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The Effect of SiO_2 Nanoparticle on the Mechanical Properties of Silica-Epoxy Nanocomposites-An Experimental Study

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Abstract

Polymer nanocomposites, featuring reinforcing particles smaller than 100 nm, exhibit superior mechanical properties compared to conventional composites. This study investigates the effect of nanoparticle size and weight fraction on the Young's modulus and tensile strength of epoxy-silica nanocomposites. To evaluate their mechanical behavior, epoxy-silica samples were prepared using nanoparticles sized 15 nm, 20 nm, and 80 nm at 3% and 5% weight fractions. Ultimate stress, yield stress (0.2%), maximum strain, and Young's modulus were measured. Results showed that adding silica nanoparticles enhanced the ultimate tensile stress, yield stress, and Young's modulus of pure epoxy. Notably, nanocomposites with 80 nm particles at 3% loading displayed the highest strain. At 5% loading, 20 nm nanoparticles exhibited the highest tensile strength and stiffness among the tested samples, while 15 nm particles showed comparatively lower improvements, likely due to increased agglomeration. Additionally, a general trend of increased stiffness was observed with smaller particle sizes, although deviations occurred due to dispersion and porosity effects.

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Keywords: *Polymer Nanocomposites; Nanoparticle; Tensile stress; Young's modulus; Silica-epoxy.*

I. INTRODUCTION

A. Nanocomposites

Nanocomposites are advanced materials that integrate nanoscale reinforcements into a matrix material (polymer, metal, or ceramics) to achieve synergistic mechanical, thermal, electrical, and optical properties superior to conventional composites. These multi-phase nanomaterials have at least one dimension in the nanometer scale (10^{-9}m). The nanoparticles are often in the form of nanofibers, nanotubes, nanoclays, or spherical nanoparticles. A prominent area of research in nanotechnology is polymer nanocomposites (PNCs). The major advantage of PNCs is improved mechanical properties with small filler loading levels. An important thermosetting polymer used in nanocomposites is epoxy resin. It was selected for this research due to its broad applicability and combination of mechanical strength, chemical durability, adhesion, and thermal performance. Epoxy nanocomposites are multifunctional materials with the potential for lower-cost, high-performance applications in adhesives, coatings, electronics, automotive, aerospace, and marine industries, where lightweight structural components with optimal mechanical properties are preferred [1] [2] [3] [4].

B. Effects of Filler Size and Loading

Generally, the large surface-area-to-volume ratio of nanoparticles increases the available interfacial contact within nanocomposites, enabling effective load transfer between the filler and polymer matrix and ultimately enhancing the mechanical strength [3]. Particle–particle interactions also significantly influence nanocomposite mechanical performance. Unlike particle-matrix interaction, which improves mechanical strength, particle-particle interaction has an undesirable effect. Interparticle attraction and repulsion, governed by van der Waals and electrostatic forces, can lead to agglomeration or clustering of nanoparticles. The dense and strong particle collectives are called aggregation, whereas agglomeration refers to looser, larger structures that their mechanical forces can easily break. High loadings of large nanoparticles produce aggregation and weak interfacial properties, negatively impacting tensile strength [5]. Interparticle forces can be tuned through variations in particle size, concentration (wt.% or vol.%), and surface treatments. Research optimizing nanocomposite performance has focused on tailoring particle dimensions and filler content, including size, weight, and volume fractions, in recent years [5] [6] [7] [8] [9] [10].

Fu et al. comprehensively examined how particle dimensions, loading levels, and filler–matrix bonding influence nanocomposite mechanical behavior [11]. They concluded that each of the three factors plays an important role in nanocomposites' strength and toughness properties; higher particle loadings were found to improve stiffness significantly, and for a given volume fraction, the strength increased with decreasing particle size [11]. Increasing nanoparticles' weight fraction has been reported to improve Young's modulus in nanocomposites significantly. Singh et al. reported a maximum increase in elastic modulus with 4 wt.% SiO_2 nanoparticles dispersion in an epoxy matrix [12]. Filippov et al. reported a 25% increase in the modulus of elasticity when the content of silicon dioxide nanoparticles in the epoxy resin was increased to 5 wt.% [13]. Soni et al. showed that adding 0.5 wt.% of SiO_2 nanoparticles, improved the elastic modulus, ultimate tensile strength, and failure strain of the SiO_2 epoxy nanocomposites by 18%, 15%, and 33%, respectively [14]. Studies have also shown that the interfacial bonding strength and thickness determine the mechanical properties of nanocomposites [15]. The surface modification of silica nanoparticles positively impacts the interfacial region of epoxy nanocomposites. Battistella et al. found that in silica-epoxy nanocomposites, the fracture toughness significantly increased by 54% by adding only 0.5 vol% of surface-modified fumed silica [16]. Islam et al. developed empirical models to predict the mechanical performance of silica–epoxy composites across different particle sizes and loadings, as shown in Table 1 [17].

