Research Article

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Mechanical Characterization of Nanosilica-enhanced Glass Fiber-reinforced Polymer Composites

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ABSTRACT

Glass Fiber-reinforced Polymers (GFRP) are widely recognized for their superior mechanical performance and resistance to environmental degradation. Incorporating nano-scale fillers into these composites offers a promising way to further enhance their structural and functional properties. In this study, nanosilica particles were used as reinforcement in a polymer matrix composite system containing E-glass fibers to evaluate the improvement in mechanical properties. The composites were fabricated using the hand lay-up technique with Nano silica content varied from 0.5 wt.% to 3.5 wt.% in 0.5% increments. Mechanical characterization included tensile strength, flexural strength, and surface hardness testing. Results indicated a consistent improvement in all evaluated properties with increasing nanosilica content, attributed to better stress transfer and enhanced interfacial bonding between the fibers, matrix, and nano-fillers. Among all the samples, the composite containing 2.5% nanosilica exhibited the highest performance, demonstrating optimal dispersion and reinforcement efficiency. The observed enhancement confirms that even small additions of nanosilica can significantly influence the mechanical response of GFRP composites. These findings suggest that nanosilica-reinforced GFRP composites hold strong potential for high-performance applications in aerospace structures, defense components, marine systems, and advanced sporting equipment where weight reduction and mechanical reliability are critical. The successful integration of nanosilica with traditional glass fiber systems provides a viable pathway for the development of next-generation lightweight structural materials.

Keywords: Nanosilica; GFRP; Mechanical properties; Nanocomposite materials; Lightweight structural composites.

1. INTRODUCTION

Glass Fiber-reinforced Polymer (GFRP) composites are extensively used due to their excellent mechanical properties and corrosion resistance. Enhancing these composites with nano-sized fillers like nanosilica further improves their strength and durability. Nanosilica offers high surface area and good dispersion, making it an effective reinforcing agent at low concentrations. Incorporating nanosilica into GFRP can significantly boost tensile, flexural, and hardness properties. This study focuses on evaluating the mechanical performance of nanosilica reinforced GFRP composites fabricated by the hand lay-up method.

Parizi *et al.* (2020) explored surface nanoengineering strategies for enhancing the mechanical properties of GFRP composites and demonstrated that modifying commercial woven glass fibers with silica-based coatings significantly improved the mechanical performance, with the best results observed in mesoporous silica-coated fibers, which increased Young's and flexural moduli up to 31% compared to bare fibers.

VijayKiran *et al.* (2019) carried out the fabrication and testing of E-glass fiber-reinforced epoxy nanocomposites enhanced with varying weight percentages of graphene oxide nanoplatelets (GONP). Results showed significant improvements in tensile, compressive, and flexural strengths, demonstrating the material's potential for critical structural applications in aerospace, automotive, and renewable energy sectors. Glass fiber reinforced polymer (GFRP) composites exhibit enhanced mechanical properties when the interphase between filler and matrix is carefully engineered. Surface nanoengineering of woven glass fibers with silica-based coatings significantly improves stress transfer and mechanical strength (Parizi *et al.* 2020). Chillu *et al.* (2019) found that incorporating silica nanoparticles into GFRP composites enhanced surface wettability, dielectric performance, and mechanical strength. Optimal filler concentration improved corona inception voltage, space charge behavior, and insulation reliability.

