two pieces with a cavity dimension (260 cm × 105 cm), to prepare layers with a thickness of 6 mm (see in Figure 2) using AutoCAD software. As seen in Figure 3 the samples were drawn according to their standard dimensions using AutoCAD software. Then, they were converted to a G-function machine by SURFCAM software to cut them according to the standard sizes of the tensile samples shown in Figure 4. The weights of the carbon fibers and nano silica powder were measured to produce the composite material using the four-digit weighing scale shown in Figure 5. The weight of the polyester was measured as the difference between the weight of the composite samples and the weight of the carbon fibers with the nano-silica powder.

The process of homogenizing the mixing of polyester and nanoparticles is necessary to create a homogeneous configuration composition of the composite material before it is poured into the die. It took 5 min to mix the silicon nanoparticles with the polyester resin. The polyester and hardener were mixed with a stir stick, blending the properly metered resin, and the hardener was added at a ratio of 0.1% and mixed for 1 min scraping the sides of the mixing container to avoid forming bubbles. The study used a scanning electron microscope (SEM) to analyze the microstructure near the fracture region of the samples.

Figure 1. Ultrasonic processor (UP200Ht)

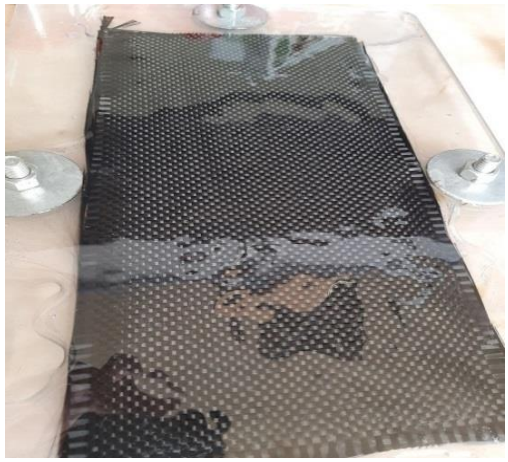

Figure 2. Die for casting the specimens

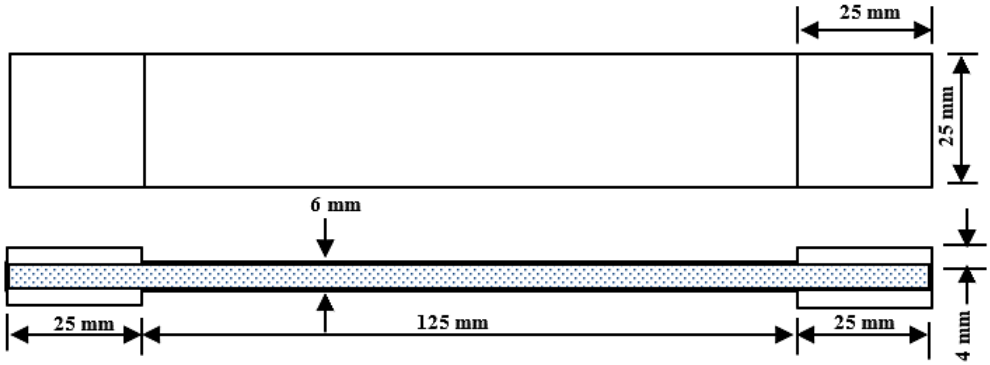

Figure 3. Standard for the tensile specimen

Figure 4. Tensile test specimens before and after fracture

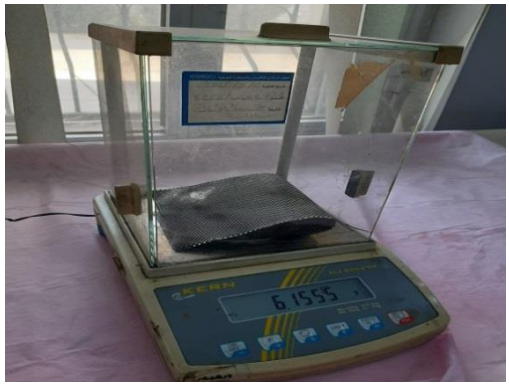

Figure 5. High precision weighing scale

RESULTS AND DISCUSSION

The results discuss the experimental tensile tests of the composite materials at different weight fraction of carbon fiber reinforced at various weights of silicon dioxide nanopowder. This section includes three axes related to the effect of, (1) changing the weight fraction of the carbon fibers, while (2) changing the weight of the silicon dioxide, and (3) the tensile stress on the microscopic structure of the samples using (SEM).