In Table 1, E is Young's modulus, σ is tensile stress, SSA is specific surface area in m^2/kg, g is gravitational acceleration in m/s^2, A is the average surface area of nanoparticle in m^2, W is the average weight of nanoparticles in N, wt., and vol are weight and volume fractions $[0 \leq \mathrm{wt} \leq 100, 0 \leq \mathrm{vol} \leq 100]$, σ_{cy} is the compressive yield stress, and E_c is the compressive modulus, [17].

Table 1: Suggested expressions to estimate the mechanical behavior of silica-epoxy nanocomposites at different weight fractions of nanoparticles [17].

Nanocomposite	**Suggested equation**	**Ranges of applications**		
		Nanoparticle dimension	**wt.% or vol.%**	**Remark**
Silica-epoxy	$E = 3.639 \times 10^4 \frac{W}{A} wt^{0.04}$ [in GPa]	8-50nm	1-40 (wt.%)	Sol-gel processing
Rubbery silica epoxy mesocomposite	$E = \frac{g}{SSA} 288 \times 10^{0.053wt}$ [in GPa]	10-100nm	2-10 (Wt.%)	Nanoparticle's pore size: 4-21 nm
Silica-epoxy	$\sigma = \frac{w}{A} 10^6 \times wt^{-0.069}$ [in MPa]	8-50nm	1-40 (wt.%)	Sol-gel processing
Rubbery silica epoxy mesocomposite	$\sigma = \frac{\mathrm{g}}{\mathrm{SSA}} 55.8 \times 10^{0.04\mathrm{wt}}$ [in GPa]	10-100nm	2-10 (wt. %)	Nanoparticle's pore size: 4-21 nm
Epoxy-silica-rubber	$\sigma_{\mathrm{cy}} = 56.8 \times 10^{-0.004\mathrm{vol}}$ [in MPa]	20nm, 80nm	0-6.4 (vol.%)	CTBN processing
Epoxy-silica-rubber	$\mathrm{E_c} = 1.53 \times 10^{0.001\mathrm{vol}}$ [in GPa]	20nm, 80nm	0-6.4 (vol.%)	CTBN processing

C. Health Concerns and Safety Issues

Nanotechnology has significant environmental, health, and safety (EHS) concerns, particularly in product application and safe utilization of nanoparticles. Nanoparticles can be combustible and initiate catalytic reactions, so precautions should be taken to reduce exposure during processing, maintenance, machining, sanding, and drilling processes. Toxicological responses are influenced by particle size, geometry, surface area, and surface reactivity. Prediction of health risks depends on routes of exposure, translocation, toxicity, duration, and immune system effects. Control of airborne exposure can be achieved using personal protective equipment and risk management programs. Sub-100 nm diameter nanotechnologies have been found to affect the human heart and lung, and agglomerates of 20nm titania (TiO_2) nanoparticles and pigment grade TiO_2 have a great impact on animal lungs due to their nanoscale nature [18]. All nanoparticle handling was conducted in a designated area with controlled ventilation to minimize exposure risks. Researchers wore appropriate personal protective equipment, including N95 respirators, nitrile gloves, lab coats, and safety goggles. Nanoparticle containers were only opened within a ventilated enclosure to prevent aerosolization. All waste materials containing nanoparticles were collected in sealed containers and disposed of according to institutional hazardous waste protocols.

Most previous studies have examined the effects of particle weight fraction, volume fraction, or surface modification on the mechanical behavior of nanocomposites. Consequently, the interaction between particle size and weight fraction on mechanical performance remains insufficiently explored, particularly under controlled experimental conditions. Understanding the synergistic and individual effects of particle size and weight fraction is essential. This requires controlling all other parameters while varying only one variable, such as maintaining a constant weight fraction while altering particle size. Such an approach helps isolate the effects of particle size from other variables and supports the interpretation of trends in strength and stiffness. Additionally, it helps identify trends in mechanical behavior associated with different nanoparticle sizes and loading levels while acknowledging the limitations of the selected size resolution. This study utilized silica nanoparticles of different sizes (15 nm, 20 nm, and 80 nm) as nano-fillers. The weight fraction was kept constant at 3% and 5% to isolate the effect of particle size. The mechanical properties of the prepared nanocomposites were measured and compared to those of pure epoxy specimens.

The key contributions and novelty of this study are:

- Introduces an experimental design to assess the combined effect of nanoparticle size (15, 20, 80 nm) and weight fraction (3%, 5%) on tensile properties of silica-epoxy nanocomposites.
- Performs indirect porosity analysis and SEM imaging to explain variations in mechanical behavior beyond raw data.
- Uses practical loading levels and commercially available silica nanoparticle sizes, reflecting real-world constraints in manufacturing and design.