Somaiah *et al*. (2022) researched hybrid composites reinforced with sisal and S-glass fibers, showing that epoxy matrices perform better mechanically than polyester, particularly when nanoclay is included. The laminates' tensile and flexural strengths were improved by optimal nanoclay loading, making them suitable for structural aerospace applications. Megahed *et al*. (2018) examined hybrid nanocomposites reinforced with woven and non-woven E-glass fibers and found notable enhancements in tensile, impact, and fatigue properties with the inclusion of silica and carbon black nanoparticles. Optimal filler combinations significantly enhanced mechanical performance compared to neat glass fiber-reinforced epoxy composites. Fathy *et al*. (2016) observed that the incorporation of nanoparticles significantly enhances the tensile strength and fatigue life of alumina-pultruded glass fiber-reinforced epoxy composites. On the other hand, silica nanoparticles only slightly enhance performance, with smaller weight fractions showing the best results. Chowdary *et al*. (2020) demonstrated that sisal/Kevlar fiber-reinforced composites' mechanical qualities significantly improve when nanosilica is dispersed in polyester resin with ultrasonic assistance. The KSSK and KSKS stacking sequences produced the highest tensile and flexural strengths, respectively, with optimal performance noted at 4 wt.% nanosilica. Rezvani *et al*. (2016) found that the incorporation of silica nanoparticles into dental fiber-reinforced composite resins significantly enhanced flexural strength and modulus. Optimal improvements were observed across 0.2–5 wt.% without notable differences between concentrations.

Khanna *et al*. (2003) reported that nano-indentation techniques are effective for investigating the mechanical properties of the interphase in glass fiber-reinforced polyester composites. Achieving ultra-smooth surfaces through abrasion and etching is essential for accurate nanomechanical characterization. Asrofi (2023) showed that the incorporation of nanosilica derived from granite waste into basalt and glass fiber-reinforced polyester composites significantly enhanced impact strength, energy absorption, and ductility up to 1 wt.%. This sustainable approach demonstrates the dual benefit of improved mechanical performance and effective granite waste utilization. Megahed *et al*. (2020) found that ultrasound sonication effectively enhances nanoparticle dispersion in polymer matrices, significantly improving the mechanical properties of glass fiber/polyester composites. Optimal sonication parameters resulted in increased tensile and fatigue strengths. Feli *et al*. (2016) established that adding nanosilica to epoxy and epoxy/fiberglass composites significantly enhances mechanical properties such as Young's modulus, yield stress, and tensile strength beyond 1 wt.% loading. Polynomial modeling using the imperialist competitive algorithm effectively predicted these improvements, confirming up to 56.87% property enhancement. Vijayan *et al*. (2023) showed that incorporation of nanosilica into E-glass-aluminum fiber metal laminates enhances impact resistance and energy absorption, with 1 wt.% showing optimal elastic modulus and thermal performance. Dynamic mechanical analysis confirms improved load-bearing capacity and homogeneity at this concentration. Jeyakumar *et al*. (2017) demonstrated that incorporation of 5 wt.% cloisite clay into glass fiber-reinforced epoxy composites significantly enhanced tensile, flexural, and impact properties, with HR-SEM confirming uniform nanoparticle dispersion. Higher clay content led to property deterioration, indicating an optimal threshold for mechanical performance.