Effect of the Weigh Fraction of the Carbon Fibers

Figure 6 displays the results of an experimental test to determine the effect of increasing the weight fraction the carbon fibers on the tensile stress. Increasing the weight fraction from 25 to 40% achieved an increase in the stress by 33.49%, which is a significant increase. In contrast, an increase in the stress by 28.29% resulted from increasing the weight fraction from 40 to 55%, with a 0.16% weight fraction of silicon dioxide nanopowder. The homogeneity of the ratio of the carbon fiber to the weight ratio of the polyester resin fostered a significant improvement in the tensile stress, and it indicates the specific range of the weight of the carbon fiber (fiber) to the polyester resin (matrix), required in the composite material.

Figure 7 illustrates the effect of increasing the weight fraction of the carbon fibers on the tensile stress at a weight of 0.2% silicon dioxide nanopowder, such that the stress increased by 5.41% as a result of increasing the weight fraction of the carbon fibers from 25 to 40%, while it increased by 19.2% after increasing the weight fraction from 40 to 55%. Figure 8 shows the influence of increasing the weight of the carbon fibers on the stress when the weight of the nano-silicon dioxide powder was 0.24. The stress increased by 7.65% as a result of increasing the weight fraction of the carbon fibers from 25 to 40%, while it increased by 11.59% when raising the weight fraction from 40 to 55%.

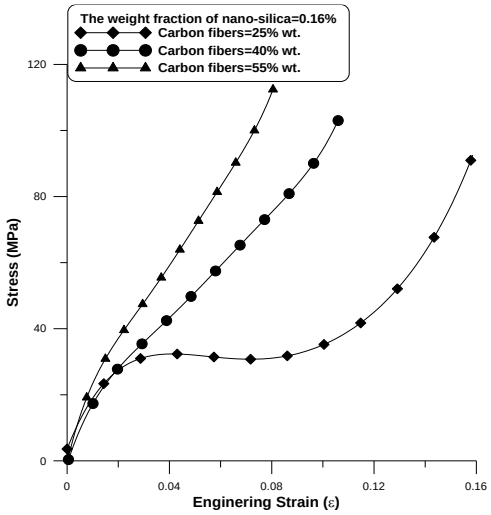

Figure 6. Relationship between the stress and strain of different weight fractions at a nano-silica weight of 0.16%

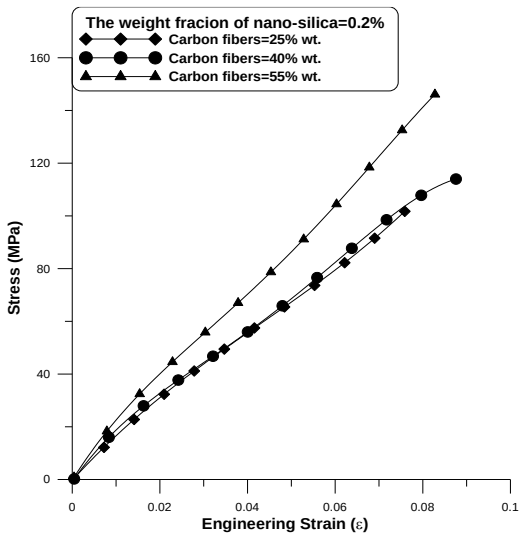

Figure 7. Relationship between the stress and strain of different weight fractions at a nano-silica weight of 0.2%