- Acknowledges the limited resolution in particle sizing and proposes this as a future research direction to refine the identification of optimal nanoparticle dimensions.

II. EXPERIMENTS

A. Materials and Preparation

Fibre Glast Developments Corporation supplied 2000 epoxy resin and 2120 hardener (with a 3 to 1 mixing ratio). The silica (Silicon Oxide) nanoparticle, supplied by Nanostructured and Amorphous Materials Inc., was used as nanofillers. Silica (SiO_2) nanoparticles of three different sizes (particle diameters of 15, 20, and 80 nm) were selected for this research. All silica nanoparticles are spherical and white in color. All composite samples were made with a 5% and 3% nanoparticle weight fraction.

1. Making Samples

To make the pure epoxy samples, a water bath indirectly heated the resin to decrease its viscosity using the same condition used for composites. Then, the curing agent was added and stirred rapidly for 5 minutes using a magnetic stirrer and a hand. The mixture was poured into the mold and kept at room temperature for one day to cure.

The silica-epoxy nanocomposites were made by mixing epoxy resin with silica nanoparticles. The epoxy resin of volume 90ml (101.26 g) was poured into a small beaker while the beaker was placed inside a larger beaker filled with water. The large beaker was placed over a hot plate with a magnetic stirrer at 90°C and 1150 rpm for 30 minutes to decrease the resin's viscosity and release the bubbles. An amount of 6.96 g of silica nanoparticles (5% weight fraction of the total weight of the epoxy-hardener-silica mixture) was placed into a small beaker on a hot plate at 110°C for 30 minutes to evaporate the moisture from the particle surfaces, as silica is hydrophilic. Then, epoxy resin and silica were mixed, placed over a magnetic stirrer at 1150 rpm, and stirred rapidly for 5 minutes. Afterward, 30ml (30.9 g) of hardener was added to the mixture and then stirred using both-magnetic stirrer and hand for 5 minutes. After spraying a mold release agent, the mixture was poured into an open aluminum mold of size $162mm \times 135mm \times 4mm$.

The mold was placed on a hot plate for 60 minutes at 60°C and 1150 rpm using a magnetic stirrer and 30 minutes at 40°C. After heating and stirring, the mold was kept at room temperature for 5 hours to cure partially. The composite, partially cured at this stage, allowed a little bending, making it easier to retrieve from the mold. The retrieved composite was maintained at room temperature for another 6 hours to cure completely.

Table 2 lists four samples with their material codes, nanoparticle weight fractions, and particle diameters. In the material code, ‘E’ denotes pure epoxy resin, and ‘S’ denotes silica nanoparticle; the next two digits after ‘S’ represent the diameter of the nanoparticle (in nm), and the third number after ‘S’ denotes the weight percentage (%) of nanoparticles in the matrix. For example, ES155 means epoxy-silica nanocomposites with a 5% nanoparticle size of 15nm.

Table 2: Material codes, particle sizes (nm), and weight fractions of nanoparticles in each nanocomposite sample.

Material code	**Particle diameter (nm)**	**Nanoparticle weight fraction (%)**
E	-	-
ES155	15	5
ES205	20	5
ES805	80	5
ES153	15	3
ES203	20	3
ES803	80	3

2. *Cutting and specimen preparation*

The load test specimens (also known as test coupons or dog bones) were prepared by cutting the composite sheets to the standard size using a cutting machine (Microlux band saw) having a band saw with a diamond-tipped blade. The standard ASTM D638 [19], was used to size the samples and test the tensile properties.

Figure 1: Prepared epoxy-silica nanocomposite (ES153) dog-bone specimens prior to tensile testing, conforming to ASTM D638 standard dimensions.

B. Mechanical Behavior

The pure epoxy and the silica-epoxy composites were tested for their mechanical (tensile) behavior according to ASTM D638 [19], Figure 2. Five specimens of pure epoxy and each composite type were prepared, considering the dimensions required by the standard. The specimens were conditioned for one hour at a temperature of 20±1ºC and a relative humidity of 65±2% before testing. The tests were performed using an Instron 5500R tensile testing machine. The crosshead speed of 1mm/min was chosen for tests, and all experiments were performed at 20±1ºC and 65±2% relative humidity. Measurements were ultimate tensile stress, maximum strain, Young's modulus, and yield stress (0.2% offset). The broken samples were used for porosity analysis (indirect porosity measurements). Some broken parts were also used to observe particle agglomerations using an SEM of the Topcon model ABT-32.