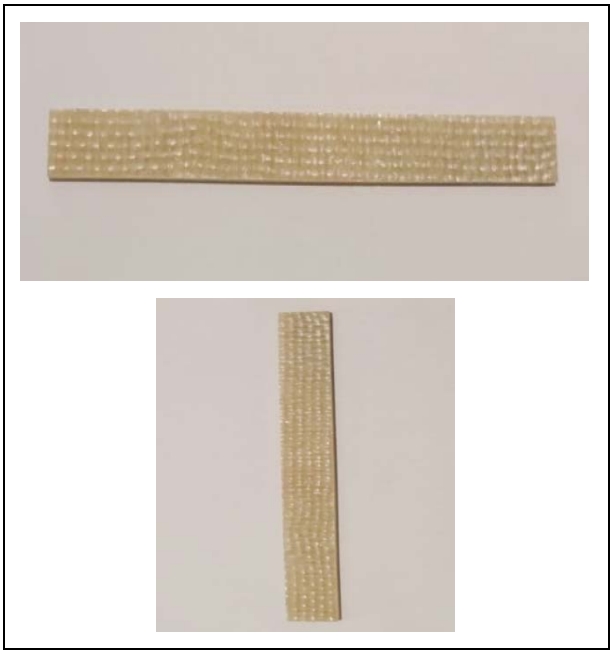


Fig. 1: GFRP composite reinforced with nanosilica

The mechanical properties of fiber-reinforced polymer composites can be improved by nanosilica and other nanofillers like nano-clay, graphene oxide, and alumina, according to earlier research. However, the majority of these studies have concentrated on small weight fractions (usually 1–5%) or particular property domains like flexural strength, dielectric behavior, or interfacial bonding. Furthermore, a number of studies focused on epoxy or polyester matrices, but few have methodically investigated how hand lay-up manufacturing affects GFRP systems when incremental nanosilica loading is applied below 3 wt.%. The current study is a relatively new approach, since it thoroughly examines low concentrations of nanosilica (0.5–2.5 weight percent) in composites reinforced with E-glass fiber and found that even small additions greatly improve the tensile, flexural, and hardness properties. By setting an ideal filler threshold at 2.5 3 wt.%, the study closes a clear knowledge gap about how precisely calibrated nanosilica loading affects stress transfer and interfacial bonding in GFRP composites made using readily

available methods. This aids in the creation of mechanically strong, lightweight composites that can withstand demanding structural applications.

2. MATERIALS AND METHODS

2.1 Fabrication of Composites

In this study, nanosilica-reinforced GFRP composites were prepared using the hand lay-up method. To achieve uniform mixing of nanosilica in the epoxy resin, both mechanical stirring and ultrasonication were used. Nanosilica was added in different weight percentages—0.5% to 3.5% in steps of 0.5%. The resin and nanosilica were first stirred using a magnetic stirrer with a hot plate at speeds between 300 and 1150 rpm. Heat was applied to lower the resin's viscosity for better mixing. Once a stable vortex formed, the mixture underwent ultrasonication at 600 Hz for 45 minutes to break down clumps and distribute the nanosilica evenly.

Fig. 1 shows a strip of GFRP composite enhanced with nanosilica, exhibiting a uniform surface texture. The reinforcement improves the mechanical strength and thermal stability of the composite.

Table 1. Tensile strength for different wt.% of nanosilica

S. No.	Wt. % of Nanosilica	Peak Load (kN)	Tensile Strength (MPa)
1	0.5	36.80	312.45
2	1.0	39.25	328.60
3	1.5	40.10	339.75
4	2.0	41.80	354.62
5	2.5	43.20	372.80
6	3.0	41.75	360.40
7	3.5	39.10	335.15

For fabricating the composite, a flat glass plate served as the base mold. Its surface was first coated with wax and then covered with a plastic sheet to ensure easy removal of the laminate after curing. E-glass fibers were cut to equal size and arranged in 13 layers for each laminate. The nanosilica and epoxy resin mixture was mixed with a hardener in the specified ratio and applied manually using the hand lay-up technique. Each fiber layer was coated with the resin mixture, maintaining a unidirectional alignment. Once lay-up was complete, a uniform pressure of 5 kg/sq. ft. was applied using a weight to remove air pockets and improve bonding. The laminates were then left to cure at room temperature for 48 hours. After curing, they were carefully removed from the mold and prepared for mechanical tests.

3. RESULTS AND DISCUSSION

3.1 Tensile Strength

Table 1 shows that as the nanosilica content increases from 0.5% to 2.5%, both peak load and tensile strength improve significantly, indicating better stress-bearing capacity. The tensile strength rises from 312.45 MPa at 0.5% to a maximum of 372.80 MPa at 2.5%. This enhancement is due to effective load transfer and improved interfacial bonding. But on further addition of the 2.5 wt.% that is at 3.0 wt.% and beyond, there is a sudden decrease in tensile strength, likely caused by filler agglomeration. Thus, 2.5 wt.% nanosilica offers the optimal reinforcement for tensile performance.

