CHARACTERIZATION OF EPOXY RESIN MATRIX REINFORCED WITH SILICA NANOPARTICLES FOR ENHANCED MECHANICAL PERFORMANCE

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Abstract: In this study, the epoxy resin matrix reinforced with silica nanoparticles is mechanically prepared and characterized using tensile and flexural tests and concretized by microscopic examination. The five samples preparation techniques involved weighing, mixing, and curing operations to create the epoxy-silica nanocomposites. Tensile tests were carried out to determine material's resistance to stretching pressures. The results showed variances in tensile strengths amongst the five samples tested as influenced by composition of the silica nanoparticles. The resilience of the nanocomposites to bending forces was assessed using flexural tests, revealing light on their possible use in load-bearing constructions, indicating a diverse mechanical response. SEM examination showed the silica nanoparticles' dispersion within the epoxy matrix and the microstructural dynamics responsible for the mechanical behaviors. The potential of the nanocomposite for engineering applications is appreciated through the combination of mechanical testing and microstructural characterization. The size of the clusters formed affects the sample's mechanical properties. The addition of silica nanoparticles reduced the tensile strength and increased the flexural strength of the 5 to 10% samples but decreased from 15 to 20% composition. Material design and selection procedures are guided by the material's properties and potential for engineering applications in industries.

Keywords: Nanoparticles, Epoxy Resin, Mechanical Performance, Silica

Introduction

Epoxy resin matrix composites are utilized in sectors like aerospace, automotive, electronics, and construction owing to high strength, stiffness, and chemical resistance. Silica nanoparticles enhance the mechanical and thermal properties of epoxy matrix composites with high strength, thermal stability, a large surface area-to-volume ratio of the particles, and chemical inertness, requiring detailed characterization for understanding structure-property correlations (Faheed, 2024).

Silica nanoparticles improve epoxy matrix energy dissipation, crack resistance, and fracture toughness, enhancing load transmission and overall performance owing to their small size and large surface area. Hybrid material structures are being developed to address mechanical, thermal, or physical deficiencies in composite materials. These structures consist of a thermosetting epoxy matrix reinforced by glass or carbon fibers. Micro- or nano-level reinforcements are being used to address issues like low toughness, low strain, and irregular interface formation. The development of new polymeric materials with enhanced strength, hardness, and heat resistance, particularly organic polymers reinforced with nano-sized inorganic fillers, is crucial for both academic and industrial applications (Choi *et al.*, 2023; Wang *et al.*, 2024).

Epoxy resins are widely used in industrial applications due to their high mechanical, adhesion, solvent, and chemical resistance and their ability to be curable at various temperatures without volatile byproducts. It is a crucial base material, and improvements have been made to enhance properties with micro- or nanoparticles, particularly inorganic particles, to increase elasticity, hardness, strength, and toughness. Epoxy resin matrix composites reinforced with silica nanoparticles show a higher modulus of elasticity than matrix material, directly proportional to silica weight fraction, promising applications in aerospace, automotive, and electronics. The stress-strain curves show a tensile and flexural test indicating that silica particles enhance the flexural modulus, but not the tensile modulus (Kiruthika, 2024).

The impact of silica sand nanoparticles on epoxy-based composites, revealing unique properties compared to macro-scale composites. A proper mixing prevents voids and increases porosity, while tensile strength and Young's modulus decrease with nanoparticles. An increasing filler content in nanocomposites increases elastic modulus, and dimensions are proportional to particle size, making the model reliable for predicting elastic properties (Mohan and Kanny, 2023).

The mechanical behavior of epoxy/silica nanocomposites was investigated using a DGEBA-based epoxy resin and Nanopox F400 for the nanocomposites, mixed, sonicated, and molded. The nanocomposites were subjected to zero-to-tension fatigue cycles and artificial short cracks, highlighting the significance of nanoparticle dispersion in polymer matrix properties. Tensile tests revealed that the weight content of silica particles affects nanocomposite tensile properties. Post-cured (PC) and non-post-cured (NPC) specimens showed different mechanical behavior. Nanomodification negatively affected NPC specimens, causing a decrease in strength and strain to failure. Fracture tests showed nanomodified specimens have higher fracture toughness than pure resin (Golakiya and Cree, 2024). The addition of nanoparticles initially increases fracture toughness. The fracture toughness of