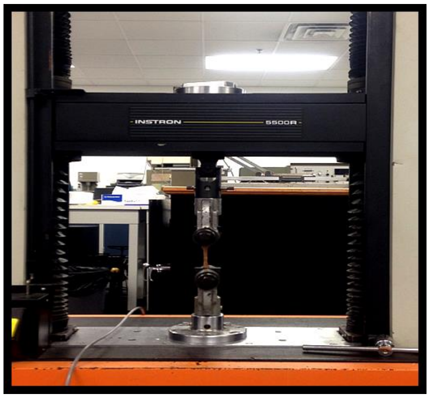


Figure 2: An experimental setup for tensile testing using the Instron 5500R machine was conducted in accordance with ASTM D638 procedures.

C. Estimation of Porosity

A factor that can significantly affect the performance of nanocomposites is the existence of voids or bubbles. The voids act as a defect to the composites, causing the composites to yield unexpected results. As a result, the theoretical density of porous composites is greater than the actual density. A decrease of two to ten percent in the mechanical properties has been reported with every one percent increase in the void content or porosity [20].

For porous composites, the volume fraction of voids or porosity ($\mathcal{E}$) is defined as:

$$\mathcal{E} = V_o / V_c \tag{1}$$

where, V_c is the volume of the composite, and V_o is the volume of the voids [20]. The total volume of the composite can be written as:

$$V_c = V_f + V_m + V_o \tag{2}$$

where, V_f is volume of the fillers (i.e., silica nanoparticles), and V_m is the volume of the matrix (epoxy resin and curing agent) [20]. The experimental density of a composite (ρ_{ce}) is defined as:

$$\rho_{ce} = \frac{m_c}{V_c} \tag{3}$$

where, m_c is the mass of composite [20]. The theoretical density (ρ_{ct}) [20], of a composite can be written as:

$$\rho_{ct} = \frac{m_c}{V_f + V_m} \tag{4}$$

Upon replacing V_o from Eq. (2) into Eq. (1) and considering Eqs. (3) and (4), the following expression is derived for the porosity:

$$\mathcal{E} = 1 - \frac{\rho_{ce}}{\rho_{ct}} \tag{5}$$

However, the theoretical density is related to densities of filler and matrix through the following expression [20],:

$$\rho_{ct} = \rho_f v_f + \rho_m (1- v_f) \tag{6}$$

where, ρ_f is the density of filler, ρ_m is the density of the matrix, and v_f is the volume fraction of the filler in the composite, which can be found using the following equation:

$$v_f = \frac{\frac{m_f}{\rho_f}}{\left(\frac{m_f}{\rho_f} + \frac{m_c - m_f}{\rho_m}\right)} \tag{7}$$

where m_f is the mass of filler in the composite [20]. To find the actual or experimental density, the following equation was used:

$$\rho_{ce} = \frac{\rho_w m_c}{(m_c - m_{cw})} \tag{8}$$

where, m_{cw} is the mass of composite inside water and ρ_w is density of water [20].

D. Particle Dispersion

The degree of particle dispersion in a polymer nanocomposite is an important factor affecting the composite's performance. Uniformly distributed nanoparticles are necessary to get an efficiently reinforced polymer nanocomposite. The Scanning Electron Microscope (SEM) can be used to study particle distribution and aggregation in a nanocomposite. SEM images in both higher and lower resolution can be used to analyze the microstructure of the composite: low resolution for studying clusters and high resolution for studying agglomeration or particle dispersion. The specimens were dipped into liquid nitrogen and torn apart to observe surface morphology. A gold sputter coating with a pressure of 0.15 Torr and voltage of 1.4 kV was maintained for five minutes to prepare samples for observation.

III. RESULTS AND DISCUSSION

A. Porosity

The theoretical densities of the nanocomposite samples were estimated using the actual densities of all the six types of nanocomposites. Using Eq. (5), the indirectly measured porosities were found to be 3.39%, 1.68%, and 1.495% for nanocomposites with 15nm, 20nm, and 80nm nanoparticles, respectively, while using a 5% weight fraction of nanoparticles. The porosities were 1.7%, 1.36%, and 1.16% for nanocomposites with 15nm, 20nm, and 80nm nanoparticles, respectively, when the nanoparticle weight fraction was 3%. Table 3 shows the indirectly measured porosities of different epoxy-silica nanocomposites with 95% confidence intervals. Figure 3 shows that porosity decreases as nanoparticle size increases. It was also observed that nanocomposites with higher particle loading (wt. %) show higher porosity. These experiments generally showed an average porosity of 1.3% and 3.3% for silica-epoxy nanocomposites.

