Mechanical characterization of epoxy - alumina composites: A study on tensile, flexural and shear properties

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Abstract. This study investigates the mechanical performance of epoxy composites reinforced with varying weight percentages of aluminium oxide (Al_2O_3) nanoparticles. Composites were fabricated with 0%, 0.25%, 0.5%, 0.75%, and 1% Al_2O_3 by weight, and tested according to ASTM D638 (tensile), ASTM D790 (flexural), and ASTM E1876 (shear/dynamic) standards. The results revealed that the incorporation of Al_2O_3 significantly enhanced the tensile, flexural, and dynamic mechanical properties up to an optimal loading of 0.5 %, beyond which a gradual decline was observed. The maximum tensile strength (50.1 MPa) and flexural strength (96.18 MPa) were obtained at 0.5% Al_2O_3, along with an improvement in Young's modulus and shear modulus, indicating improved stiffness and load-bearing capacity. The enhancement is attributed to uniform nanoparticle dispersion within the epoxy matrix, which improved interfacial bonding and stress transfer. However, excessive filler loading led to agglomeration, reducing homogeneity and mechanical performance. Overall, the results confirm that 0.5 % Al_2O_3 provides the best balance of strength and stiffness for epoxy-based composite systems.

1 Introduction:

Composites are extensively used in aerospace, automotive, construction, and sports industries due to their high strength-to-weight ratio and excellent corrosion resistance. Additive manufacturing further enhances their appeal by enabling rapid prototyping and customization in areas such as medical devices and consumer goods. This chapter provides a comprehensive overview of composite materials, covering their types, manufacturing methods, matrix and reinforcement options, and modern applications. Common manufacturing techniques include hand layup, resin transfer moulding (RTM), filament winding, and additive manufacturing each suited to specific composite structures and production scales. Popular matrix materials include epoxy, polyester, and vinyl ester, chosen for their strong adhesive properties and versatility. Reinforcements such as glass fibers, carbon fibers, and ceramic fibers are widely employed, offering varying degrees of strength, stiffness, and thermal resistance [1].

Recent research highlights advancements in composite performance. One study investigated the enhancement of flexural strength in co-cured single lap joints (SLJs) by incorporating graphene nanoparticle (GNP)-reinforced epoxy adhesives and carbon fiber-reinforced polymer (CFRP) Z-pins. Results showed that adding 1.25 wt.% GNP to the adhesive increased flexural strength by 45.59%, while SLJs with 2.5 vol.% CFRP Z-pins

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oriented at 90° achieved even greater bending strength. The combination of both reinforcements yielded the highest flexural strength, emphasizing the effectiveness of multi-reinforcement strategies in composite joint design [2]. Another study explored the mechanical properties of epoxy-based hybrid composites reinforced with E-glass fibers and various industrial waste-derived particulate fillers. The findings highlight the potential of these low-cost, sustainable fillers to enhance the performance of structural composite materials [3]. The effect of GNP concentration in co-cured adhesive joints reveals improved shear and flexural strength with increasing GNP content. Both experimental and simulation results align, demonstrating enhanced load transfer and greater resistance to failure. Microstructural analysis confirms uniform GNP dispersion, highlighting the strong contribution of nanomaterials to enhanced bonding performance [4]. A dual-scale reinforcement approach using GNPs and Z-pins has also been explored to improve mechanical performance in single lap joints (SLJs). The results indicate significant enhancements in load bearing capacity and delayed failure modes, with finite element method (FEM) validation supporting the experimental findings. This novel dual-reinforcement strategy is effectively demonstrated [5]. Further improvements in shear strength are observed by combining GNPs and Z-pins at varying angles, showing efficient bonding, increased energy absorption, and strong interfacial adhesion [6].Strain rate sensitivity is another key factor influencing the tensile strength of epoxy and glass/epoxy composites. Studies show that both materials exhibit strain rate sensitivity, with glass/epoxy composites performing better under dynamic loading conditions. Additionally, incorporating nano silica enhances the tensile strength and modulus of epoxy composites, with peak performance observed at 10 wt.% nano silica. However, further addition leads to agglomeration and reduced effectiveness. Another study combining FEM and experimental analysis investigates the tensile behaviour of CNT-reinforced carbon/epoxy laminates, offering insights into nano reinforced composite performance under tensile loading [7-9].