NPC and PC specimens is influenced by the interactions between polymer and nanofillers (Shaaban *et al.*, 2024).
The curing reaction kinetics of nanocomposites are complex, and nanoparticles can hinder molecular motion and epoxy cross-linking. Silica nanoparticles act as a toughening agent in the epoxy matrix without compromising strength or notch sensitivity. It works best in polymer (PC) specimens, where increased curing time enhances polymer cross-linking. The fracture surfaces of PC nanomodified resins show satisfactory nanofiller distribution, possibly due to nanoparticle debonding and nanovoid deformation (Vasanta *et al*., 2013; Patel *et al.*, 2018).
The impact of nanoparticle percentage on the mechanical behavior of silica-epoxy nanocomposites on size, shape, and loading effects affects material properties. Preprocessing methods, such as coupling agents and grafting polymers, help reduce surface energy and disperse nanofillers into the matrix. Surface modification can be achieved using chemical or physical methods (Sanjay *et al.*, 2016; Sharma *et al.*, 2020).
The wear mechanisms of unfilled and SiO_2-filled G-E composites reveal deeper furrows and more damage to the epoxy matrix, while higher wear rates may be attributed to lower matrix ductility and poorer fiber-matrix adhesion. Nanoindentation tests show that nanocomposites' hardness and elastic modulus are linked to wear resistance and plastic deformation, with parameters increasing with nanoparticle content. The mechanical performance of nanocomposites is significantly influenced by the interfacing quality, distribution of nanoparticles, mixing choice, and loading condition, which all contribute to the overall performance (Turayev et al., 2021).
The impact test is a widely used method to assess a material's loading, bending, torsion, and tension properties, highlighting limitations in traditional epoxy resin composites. The present study aims to enhance the mechanical characteristics of high-performance epoxy resin composites reinforced with silica nanoparticles by exploring parameters and surface modifications, addressing identified restrictions.

Materials and Methods

Materials and Equipment

Silica nanoparticles have large surface area, controllable particle size, and biocompatibility. The silica-based nanoparticles were selected owing to its well-defined structure and capability to allow fabrication of the desired surface for theranostic applications. The production of an epoxy resin matrix reinforced with silica nanoparticles before testing used silica powder, epoxy resin, hardener, and mold. The equipment used for the specimen preparation and testing includes a weigh balance, a mixing machine (homogenizer), a universal testing machine, and a scanning electron microscope.

Sample Preparation, Mixing and Curing Processes

Silicon oxide as a poor conductor of electricity is utilized as an electrical insulator in microelectronics and structural materials, as shown in Figure 1. A hardener combined with epoxy resin starts a chemical process that causes the resin to cure, changing from liquid to solid. A three-dimensional network structure formed by cross-linking results in a strong, rigid material with improved mechanical, thermal, and chemical resistance qualities. The wooden mold of size 152.4 mm by 152.4 mm by 88.9 mm was chosen as medium density fiberboard (MDF) due to its adaptability and affordability as presented in Figure 2. The weighing scale measures the silica, epoxy, and hardener before mixing as well as the dependability and quality of the final samples. The mold creates a composite sample (an epoxy-silica mixture of different percentage compositions), ensuring uniformity in composition.
The application of a mold creates a barrier that prevents the epoxy from bonding to the mold, facilitating easy release. The mixing machine (homogenizer) blends, mixed, and emulsified ingredients to produce a consistent and uniform product, lowering the size of the particles and creating a stable combination as shown in Figure 3. The mixed epoxy resin and hardener in ratio 2:1, and silica nanoparticles achieve equal dispersion of nanoparticles within the epoxy resin matrix poured into the prepared mold. The mixture was left for 24 hours to cure (solidify) in the mold to initiate the chemical reaction within the epoxy resin while the composite was demolded later. The process was repeated for all 5 samples. The percentage of silica in the epoxy and silica nanocomposites, as well as test sample specifications, are presented in Tables 1 and 2.