Table 3: Indirect measured mean porosities of epoxy-silica nanocomposites with 95% confidence intervals

Material code	**Porosity (%)**
ES155	3.37 ± 0.308
ES205	1.68 ± 0.135
ES805	1.49 ± 0.189
ES153	1.71 ± 0.256
ES203	1.36 ± 0.111
ES803	1.16 ± 0.16

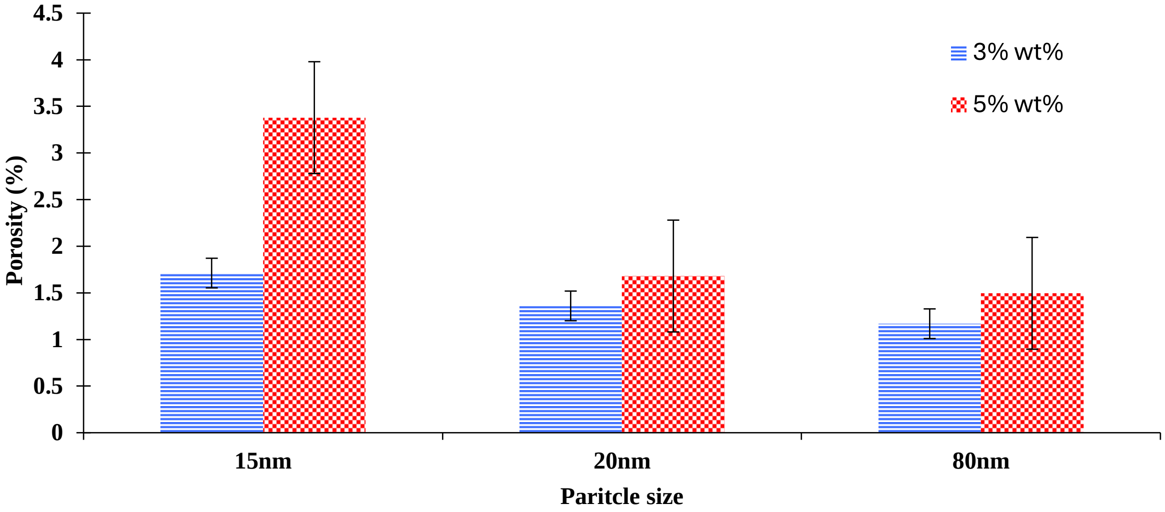


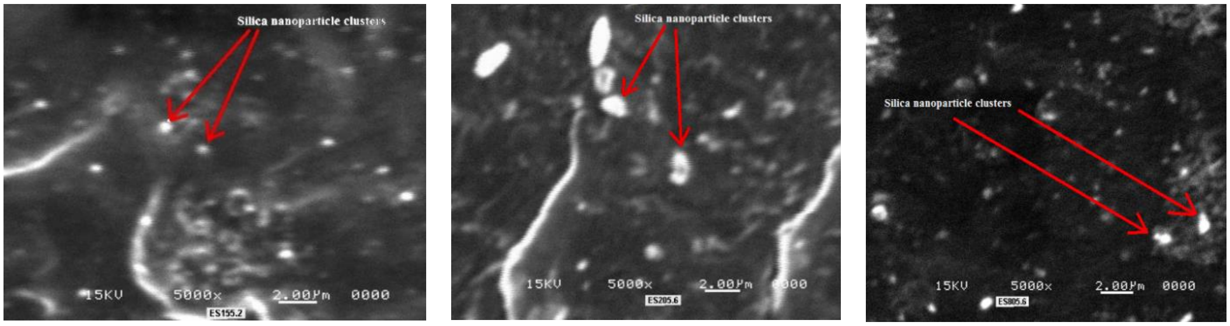
Figure 3: Indirect mean porosity measurement results with 95% confidence intervals

B. Micrographs of Nanocomposite

Particle distribution and aggregation in the nanocomposite were evaluated using an SEM analysis of fractured surfaces. Figures 4 and 5 show SEM images of different epoxy-silica nanocomposites. SEM micrographs show small clusters of nanoparticles covered by a thin polymer shell (interphase layer). Compared to the actual diameter of nanoparticles, the large particle diameter in these micrographs supports the cluster structure's formation.