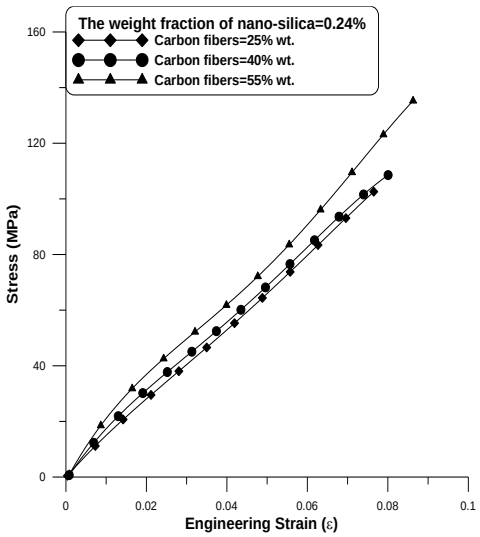

Figure 8. Relationship between the stress and strain of different weight fractions at a nano-silica weight of 0.24%

Effect of the Weigh of the Silicon Dioxide Nanopowder

Figure 9 presents the effect of the weight of the silicon dioxide nanopowder on the tensile stress. The stress reached a maximum increase of 33.53% as a result of increasing the weight of the nanoparticles from 0.16 to 0.2; however, it increased by 6.1% after raising the weight of particles from 0.2 to 0.24 when the weight fraction of the carbon fibers was 25%. The effect of the weight of the nanoparticles was evident in improving the mechanical properties of the composite material with a weight of 25% due to the role of the nanoparticles in enhancing the durability and homogeneity of the composite material with a polyester resin (matrix) and carbon fibers.

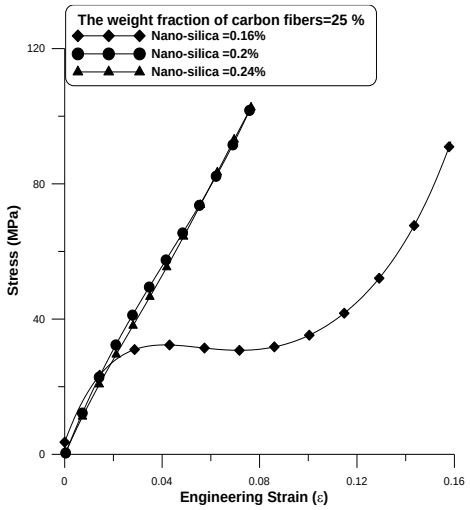

Figure 9. Relationship between the stress and strain of different nano-silica weights at a 25% weight fraction of carbon fiber

In Figure 10, the results of the tests show that the tensile stress increased by 22.4% as a result of increasing the weight of nanoparticles from 0.16 to 0.2%, while the increase ratio of stress decreased to 3.57% when increasing the weight of nanoparticles from 0.2 to 0.24% at a 40% weight fraction of carbon fibers. This study found a suitable range for adding nanoparticles to achieve an enhancement in the structure of the composite material and an increase in its resistance to tensile stress, which means improving the mechanical properties within this range of additives with weight fractions from 0.16 to 0.2% and where the maximum increase in the stress was 33.53% at a weight fraction 40%. Figure 11 shows an increase in the tensile stress by 11.45% after increasing the weight of the silica particles from 0.16 to 0.2, while there was an increase of 13.94% when the weight of the silica particles rose from 0.2 to 0.24 at a weight fraction of 55%.

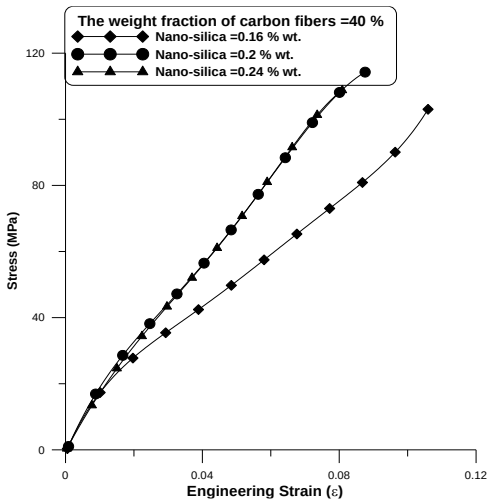

Figure 10. Relationship between the stress and strain of different nano-silica weights at a 40% weight fraction of carbon fiber