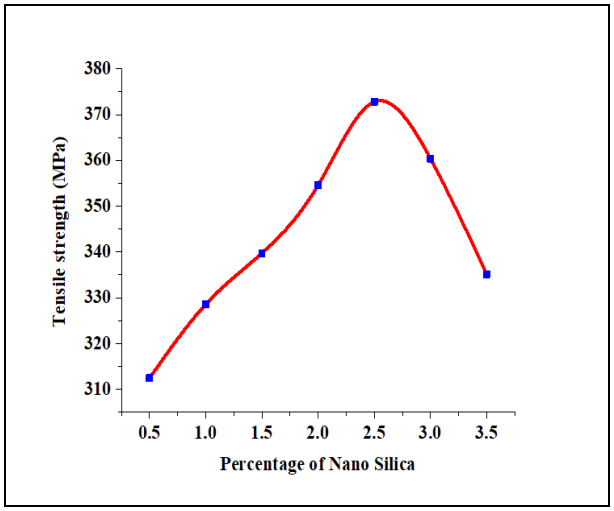


Fig. 2: Tensile strength for different wt.% of nanosilica

Fig. 2 illustrates the variation of tensile strength with different weight percentages of nanosilica in GFRP composites. The tensile strength increases up to 2.5% nanosilica, reaching a peak, and then decreases beyond that point.

Table 2. Elongation at peak load for various wt.% of nanosilica

S. No.	Wt.% of Nanosilica	Peak Load (kN)	Elongation at Peak Load (mm)
1	0.5	36.80	9.80
2	1.0	39.25	10.10
3	1.5	40.10	10.40
4	2.0	41.80	11.85
5	2.5	43.20	14.90
6	3.0	41.75	11.30
7	3.5	39.10	10.25

3.2 Elongation

As the nanosilica fraction increases from 0.5% to 2.5%, the material's ability to stretch before failure grows markedly, with elongation rising from 9.80 mm to

a peak of 14.90 mm, as presented in Table 2. This trend reflects enhanced ductility and improved stress transfer at intermediate filler levels. The sharp jump between 2.0% and 2.5% suggests optimal dispersion and interfacial bonding at that concentration. Beyond 2.5%, elongation falls to 11.30 mm at 3.0% and further to 10.25 mm at 3.5%, likely due to particle agglomeration restricting polymer mobility. Overall, 2.5 wt.% nanosilica delivers the greatest balance of strength and ductility.

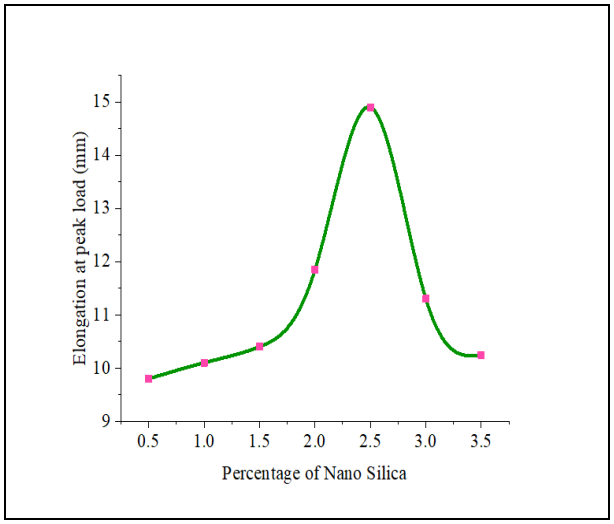


Fig. 3: Elongation at peak for different wt.% of nanosilica

Fig. 3 shows the elongation at peak load for varying nanosilica content in GFRP composites. Maximum elongation is observed at 2.5% nanosilica, after which it declines abruptly.