The microstructure and fracture patterns of glass-epoxy composites under tensile loads have been investigated using SEM analysis, revealing fiber pull-out, matrix cracking, and interfacial failures. This study effectively links microstructural behaviour with mechanical performance, providing valuable insights into failure mechanisms in polymer composites [10]. Additionally, Al_2O_3 nanoparticles have been synthesized and applied for wastewater treatment through dye removal, demonstrating high decolorization efficiency due to their large surface area and strong adsorption capacity. Characterization techniques such as XRD and SEM confirm the nanoparticles' nanoscale morphology, highlighting their environmental significance [11]. The biocompatibility, inertness, and multifunctional nature of Al_2O_3 nanoparticles further support their use in biomedical applications such as drug delivery, implants, and cancer therapy [12]. Another study on Al- Al_2O_3 graded composites examines microstructure, hardness, and densification behaviour. The results indicate that increasing Al_2O_3 content leads to higher hardness and lower density. SEM analysis confirms clean interfacial transitions and uniform ceramic particle dispersion, supporting the effectiveness of the graded design [13].

Aluminium (Al) nanoparticles have been shown to enhance the barrier performance of epoxy, particularly at concentrations between 0.75-1.0 wt.%. SEM and EDS analyses confirm uniform dispersion at these optimal levels. Electrochemical testing reveals improved corrosion resistance, although higher filler content leads to agglomeration and diminished performance [14]. Another study investigates CFRP composite sandwiches with pumice/Mg syntactic foam (PMSF) cores, focusing on how fiber orientation (0°, 45°, 90°) in the skin influences mechanical properties. The 0° CFRP/PMSF configuration exhibits superior tensile and flexural strength, offering the best balance of strength and toughness for lightweight structural applications [15]. The addition of Al_2O_3 and SiC fillers into glass fiber-reinforced epoxy composites, fabricated via hand lay-up techniques, was also explored. Mechanical tests— including tensile, flexural, compression, and hardness indicate that Al_2O_3-filled composites perform best overall, especially at 8% filler loading. While SiC enhances hardness, it reduces tensile strength, making the study valuable for optimizing hybrid composite formulations [16]. Another study examines the influence of Cu and Al fillers (1-10 wt.%) on epoxy resin. Results show that increasing filler content decreases tensile strength but improves compressive strength and hardness, with Al outperforming Cu at higher loadings. SEM analysis supports these findings, highlighting crack deviation and filler agglomeration as contributing factors [17]. Finally, a comparative study between carbon fiber-reinforced epoxy (CFRE) and glass fiber reinforced epoxy (GFRE) laminates at various fiber orientations (0°, 90°, 0°/90°) reveals that CFRE composites outperform GFRE, particularly at 0° orientation. The study underscores the importance of fiber alignment in controlling strength and anisotropy in composite laminates [18]. This advanced study introduces a novel chemical and mechanical alloying method to fabricate Cu/Al_2O_3 composites with high strength (654 MPa) and conductivity (84.5% IACS). The formation of ultrafine grains and in-situ Al_2O_3 nanoparticles enhances both mechanical and electrical properties without compromise [19]. Another study investigates the impact of Al_2O_3 filler particles (0-3 wt.%) on the tensile, flexural, compressive, and water absorption properties of sisal fiber-reinforced epoxy composites. The 2 wt.% Al_2O_3 composition exhibited the best performance across all mechanical tests, attributed to strong interfacial bonding and uniform filler dispersion. SEM analysis corroborated the enhanced strength and reduced water absorption [20]. Further research explored the influence of Al_2O_3, TiO_2, and GNP nanoparticles (0.75-1.25 wt.%) on the mechanical, thermal, and chemical properties of epoxy resin. Al_2O_3 resulted in the greatest tensile strength improvement (140.3%), TiO_2 contributed to enhanced ductility, and GNPs improved thermal conductivity. FTIR and SEM analyses confirmed robust matrix-filler interactions [21].