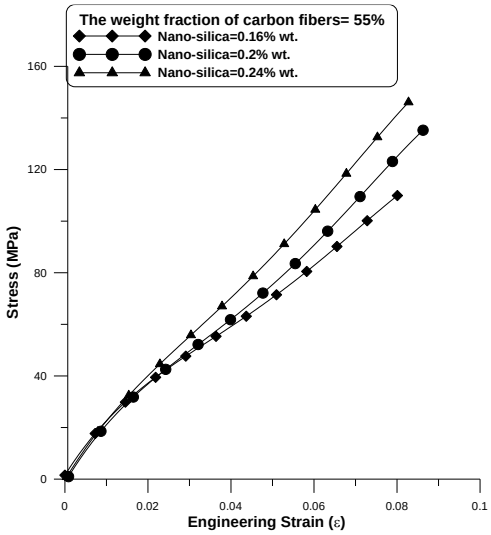

Figure 11. Relationship between the stress and strain of different nano-silica weights at a 55% weight fraction of carbon fiber

SEM Pictures of the Fracture Surface of Composite Tensile Specimens

Figure 12 displays SEM images at SEM magnifications (MAGs) of 200x, 500x, and 1000x. The photos show the microstructure of the composite material and the homogeneous overlap of the carbon fibers and nanoparticles. The images were taken of the neighboring regions near the fracture location of the composite specimens at a 25% weight fraction of carbon fiber and 0.16% nano-silicon dioxide. The limited area in the image shows the movement of the crack after applying tensile stress adjacent to the fracture region.

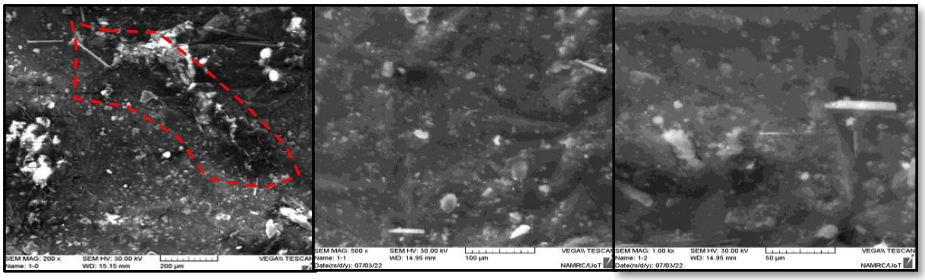

Figure 12. SEM images of the composite specimens at a 25% weight fraction of carbon fibers and 0.1 % nanosilicon dioxide

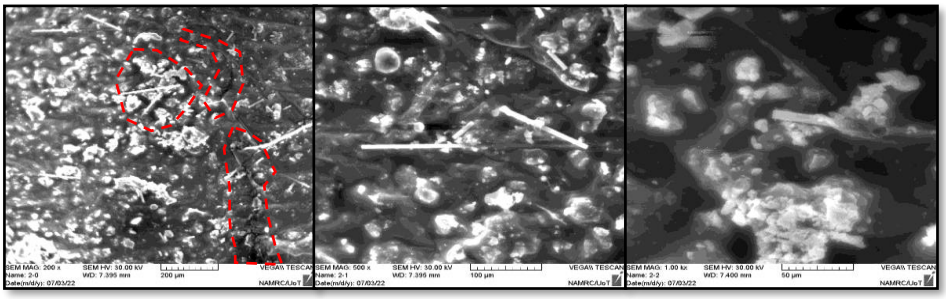

Figure 13. SEM images of the composite specimens at a 40% weight fraction of carbon fibers and 0.16% nanosilicon dioxide

Figure 13 shows images of the composite samples of the polyester reinforced with a weight fraction of 40% carbon fiber and 0.16% silicon dioxide nano-samples at SEM MAGs of 200x, 500x, and 1000x. The selected area shows the region where cracks started to grow in the composite material due to stress. The images represent the area adjacent to the fracture area in the test samples. The photographs indicate that the top of the crack stopped at the point of the assembly of the nanoparticles, demonstrating that the nanoparticles enhanced the strength of the failure resistance by diverting the crack's path.