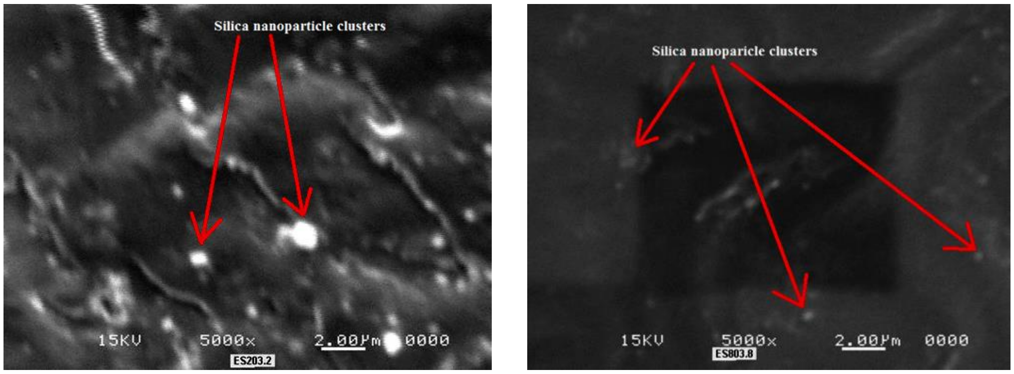
All the SEM images showed a moderate degree of particle cluster dispersion with few white spots, which are nanoparticle clusters. Composite samples with 5% loading of 20 nm particles showed more pronounced clustering than the 15 nm samples, possibly due to differences in dispersion energy and particle surface behavior. Figure 4 shows low-resolution SEM images of epoxy-silica composites with 5% loadings of 15nm, 20nm, and 80nm nanoparticles with a magnification level of ×10,000. Composite samples with 5% loading of 20nm nanoparticles showed particle clusters bigger than those observed in the 15nm nanocomposite samples. Composite samples with 5% loading of 80nm nanoparticles show few river markings (related to the initiation of matrix cracks that coalescence into larger cracks, indicating the direction of propagation) and some areas with a moderate degree of particle cluster dispersion. There are also some areas with low percentages of nanoparticles, which can lead to unpredictable results in tensile behavior.

Figures 5 show SEM images of nanocomposites with a 3% weight fraction of silica nanoparticles. Figure 5a shows the composite sample with 20nm nanoparticles. There is a moderate degree of particle dispersion with few particle clusters and some smooth areas surrounded by river markings. Figure 5b shows the composite sample with 80nm nanoparticles. The river markings and smooth areas in the case of both composite samples with 3% weight fraction silica nanoparticles indicate areas of polymer matrix with a lower percentage of nanoparticles than its surrounding areas. The SEM images of composite samples with 3% loading show more river markings and smooth areas than those with 5% loading.



(a) (b) (c)

Figure 4: SEM images with a magnification level of ×10,000 of the surface of epoxy-silica nanocomposite filled with various silica nanoparticle diameters using 5% loading: (a) 15 nm, (b) 20 nm, and (c) 80 nm. Arrows indicate the formation of small clusters of silica nanoparticles.



(a) (b)

Figure 5: SEM images with a magnification level of ×10,000 of the surface of epoxy-silica nanocomposite filled with various silica nanoparticle diameters using 3% loading: (a) 20 nm and (b) 80 nm. Arrows indicate the formation of small clusters of silica nanoparticles.

C. Tensile Tests

Pure epoxy and epoxy/silica nanocomposites were tested. The mean values of ultimate tensile stress, yield stress (0.2% offset), maximum strain, Young's modulus, and 95% confidence levels are illustrated in Figures 6 to 9. It can be concluded that ultimate strength, yield stress (0.2% offset), and Young's modulus of pure epoxy have improved after adding silica nanoparticles. Whenever a load is applied to the nanocomposite, it is transferred through the matrix to the nanoparticles, which have higher strength than the epoxy. Therefore, the addition of nano-silica increases the strength of the nanocomposite. The mean values of tensile properties and their 95% confidence intervals are summarized in Table 4.

The nanocomposite's gradual improvement in stiffness (Young's modulus) and strength (both ultimate tensile stress and yield stress) as the silica nanoparticle's size decreases is clearly distinguishable. A similar trend is also found when particle loading increases from 3% to 5%. (Figures 4 and 5). These mechanical property improvements can be attributed to enhanced interfacial adhesion and effective stress transfer between the silica nanoparticles and the epoxy matrix. In particular, the 20 nm particles provide sufficient interaction with the matrix without severe agglomeration in smaller 15 nm particles. Conversely, excessive porosity and clustering in the 15 nm and high-loading samples likely reduced their reinforcement efficiency, explaining the lower-than-expected tensile strength in some configurations.

Figures 6 and 7 show the ultimate tensile stress and Young's modules of nanocomposite. The Young's modulus of the nanocomposite sample with 80 nm nanoparticles with a 3% weight fraction was less than pure epoxy. Also, the pure epoxy sample had the highest ultimate strain. This unexpected result can be explained by the SEM images of a nanocomposite sample with 3% loading using an 80nm particle that showed a higher degree of unreinforced smooth areas and clusters. The reduction in strain with smaller particle sizes and higher loadings can be attributed to increased matrix rigidity and reduced ductility due to particle reinforcement. Nanoparticles restrict polymer chain mobility, reducing the material's deformability. However, the 80 nm particles at 3% loading may have acted more like micro-fillers, causing less interference with the polymer network and retaining more ductility. This explains the higher strain observed in these samples compared to smaller, more tightly interacting particles. (see Figure 3b). Overall, the mechanical behavior of the nanocomposites is primarily influenced by nanoparticle size, dispersion quality, and porosity, as evidenced by SEM and tensile results.

Table 4: Tensile properties of pure epoxy and epoxy-silica nanocomposite (Data are mean value ± 95% confidence level).