Additionally, a study on the mechanical and tribological performance of epoxy composites reinforced with varying percentages of Al_2O_3 particles showed peak performance at 5-6% filler loading, with a decline in properties beyond that due to particle agglomeration. SEM analysis revealed uniform dispersion at lower filler concentrations [22]. This study evaluates hybrid epoxy-glass composites with varying weight percentages of Al_2O_3 and SiC (2-6%). It finds that 4 wt.% filler results in optimal tensile and flexural strength, while higher filler content leads to degradation of properties due to agglomeration. SEM analysis reveals mixed failure modes, including fiber pull-out and matrix cracking [23]. Another work explores the effect of micron-sized Al_2O_3 particles (5-120 µm) on the thermal and dynamic mechanical properties of epoxy composites. Smaller particles enhance thermal conductivity and increase the glass transition temperature, while larger particles improve modulus but reduce heat dissipation [24]. Further research investigates epoxy nanocomposites reinforced with varying ratios of graphene and Al_2O_3 nanoparticles. The optimal combination (1.5% GNP + 8.5% Al_2O_3) significantly boosts tensile, flexural, and impact strength, as well as thermal stability. FTIR analysis confirms chemical bonding, while Scanning electron microscopy (SEM) highlights failure mechanisms such as cracks, voids, and fiber pull-out [25].

The current research focuses on investigating the properties of a composite made from two materials: epoxy and aluminium oxide (Al_2O_3), aimed at enhancing its mechanical performance. Mechanical properties such as tensile strength and flexural strength were thoroughly examined, and microstructural analysis using SEM was conducted to understand the fracture mechanisms. During the comparative study, a significant improvement in the tensile and flexural properties of the proposed material was observed.

2 Material:

2.1. Epoxy (LY556):

Epoxy is a thermoset polymer widely used in high load-bearing applications. In composite materials, epoxy resins serve as the matrix component and are available in various grades, depending on the temperature requirements of the application. Epoxy resins are particularly suitable as matrix materials in fiber -reinforced composites due to their well-rounded properties, which include: Excellent adhesion to reinforcing fibers, Low shrinkage during curing, minimizing residual stresses, Superior mechanical properties compared to many other polymers, Good thermal stability across a wide temperature range, Wide choice of forms and curing conditions.

2.2. Aluminium Oxide (Al_2O_3):

Aluminium oxide (Al_2O_3), also referred to as alumina, is a commonly used ceramic material valued for its outstanding physical and chemical attributes. It is recognized for its superior hardness and resistance to wear, making it ideal for use in structural and abrasive environments. Al_2O_3 demonstrates excellent thermal conductivity and remains stable under high-temperature conditions. Additionally, it acts as an effective electrical insulator and shows strong resistance to chemical corrosion. These properties make alumina a highly effective reinforcement in polymer-based composites, contributing to improved mechanical strength, rigidity, and resistance to both heat and chemical exposure. The aluminium oxide (Al_2O_3) nano powder used in this study was sourced from Otto Chemie private. Ltd., India. The material is γ-phase alumina with an average particle size of 20-50 nm, spherical morphology, and a purity of 99.99%.

3 Tensile test of Epoxy - Alumina composite:

3.1 Experimental Procedure Epoxy - Alumina composite:

Epoxy resin was used as the matrix, reinforced with Al_2O_3 nanoparticles at varying weight fractions (0%, 0.25%, 0.5%, 0.75%, and 1%). The preparation process is illustrated in Fig.1. Tensile testing was carried out according to ASTM D638 specifications. The specimens were prepared with dimensions of 165 mm length, 19 mm width, and 3.2 mm thickness, and three samples were tested for each filler composition (0%, 0.25%, 0.5%, 0.75%, and 1%), making a total of 15 specimens. The epoxy resin (LY556) and hardener (HY951) were mixed in a 10:1 weight ratio, ensuring proper cross-linking and uniform curing. The mixture was stirred for 10-12 minutes and poured into moulds, followed by curing at room temperature for 24 hours. These curing conditions were precisely maintained, as variations in mixing or curing can significantly alter tensile strength and modulus values. Alumina particles were first dispersed in pure acetone and subjected to 1 hour of ultrasonication to ensure proper de-agglomeration. Epoxy resin was then added to the mixture, followed by a further 1 hour of sonication. The resulting solution was gently heated to evaporate acetone, after which it was degassed in a vacuum chamber to remove entrapped air bubbles. The degassed mixture was poured into a metallic mould and cured under room conditions for 24 hours, followed by post-curing at room temperature. After curing, samples were removed from the mould and again degassed to eliminate residual voids. The prepared specimens were tested using an Instron 8071 Universal Testing Machine according to ASTM D638 standards for tensile testing. A constant crosshead speed of 2 mm/min was maintained. Stress-strain curves were recorded, and tensile strength, Young’s modulus, and elongation at break were calculated.