Fig.1: Silica powder


Fig. 2: Prepared mold


Fig. 3: Mixing of epoxy& hardener

Table 1: Percentage of silica in the epoxy and silica nanocomposites

Sample	A (%)	B (%)	C (%)	D (%)	E (%)
silica nanoparticles (SiO_2)	0	5	10	15	20

Table 2: Test Sample Specifications

TEST	Sample Specifications (mm)		
Tensile	Thickness	Length	Width
	5	40	15
Flexural	Thickness	Length	Width
	5	65	45
SEM	A small good sample		

Material Sizing

The samples were machined to the standard sizes for the tensile, flexural, and SEM tests. The universal testing machine analyzed the mechanical characteristics of specimen materials (strength, elasticity, and hardness), putting them under controlled forces and deformations. Scanning electron microscopes imaged and examined the surface topography, morphology, and elemental composition of materials at high magnifications.

Material Testing

a. Tensile Test: The ASTM D638 universal testing machine was used by positioning the test samples securely fastening to ensure grips and alignment. Applying pressure to the material gives the material's stress, stretch, strength, and maximum strain tolerance data until the breaking point.
b. Flexural Test: The specimen sample was placed on the fixture with its side aligned parallel to the load direction, and bending force was applied using a universal testing machine. Data on load and deformation characterizing flexural stress, modulus, and ultimate strength were recorded.
c. SEM: Checking the microscopic structure of the nanocomposite and samples was done by cutting to fit in the specimen chamber. A specimen stub at high pressure, short working distance, and differential pumping of the electron optical column was mounted to maintain a vacuum and quantitatively X-rays for microanalysis.

Results and Discussions

Figure 4 shows the finished composite samples (A to E), which were prepared for further analysis to evaluate their structural integrity. The mechanical tests were conducted to assess how the composite material behaves under different loads, including its strength, resilience, and overall structural performance. The results of these tests provide a clear understanding of the material's mechanical properties, such as its strength and durability under stress.