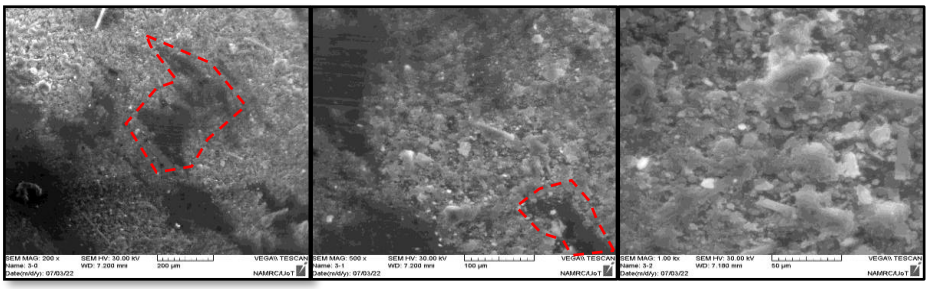

Figure 14. SEM images of the composite specimens at a 55% weight fraction of carbon fibers and 0.16% nanosilicon dioxide

In the SEM images of the composite specimens at a 55% weight fraction of carbon fiber and 0.16% nano-silicon dioxide (see Figure 14), a gap appeared in the distribution of the nanoparticles in the microstructure of the composite material, which indicates an area of stress concentration during the tensile process. Increasing the weight fraction of the carbon fiber and nano-silica reinforced the positive mechanical properties. The experimental results show that the increased weight fraction of the carbon fibers was more effective at enhancing the mechanical properties than increasing the weight fraction of the nano-silica powder; however, together they provided a more effective improvement.

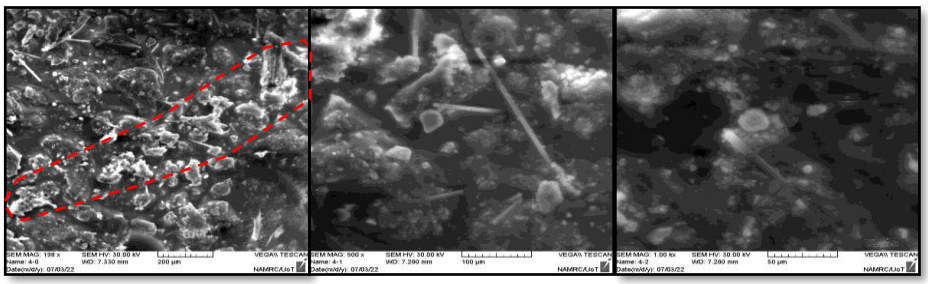

Figure 15. SEM images of the composite specimens at a 25% weight fraction of carbon fibers and 0.2% nano-silicon dioxide

The images in Figure 15 illustrates the diffusion of the silica nanoparticles in the microstructure of the composite material containing carbon fibers, where the SEM images of the composite samples occurred with a 25% weight fraction of carbon fiber and 0.2% nano-silicon dioxide. The selected area focused on the region of stress concentration in the microstructure of the composite material, which represented the path of the crack's growth before the failure process. The selected area in the image shows the path of stress concentration in the composition of the microstructure of the composite material due to the effect of the tensile stress on the test samples, which agrees with Gao et al. [30].

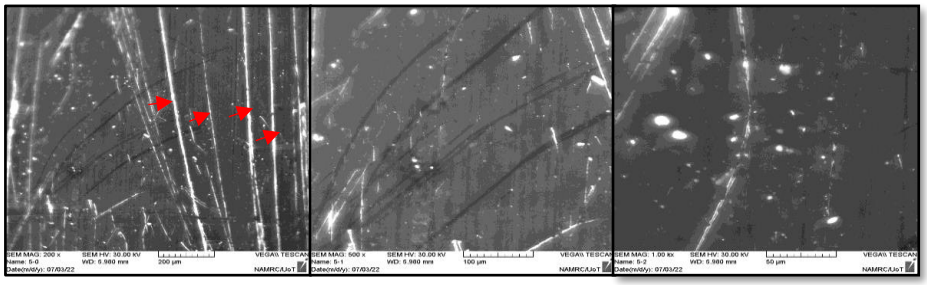

Figure 16. SEM images of the composite specimens at a 40% weight fraction of carbon fibers and 0.2% of nanosilicon dioxide

Figure 16 presents images of the the composite samples of polyester reinforced at a weight fraction of 40% carbon fiber and 0.2% silicon dioxide nano-samples at SEM MAGs of 200x, 500x, and 1000x. The images show cracks in the polyester material in the surface layer resulting from the stress concentration on the surface of the composite tensile sample during the tensile test in the area adjacent to the fracture area in the sample. The distribution of silica nanoparticles are also visible in the region near the surface. The non-zigzag paths of the cracks indicate that the surface was devoid of carbon fibers, which enhanced the material's resistance to failure by changing the crack growth paths and resulting in zigzag cracks. The marked paths in Figure 16 indicate the cracking paths in the polyester material at the surface of the composite samples.