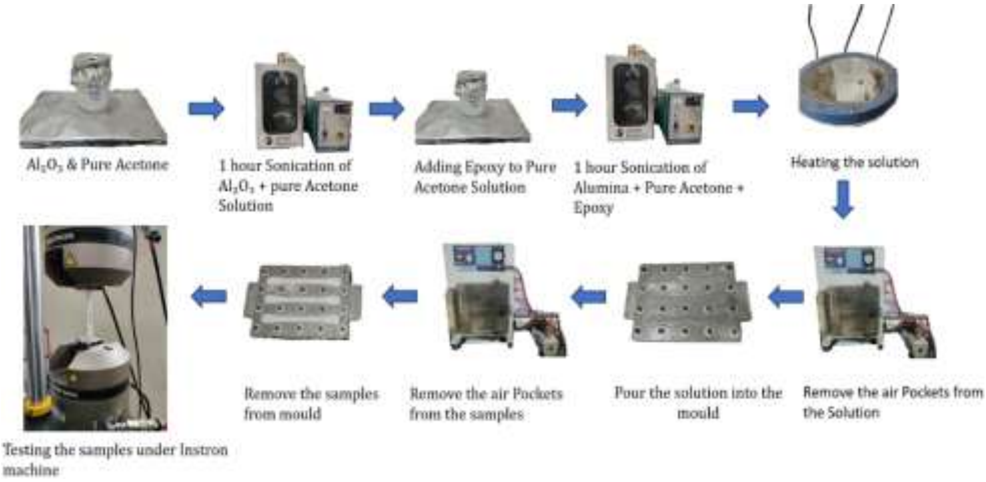
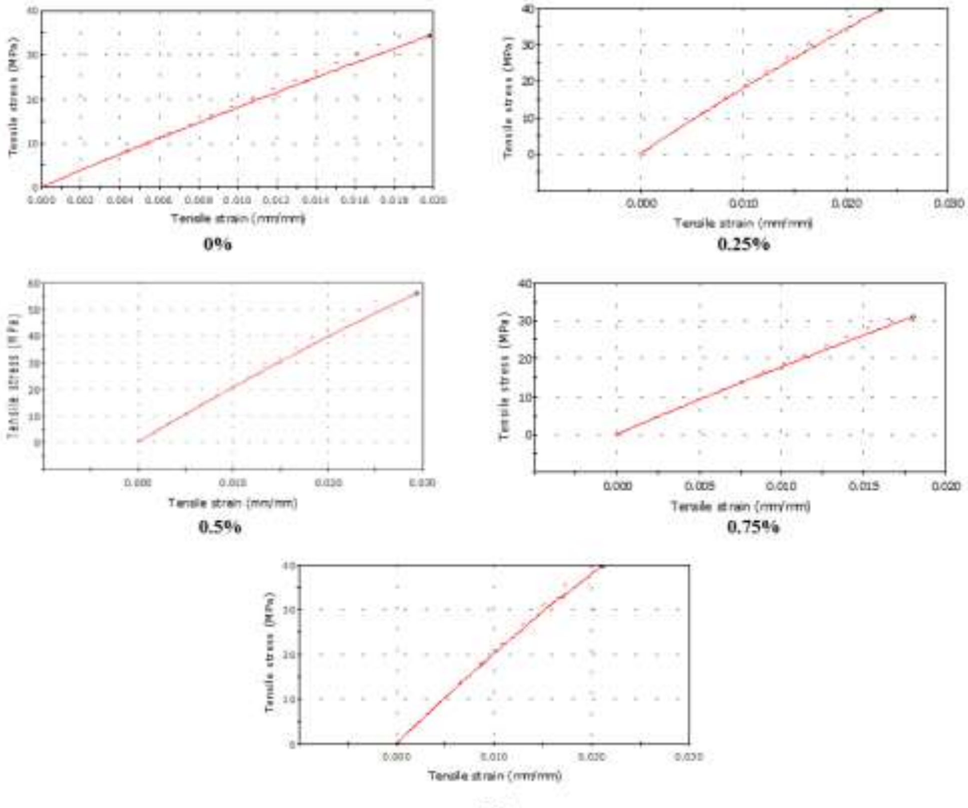


Fig. 1.1 Experimental setup and procedure for the tensile test of epoxy- Al_2O_3 composites as per ASTM D638, including specimen preparation, gripping, and testing on the INSTRON universal testing machine.