Material code	Ultimate tensile stress (MPa)	Yield Stress (0.2% offset) (MPa)	Ultimate Strain (%)	Young's modulus (GPa)
E	34.236 ±3.53	13.138 ±0.83	2.3 ±0.31	1.38 ±0.05
ES155	41.19 ±1.96	23.896 ±2	2.30 ±0.24	1.55± 0.03
ES205	38.99 ±3.54	22.68 ±2.11	2.55 ±0.38	1.52 ±0.127
ES805	34.76 ±4.89	22.49 ±0.71	2.74 ±0.38	1.46 ±0.07
ES153	37.26 ±4.3	21.27 ±0.95	3.21± 0.49	1.46 ±0.075
ES203	35.66 ±2.49	20.92 ±0.72	3.39 ±0.24	1.45 ±0.046
ES803	34.19 ±2.67	19.498 ±1.13	3.47 ±0.33	1.34 ±0.06

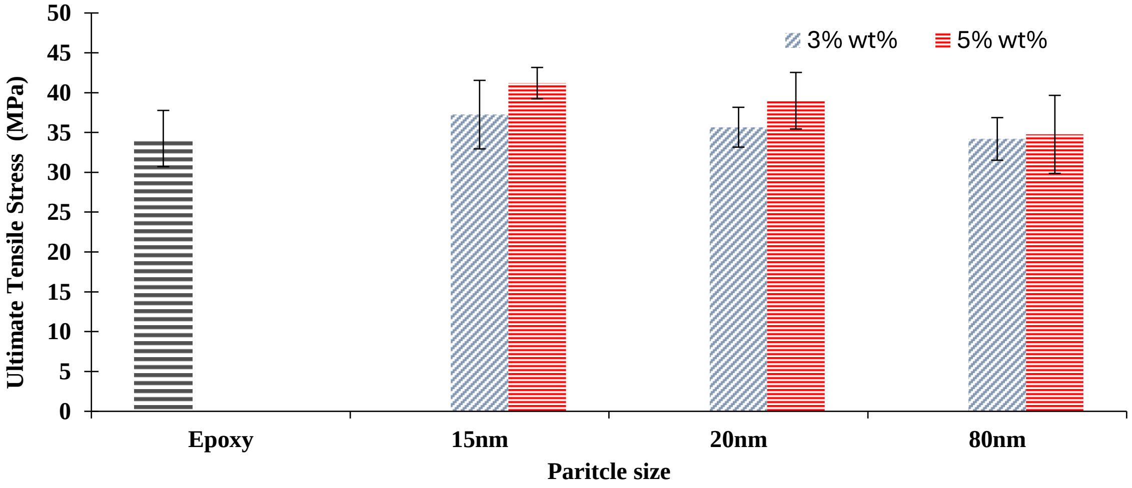


Figure 6: Ultimate tensile stress of pure epoxy and epoxy-silica nanocomposites.

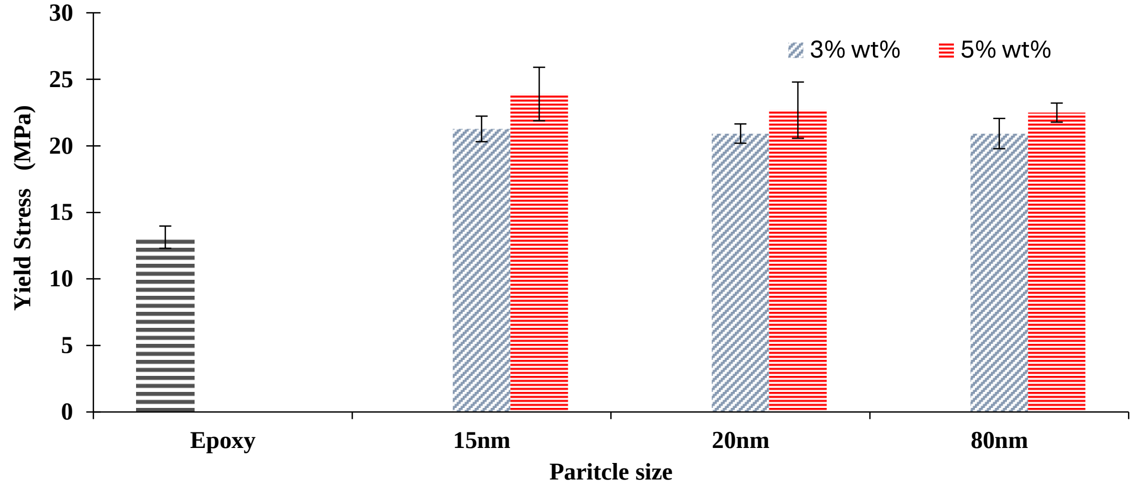


Figure 7: Yield stress of pure epoxy and epoxy-silica nanocomposites.