Table 3. Load and displacement for various wt.% of nanosilica

S. No.	Wt.% of Nanosilica	Peak Load (N)	Displacement (mm)
1	0.5	1480.5	5.100
2	1.0	1525.0	5.250
3	1.5	1565.0	4.890
4	2.0	1590.0	5.340
5	2.5	1608.0	5.480
6	3.0	1550.0	5.220
7	3.5	1495.0	4.980

3.3 Displacement

From Table 3, it is evident that peak load and displacement gradually increase with nanosilica content up to 2.5%, where the composite reaches a maximum load of 1608.0 N with a displacement of 5.480 mm. This indicates enhanced flexural resistance and energy absorption at this composition. However, beyond 2.5 wt.% specifically at 3.0 wt.% and above there is an abrupt drop in tensile strength, which can be correlated to the filler agglomeration and reduced stress distribution. The displacement remains relatively stable, reflecting consistent deformation behavior across most samples. Overall, 2.5 wt.% nanosilica provides the best balance of load capacity and flexibility.

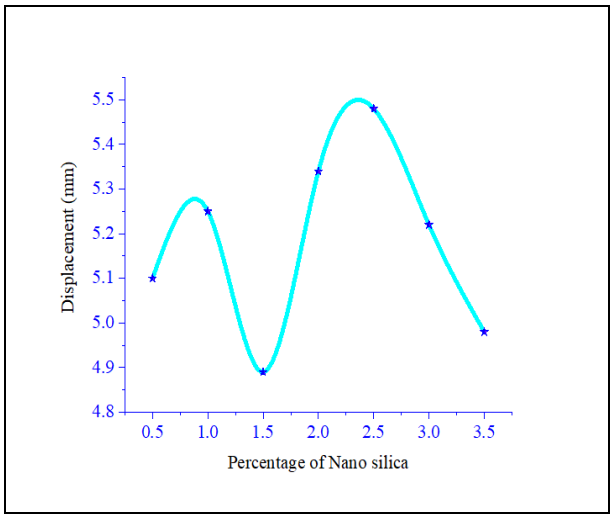


Fig. 4: Displacement vs. Wt.% of nanosilica

Fig. 4 presents the displacement behavior of GFRP composites with varying nanosilica content. The displacement shows a fluctuating trend across different weight percentages, peaking at 2.5 wt.% nanosilica.

Table 4. Effect of nanosilica Content on peak load and flexural strength of GFRP composites

S. No.	Wt.% of Nanosilica	Peak Load (N)	Flexural Strength (MPa)
1	0.5	1480.5	20.30
2	1.0	1525.0	21.75
3	1.5	1565.0	22.90
4	2.0	1590.0	23.45
5	2.5	1608.0	24.10
6	3.0	1550.0	22.40
7	3.5	1495.0	21.35

3.4 Flexural Strength

The flexural strength increases steadily from 20.30 MPa at 0.5% to a peak of 24.10 MPa at 2.5% nanosilica content, showing enhanced bending resistance (Table 4). This rise is supported by increasing peak loads, indicating improved load-bearing capability. The highest performance at 2.5% suggests optimal particle dispersion and matrix bonding. Beyond this point, both peak load and strength begin to decline due to possible nanosilica agglomeration. Thus, 2.5 wt.% offers the most effective reinforcement for flexural properties.