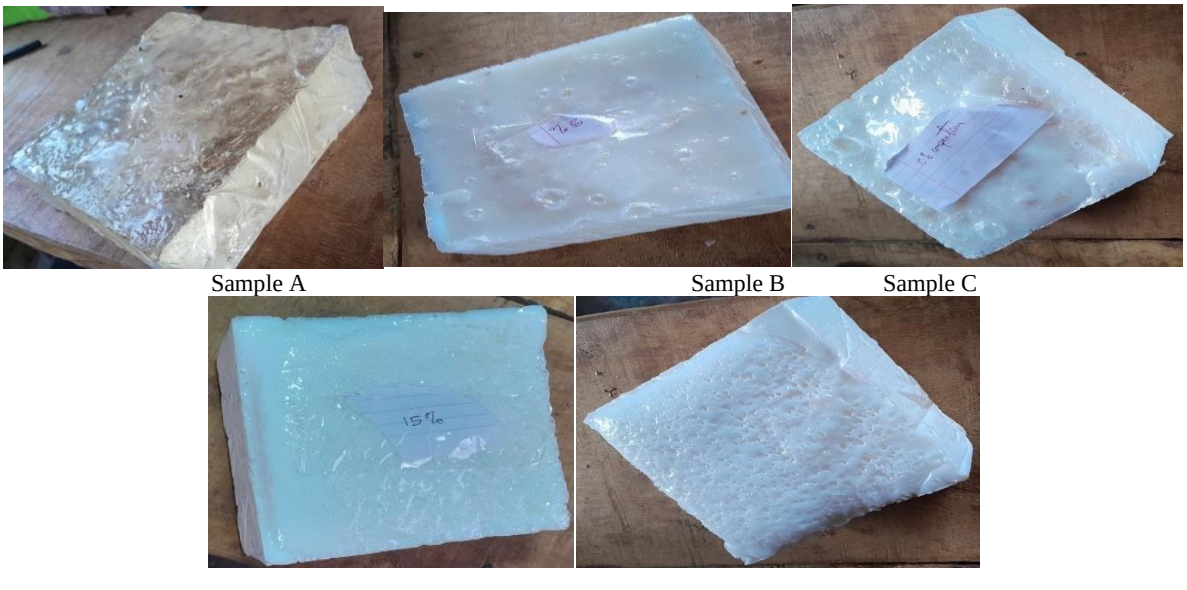
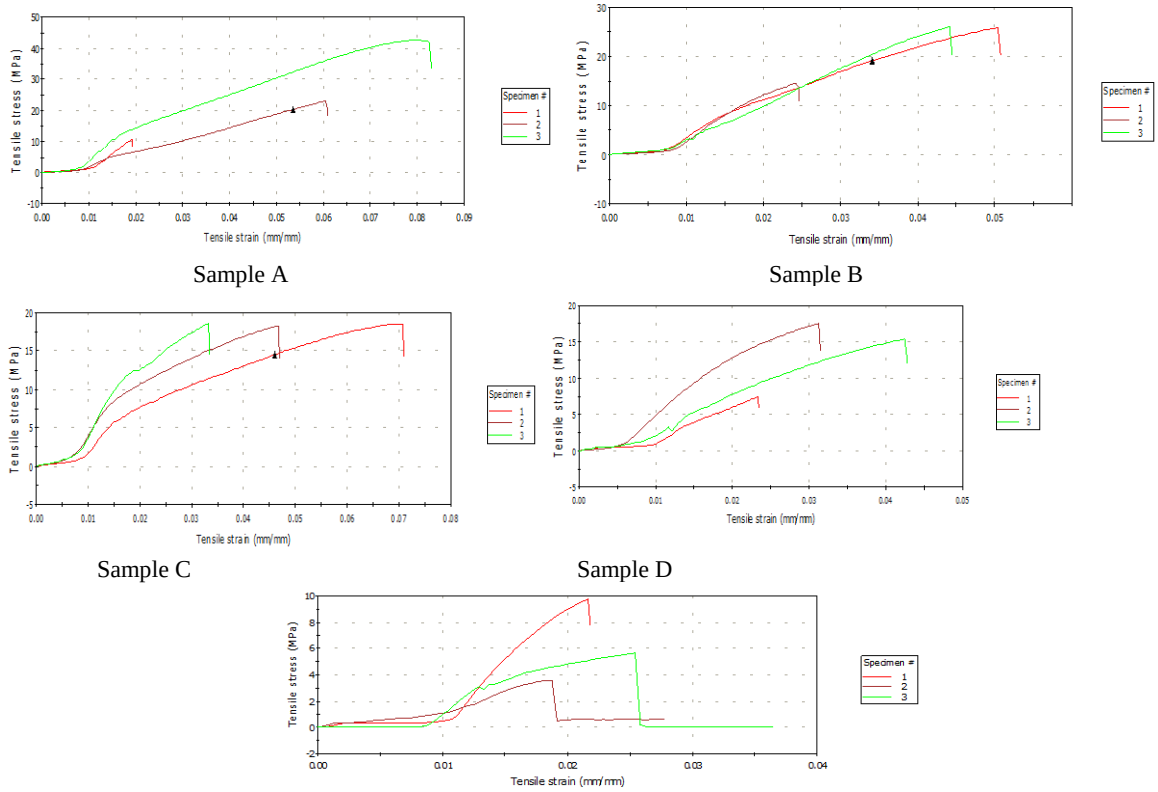


Figure 4: Composite samples (A -E)

Tensile Strength

Results of the tensile test on the nanocomposite material are shown in Figure 5 better in strength than existing materials owing to the particles compositions. It showed the behavior of each specimen during the tensile test as mechanical properties respond to varying subjected loads, as depicted in Figure 6, with samples A and B having the highest toughness. Samples A-E demonstrated a decline in mechanical tensile-strain behavior of the tested materials subjected to pressure with 22.27, 22.11, 6.34, 13.48, and 18.49 MPa, respectively.