Figure 16 provides images of the composite samples of the polyester reinforced at a weight fraction of 40% carbon fiber and 0.2% silicon dioxide nano-samples at SEM MAGs of 200x, 500x, and 1000x. The images show cracks in the polyester material in the surface layer, which is due to the stress concentration on the surface of the composite sample during the tensile test at the fracture region. The photos also show the distribution of the silica nanoparticles near the surface. The non-zigzag paths of the cracks in the polyester plane at the surface of the samples indicate that the path was empty of carbon fibers, where carbon fibers improved the material's resistance to failure by changing the crack growth paths, resulting in zigzag cracks.

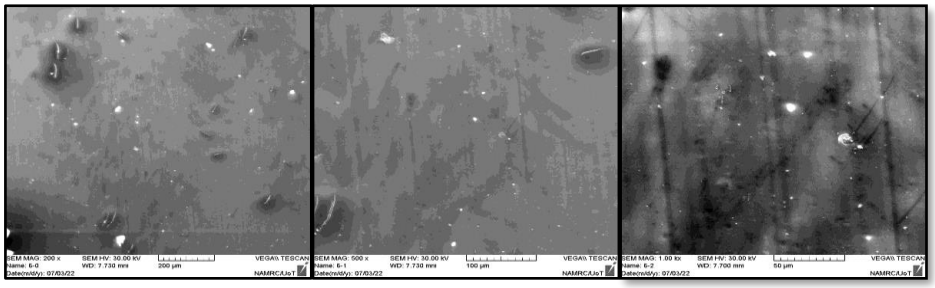

Figure 17. SEM images of composite specimens at a 55% weight fraction of carbon fibers and 0.2% nanosilicon dioxide

The images in Figure 17 show good homogeneity in the microstructure of the composite material between the carbon fibers and polyester resin as well as the distribution of the nanoparticles (seen as white particles in the images). The uniformity of the distribution depends on the method and duration of the mixing time with the polyester. The increase in the weight fraction of the carbon fibers improved the toughness of the composite material and conferred greater homogeneity of the nanoparticles, which enhanced the material's resistance to failure. Figure 17 presents the SEM images of the composite specimens at a weight fraction of carbon fiber of 55% and nano-silicon dioxide at a ratio of 0.2%.

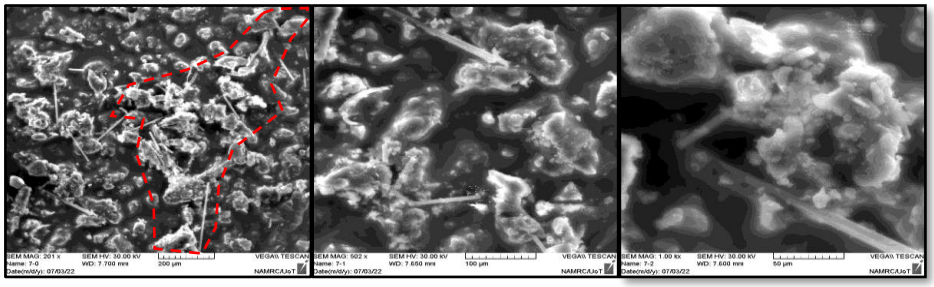

Figure 18. SEM images of the composite specimens at a 25% weight fraction of carbon fibers and 0.24% nanosilicon dioxide

Figure 18 displays the SEM images of the composite specimens at a 25% weight fraction of carbon fiber and 0.24% nano-silicon dioxide, where the images show that the nanoparticles were densely distributed along the mat of carbon fibers. The images indicate the path of the concentration of stresses in the microstructure of the composite material near the failure region in the specimen due to the tensile process. Increasing the weight fraction of the nanoparticles in the composite material to 0.24% had less effect than increasing it from 0.16 to 0.2% due to the material reaching the maximum effect of increasing nanoparticles at a 25% weight fraction of the carbon fiber.