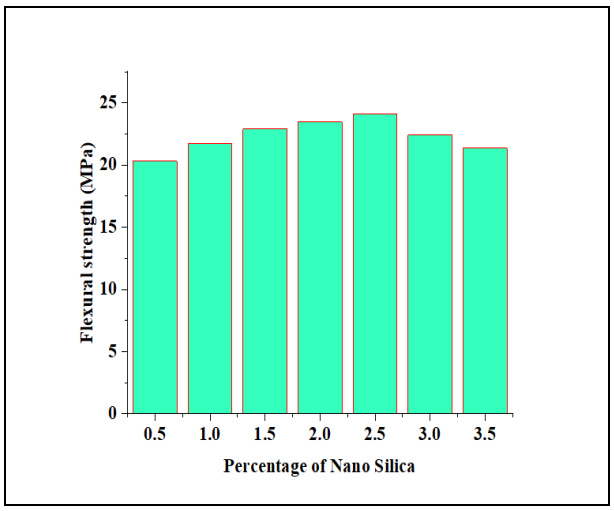


Fig. 5: Flexural strength analysis

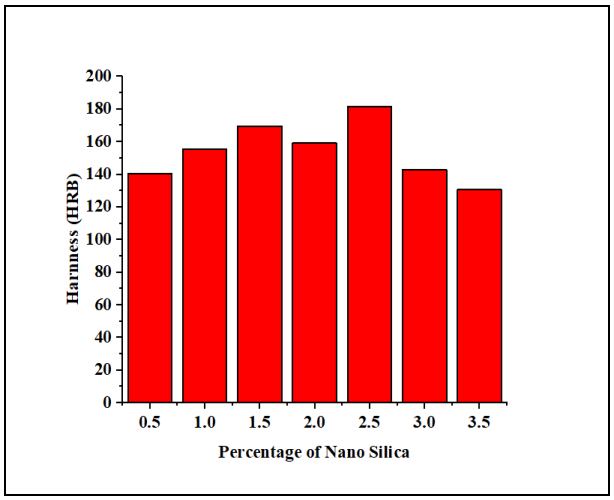


Fig. 6: Hardness test analysis

Fig. 5 shows the flexural strength of GFRP composites with varying nanosilica content. The strength increases up to 2.5% nanosilica, after which it begins to decline.

Table 5. Effect of nanosilica content on peak load and hardness of GFRP composites

S. No.	Wt.% of Nanosilica	Peak Load (N)	Hardness (HRB)
1	0.5	1480.5	140.10
2	1.0	1525.0	155.35
3	1.5	1565.0	169.45
4	2.0	1590.0	158.90
5	2.5	1608.0	181.25
6	3.0	1550.0	142.50
7	3.5	1495.0	130.40

3.5 Hardness Test

As presented in Table 5, the hardness of the composite increases with nanosilica content up to 2.5 wt.%, reaching a peak value of 181.25 HRB, indicating enhanced surface resistance and strength. This improvement is supported by a gradual rise in peak load from 1480.5 N to 1608.0 N. At 3.0% and 3.5%, hardness drops significantly to 142.50 HRB and 130.40 HRB, suggesting reduced effectiveness due to particle clustering. The variation highlights the importance of optimal dispersion for maximum hardness. Hence, 2.5 wt.% nanosilica delivers the best surface performance in the composite.

Fig. 6 displays the hardness of GFRP composites with varying nanosilica content. The hardness peaks at 2.5 wt.% nanosilica, followed by a noticeable drop.

4. CONCLUSION

- The incorporation of nanosilica significantly enhances both tensile and flexural properties of the composite. The peak performance was recorded at 2.5 wt.% nanosilica, with a tensile strength of 372.80 MPa and a flexural strength of 24.10 MPa, indicating superior load-bearing and bending resistance due to improved filler-matrix interaction.

- Elongation at break and displacement values increased steadily up to 2.5 wt.% nanosilica, reflecting enhanced ductility and energy absorption capacity. The maximum elongation of 14.90 mm and displacement of 5.480 mm confirm that the material maintains flexibility without sacrificing strength at this optimal filler level.

- Hardness values showed a clear upward trend with increasing nanosilica content, peaking at 181.25 HRB for 2.5 wt.%. This demonstrates improved surface integrity and wear resistance, beneficial for applications requiring high durability under surface contact or friction.

- Beyond 2.5 wt.% nanosilica, a decline in the mechanical properties such as tensile strength, elongation, flexural strength, and hardness was observed. This deterioration can be attributed to nanoparticle agglomeration, which hinders uniform stress distribution and reduces interfacial bonding efficiency.

- Based on the comprehensive analysis of mechanical performance indicators—including tensile strength, elongation, flexural properties, displacement, and hardness—2.5 wt.%

nanosilica reinforcement in GFRP composite is identified as the most effective concentration for achieving optimal composite performance.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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