Sample A

Sample B

Sample C

Sample D

Sample E

Figure 5. Tensile Stress -Tensile Strain Curve for Samples A – E

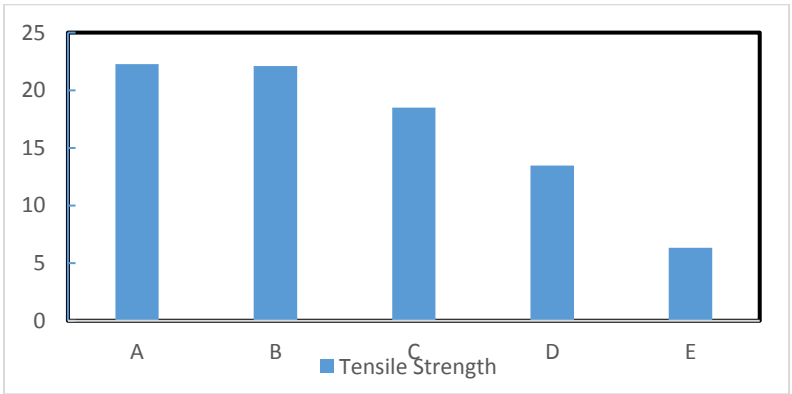
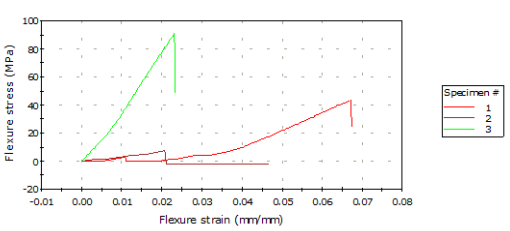


Figure 6: Combined Tensile Stress -Strain (MPa) Curve Samples A - E

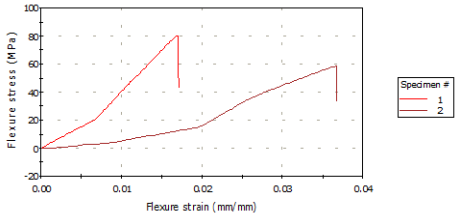
Flexural Test

The results of the flexural tests on the developed epoxy silica nanocomposite material's strength are shown in Figure 7. This indicates its resistance to bending forces and its potential for a range of technological applications such as automotive, sports goods and construction materials. Samples strength and maximum strain tolerance provide insights into how it behaves when subjected to pulling or stretching forces as confirmed in Sharma et al., 2020. The test results showed sample C

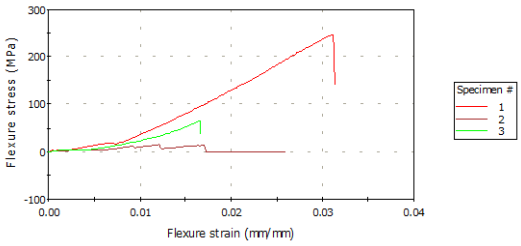
emerged with the highest sample flexural strength value of 108.83 MPa, whereas sample E has the lowest (6.26 MPa), respectively. The five samples, each made with a different amount of silica powder, show substantial changes in their mechanical responses when flexural strength data is compared. Sample B exhibits strong flexural strength at 69.65 MPa, highlighting a notable resistance to bending forces suitable for aerospace, electronics and construction works as contained in Faheed, 2024 report. The combined flexural strength of all samples is presented in Figure 8.