Fig. 1.2 Tensile testing setup for epoxy- Al_2O_3 composite and Tensile test specimen prepared as per ASTM D638



0% **0.25%**

0.5% **0.75%**

1%

Fig. 1.3 Tensile stress-strain graph of 0, 0.25, 0.5, 0.75 and 1%

3.2 Results and Discussion:

Table 1. Tensile strength, Young's modulus, and standard deviation of epoxy- Al_2O_3 composites (ASTM D638).

Sr. No.	Alumina (%)	Mean Tensile strength (MPa)	Avg. Young's modulus (GPa)	S.D of strength
1	0	34.8	1.81	3.5
2	0.25	41.1	1.87	2.0
3	0.5	50.1	2.08	4.2
4	0.75	42.3	1.98	1.0
5	1	39.0	1.85	4.1

The tensile test was conducted according to ASTM D638 standards to determine the tensile strength and Young's modulus of epoxy–alumina composites. The results are summarized in Table 1. From the data, it is evident that the incorporation of alumina (Al_2O_3) significantly influences the tensile performance of the epoxy matrix. The pure epoxy sample (0 % Al_2O_3)

exhibited a mean tensile strength of 34.8 MPa and an average Young's modulus of 1.81 GPa. With the addition of 0.25 % alumina, the tensile strength increased to 41.1 MPa, and at 0.5%, the composite achieved the maximum tensile strength of 50.1 MPa with a corresponding Young's modulus of 2.08 GPa. This enhancement can be attributed to the uniform dispersion of Al_2O_3 nanoparticles within the epoxy matrix, which improves stress transfer efficiency and restricts polymer chain mobility under load. Beyond 0.5%, a decline in tensile strength was observed 42.3 MPa for 0.75 % and 39.0 MPa for 1% alumina. This reduction is likely due to nanoparticle agglomeration at higher filler contents, which acts as a stress concentrator and weakens the interfacial bonding between the matrix and the filler. The standard deviation values also support this trend, indicating consistent behaviour at the optimum loading and greater variability at higher concentrations. Overall, the results suggest that 0.5 % Al_2O_3 provides the optimal balance between matrix reinforcement and particle dispersion, resulting in the best tensile performance among all compositions tested. The comparatively lower tensile strength and Young's modulus than those reported in literature are attributed to particle agglomeration, porosity, and weak interfacial bonding between epoxy and Al_2O_3. The absence of surface treatment and minor variations in curing and mixing conditions further reduced the stress transfer efficiency.