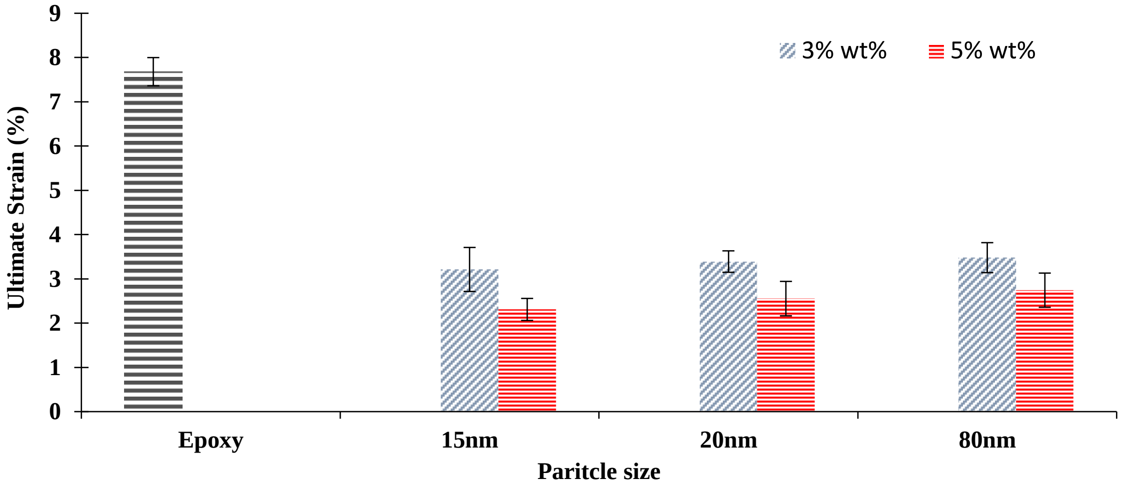


Figure 8: Ultimate Strain of pure epoxy and epoxy-silica nanocomposites.

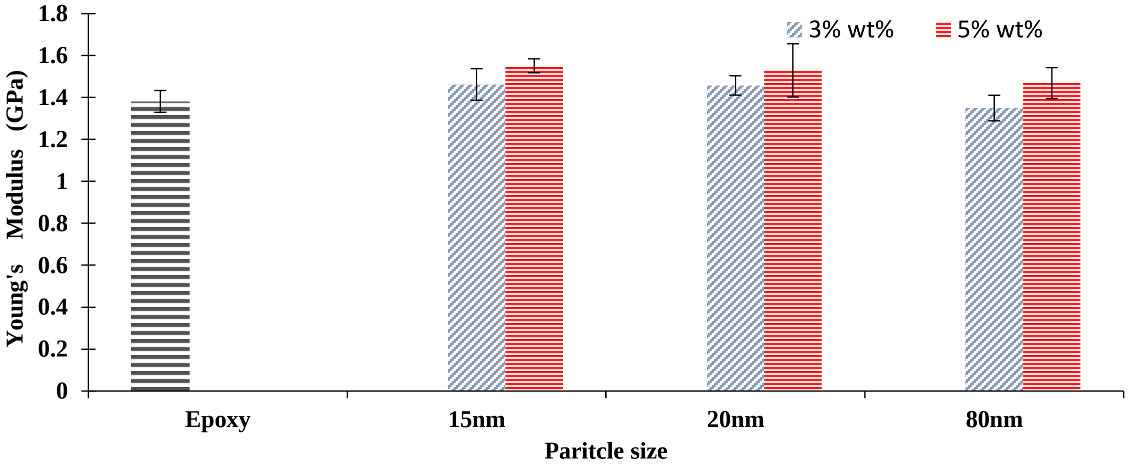


Figure 9: Young’s modulus of pure epoxy and epoxy-silica nanocomposites.

IV. SUMMARY AND CONCLUSION

Pure epoxy and epoxy-silica nanocomposite specimens were prepared to investigate the impact of nanoparticle size and weight fraction on mechanical behavior. The nanocomposites contained 3% and 5% weight fractions of silica nanoparticles with diameters of 15 nm, 20 nm, and 80 nm. Specimens for tensile tests were produced following ASTM D638 standards. The mean porosity in each nanocomposite was indirectly estimated to assess the influence of porosity on mechanical properties. SEM imaging confirmed efficient nanoparticle distribution with no significant clustering. Mechanical testing revealed that adding 5% silica nanoparticles significantly enhanced the stiffness of the epoxy polymer. Among the tested sizes, the 20 nm nanoparticles yielded the highest ultimate tensile stress, yield stress (0.2% offset), and maximum strain. Additionally, the results indicated that larger nanoparticles increased the stiffness of the nanocomposite, while Young’s modulus improved as particle size decreased.

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