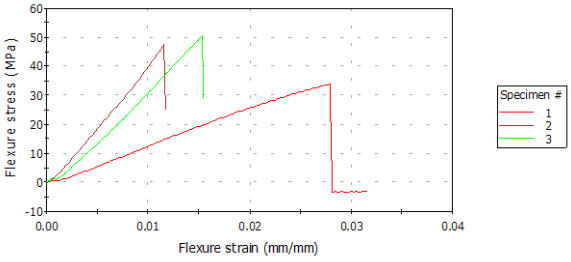
Sample A



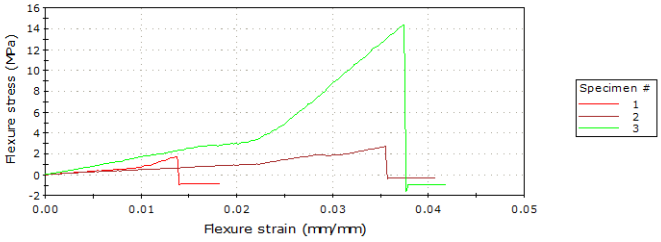
Sample B



Sample C



Sample D



Sample E

Figure 7: Flexural Stress - Strain Curve for Samples A – E

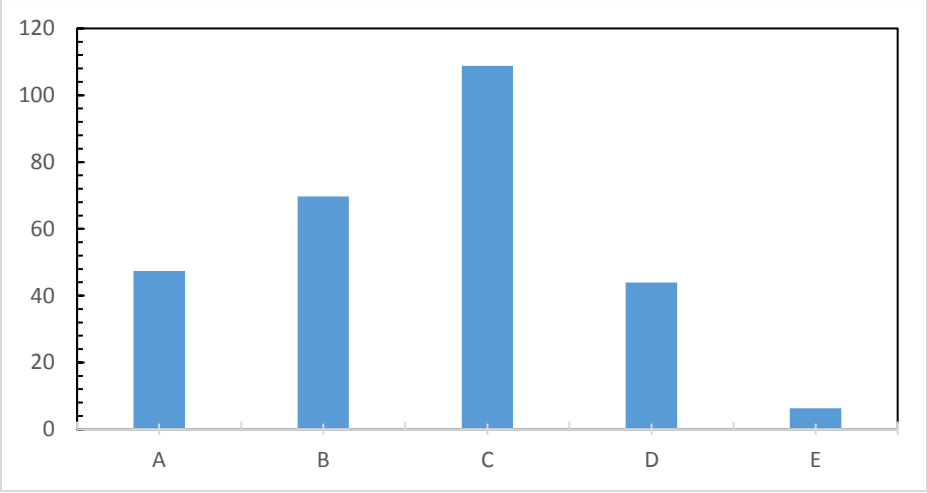
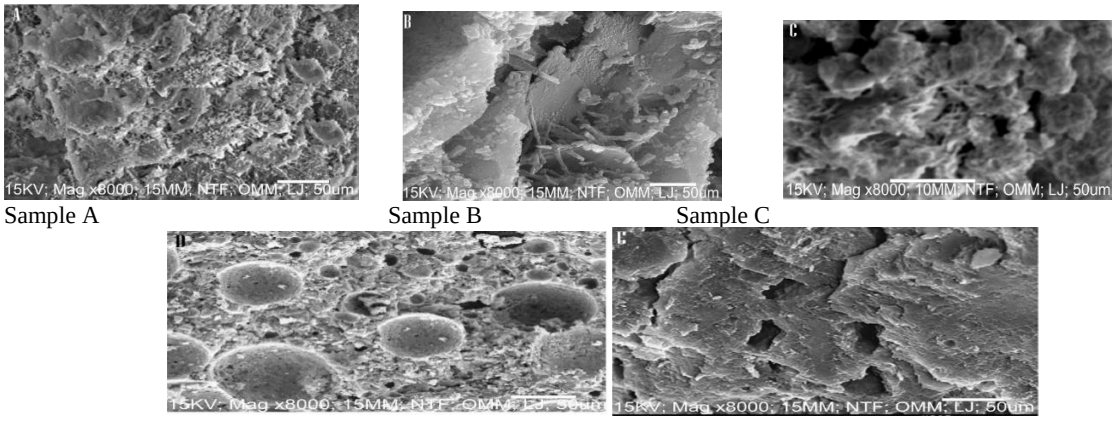


Figure 8: Combined Flexural Strength of Samples A - E

Scanning Electron Microscope (SEM)

The SEM images in Figure 9 provide visual representations of the surface morphology, structure, and composition of the silica nanocomposite sample analyzed at a micro-to-nanoscale level. The five nanocomposite samples indicate the effects of silica nanoparticles on the microstructure of epoxy resin. The SEM images show the microstructure of the composites and the structural impact of silica nanoparticles on epoxy resin. Pure epoxy resin (sample A) has a distinctive microstructure. But proportional increases in silica nanoparticles led to cluster formation in the composite. It is observed that the silica nanoparticles in the composite formed clusters in the mixture that increased with respect to the percentage increase of silica nanoparticles in the composite. The findings divulged different silica nanoparticle compositions influencing material's mechanical performance and identified samples best and weak locations.