4 Flexural Test of Epoxy - Alumina composite :

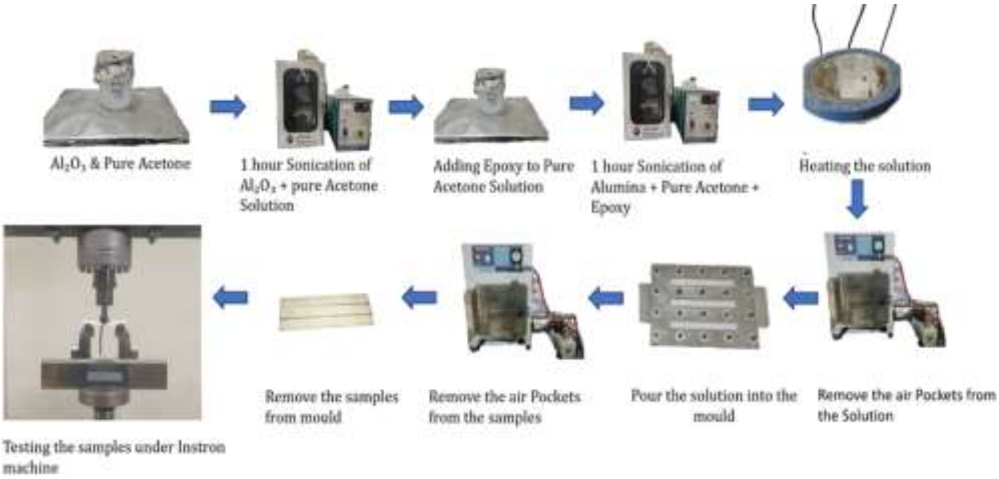
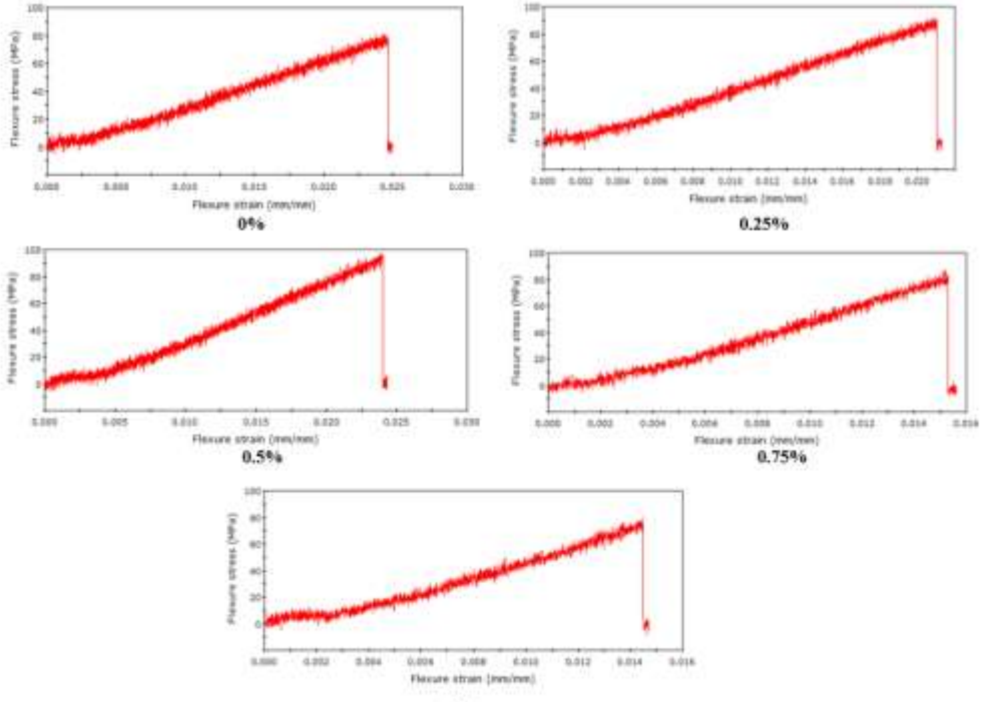


Fig. 2.1 Experimental setup and procedure for the flexural test of epoxy - Al_2O_3 composites conducted according to ASTM D790, showing specimen moulding, three-point bending setup, and data acquisition on the INSTRON machine.

4.1 Experimental Procedure of Epoxy - Alumina composite :

The epoxy-alumina composite specimens were prepared using the solution blending and casting method, as illustrated in Figure 2.1. Araldite LY556 epoxy resin was used as the matrix material, while alumina (Al_2O_3) particles were employed as reinforcement in varying weight percentages of 0%, 0.25%, 0.5%, 0.75%, and 1%. Flexural tests were performed as per ASTM D790 three-point bending standards. The composite samples were fabricated to dimensions of 127 mm × 12.7 mm × 3.2 mm and three specimens for each composition (0%, 0.25%, 0.5%, 0.75%, and 1%) were tested, resulting in a total of 15 flexural samples. The epoxy matrix was prepared using LY556 resin and HY951 hardener in a 10:1 mixing ratio. After uniform mechanical stirring and degassing, the material was poured into molds and allowed to cure for 24 hours at room temperature. This controlled mixing and curing procedure is essential, as it directly affects matrix continuity and consequently the flexural strength and stiffness. Initially, the required amount of alumina powder was dispersed in pure acetone to enhance particle wetting and prevent agglomeration. The mixture of Al_2O_3 and acetone was then sonicated for one hour using a Johnson Plastosonic ultrasonic processor to achieve uniform dispersion of the particles. Subsequently, the pre-measured epoxy resin was added to the alumina–acetone solution, and the resulting mixture was again sonicated for an additional hour to ensure homogeneous distribution of alumina within the epoxy matrix. The prepared suspension was then gently heated to remove acetone and to reduce the viscosity of the epoxy resin, facilitating better mixing and mould filling.