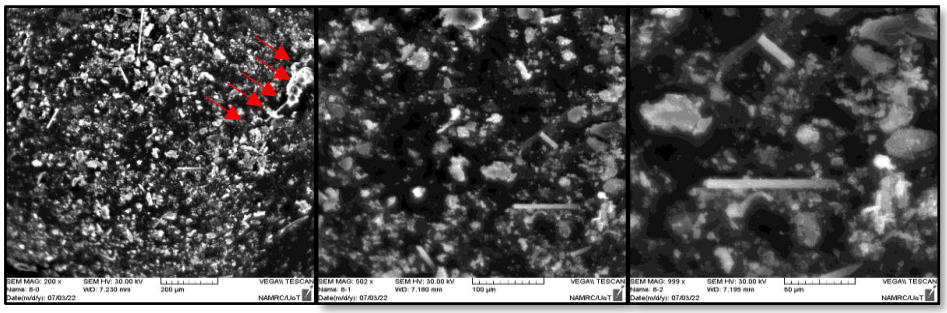

Figure 19. SEM images of the composite specimens at a 40% weight fraction of carbon fibers and 0.24% nanosilicon dioxide

The images in Figure 19 show the samples at a weight fraction of carbon fibers in the proportion of 40% and at the weight ratio of 0.24% of the silica nanoparticles, with a dense distribution of the nanoparticles in the microstructure of the composite material. The pictures illustrate the formation of the path of stress concentration in the microstructure, which is indicated in the pictures taken by SEM at MAGs of 200x, 500x, and 1000x.

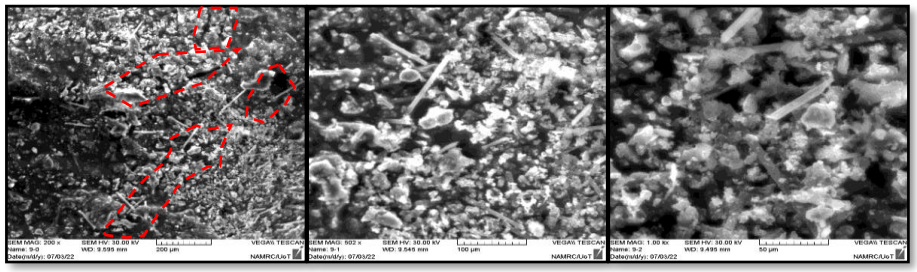

Figure 20. SEM images of the composite specimens at a 55% weight fraction of carbon fibers and 0.24% nanosilicon dioxide

The images in Figure 20 illustrates the density of the nanoparticles and carbon fibers in the microstructure of the composite samples at a weight fraction of 55% for carbon fibers and 0.24% for nanoparticles. The increase in the nano-silica powder in the range from 0.2 to 0.24% at a 55% weight fraction led to the high density of nanoparticles and carbon fibers in the microstructure. The locations of cracks that appeared in the microstructure of the composite material, which were caused by the application of tensile stress, are indicated on the SEM images taken at MAGs of 200x, 500x, and 1000x.

CONCLUSION

This study showed an improvement in the mechanical properties of the hulls of fast boats made of carbon fibers at different breaking weights and ratios of nano-silicon dioxide. The maximum stress increased by 33.49% when the weight fraction of the carbon fibers was increased from 25 to 40% by adding 0.16% silicon dioxide nanopowder, while the maximum nano-silica effect on the stress increased by 33.53% due to the increase in the weight fraction of the silicon dioxide nanopowder from 0.2 to 0.24%. The SEM images show a good distribution of the nano-silica particles that produced the improvement in the mechanical properties of the composite material. Finally, the importance of this study lies in improving the mechanical specifications of many marine structures and boat hulls by using a low-cost matrix (polyester) with carbon fibers and silicon dioxide nanopowder as a filler.

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