Sample A Sample B Sample C

Sample D Sa

Figure 9: SEM Image for Samples A- E

Conclusions

The study characterized an epoxy resin matrix reinforced with silica nanoparticles. Different percentage compositions of silica powder were used to make the epoxy silica nanocomposite. The silica nanoparticles were found to improve the properties of epoxy resin, thereby enhancing the mechanical behavior of the materials. The tensile tests revealed a tensile strength in samples E to A of 6.34, 13.48, 18.49, 22.11, and 22.27 MPa, respectively. This indicates a restricted capacity to tolerate stretching stresses, marginally better, moderate, and suggests a balanced capacity, consistent, and potent resistance to stretching pressures required in aerospace industry. Sample C has the highest flexural strength (108.83 MPa) among all samples, demonstrating exceptional ability to withstand bending loads, while sample E has the lowest flexural strength (6.26 MPa), indicating a vulnerability to bending forces.The findings offer guidance for specialized automobile and aeronautical engineering applications that require flexural strength profiles as well as distinctive mechanical properties of materials. The clustered patterns in the SEM composites increased with an increase in the percentage of silica nanoparticles, which affects the mechanical properties of the composite. The addition of silica powder to epoxy reduces the tensile strength, increases the flexural strength of the epoxy for 5% and 10% compositions of silica in the epoxy, and decreases the flexural strength for 15% to 20% compositions of silica in the epoxy.

Reference

Choi, J.Y., Jeon, J.H., Lyu, J.H., Park, J., Kim, G.Y., Chey, S.Y., Quan, Y.J., Bhandari, B., Prusty, B.G. and Ahn, S.H. (2023). Current applications and development of composite manufacturing processes for future mobility. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 10(1), 269-291. https://doi.org/10.1007/s40684-022-00483-3.

Faheed, N.K. (2024). Advantages of natural fiber composites for biomedical applications: a review of recent advances. *Emergent Materials*, 7(1), 63–75. https://doi.org/10.1007/s42247-023-00620-x.

Golakiya, G. and Cree, D. (2024). Valorization of purified agricultural brown eggshell by-product as filler in bio-epoxy composites. *Waste Management Bulletin*. 2(1), 306-315. https://doi.org/10.1016/j.wmb.2024.02.006.

Kiruthika, A.V. (2024). A review of leaf fiber reinforced polymer composites. *Journal of Engineering and Applied Science*, 71(24), 1-31. https://doi.org/10.1186/s44147-024-00365-2.

Mohan, T.P. and Kanny, K. (2023). Dynamic mechanical analysis of glass fiber reinforced epoxy filled nanoclay hybrid composites. *Materials Today: Proceedings*, 87(1), 235-245. https://doi.org/10.1016/j.matpr.2023.05.282.

Patel, M., Pardhi, B., Chopara, S. and Pal, M. (2018). Lightweight composite materials for automotive-a review. *International Research Journal of Engineering and Technology*, 5(11), 41-47.

Sanjay, M.R., Arpitha, G.R., Naik, L.L., Gopalakrishna, K. and Yogesha, B. (2016). Applications of natural fibers and its composites: an overview. *Natural Resources*, 7(1), 108-114.

Shaaban, S., El-Abden, S.Z. and Ali, W.Y. (2024). Electrostatic charge generated from sliding of rubber on epoxy filled by natural fibers. *Journal of the Egyptian Society of Tribology*, 21(1), 120133. https://doi.org/10.21608/JEST.2024.336522.

Sharma, S., Sudhakara, P., Misra, S.K. and Singh, J. (2020). A comprehensive review of current developments on the waste-reinforced polymer-matrix composites for automotive, sports goods and construction applications: Materials, processes and properties. *Materials Today*, 33(2), 1671-1679. https://doi.org/10.1016/j.matpr.2020.06.523.

Turayev, S., Tuychiyev, X., Sardor, T., Yuldashev, X. and Maxsudov, M. (2021). The importance of modern composite materials in the development of the automotive industry. *Asian Journal of Multidimensional Research (AJMR)*, 10(3), 398-401. http://dx.doi.org/10.5958/2278-4853.2021.00144.0.

Vasanta, V.C., Udayakumar, P.A. and Ramalingaiah, P. (2013). Mechanical characterization of coir and rice husk reinforced hybrid polymer composite. *International Journal of Innovative Research in Science, Engineering and Technology*, 2(8), 96-104.

Wang, S., Zheng, Z., Long, J., Wang, J., Zheng, K., Ke, Z., Luo, Z., Pokrovsky, A.I. and Khina, B.B. (2024). Recent advances in wear-resistant steel matrix composites: a review of reinforcement particle selection and preparation processes. *Journal of Materials Research and Technology*, 29(2), 1779-1797. https://doi.org/10.1016/j.jmrt.2024.01.195.