After heating, the mixture was placed in a vacuum chamber to remove entrapped air bubbles and residual acetone, ensuring a void-free matrix. The degassed mixture was then poured into a steel mould designed as per ASTM D790 specimen dimensions for flexural testing. To eliminate any remaining air pockets, the filled mould was again subjected to vacuum degassing. The samples were then cured at room temperature and carefully removed from the mould after complete solidification. Flexural testing of the cured specimens was performed using an Instron Universal Testing Machine (UTM) in accordance with ASTM D790 standards. A three-point bending configuration was employed with a crosshead speed of 2 mm/min. The maximum load at fracture was recorded, and the corresponding flexural strength was calculated based on specimen geometry. For each composition, three specimens were tested to ensure repeatability, and the mean flexural strength along with standard deviation was reported. This fabrication and testing methodology ensured uniform dispersion of alumina particles, minimized void formation, and produced reliable mechanical property data for comparative evaluation.



0%

0.25%

0.5%

0.75%

1%

Fig. 2.2 Flexure stress-strain graph of 0, 0.25, 0.5, 0.75 and 1%

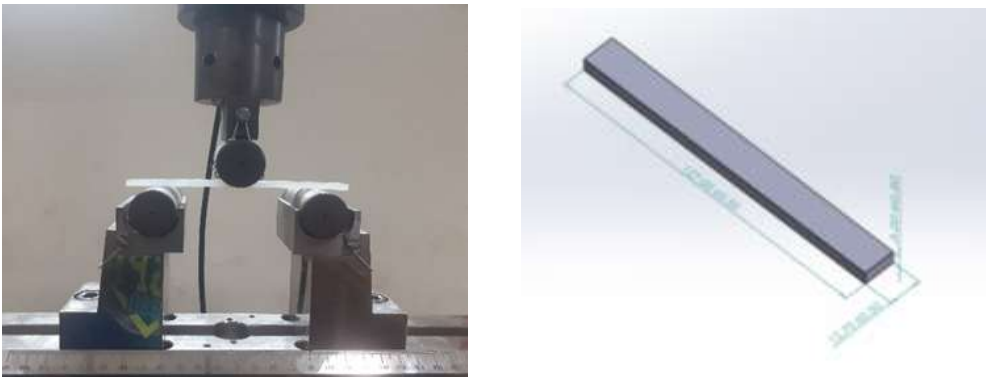


Fig. 2.3 Flexural testing setup for epoxy- Al_2O_3 composite and Flexural test specimen prepared according to ASTM D790

4.2 Result and Discussion:

Table 2. Flexural strength and standard deviation of epoxy- Al_2O_3 composites (ASTM D790)

Sr. No.	Alumina (%)	Max. force (N)	Mean Flexural strength (MPa)	S.D of strength
1	0	81.89	80.83	1.37
2	0.25	88.48	88.31	2.93
3	0.5	94.29	96.18	1.46
4	0.75	84.26	88.29	0.81
5	1	78.46	82.89	0.92

The flexural strength of epoxy and alumina-reinforced epoxy composites was determined according to ASTM D790 standards, and the results are summarized in Table 2. The pure epoxy specimen (0% Al_2O_3) exhibited a mean flexural strength of 80.83 MPa, which falls within the standard range for LY556 epoxy systems. With the incorporation of alumina particles, a noticeable improvement in flexural performance was observed up to 0.5% filler content. The composite containing 0.25% Al_2O_3 demonstrated a mean flexural strength of 88.31 MPa, while the 0.5% Al_2O_3 composite achieved the highest strength of 96.18 MPa, indicating an approximate 19% increase over the unreinforced epoxy. This enhancement can be attributed to the uniform dispersion of alumina particles, which act as effective stress transfer sites between the matrix and reinforcement, thereby delaying crack initiation and improving load-bearing capability. However, further addition of alumina beyond the optimal concentration resulted in a decline in flexural strength. The 0.75% and 1 % composites exhibited mean flexural strengths of 88.29 MPa and 82.89 MPa, respectively. The reduction in strength at higher filler loading is likely due to particle agglomeration and the formation of micro-voids, which reduce the effective bonding area between the epoxy matrix and alumina particles. Such agglomerates act as stress concentrators, leading to premature failure under bending loads. The standard deviation values were relatively low across all compositions, indicating consistent and repeatable results, with minor variation at 0.25% due to dispersion sensitivity. The overall trend suggests that 0.5% alumina offers the best balance between particle dispersion and matrix interaction, resulting in optimal flexural performance.

Similar behaviour has been reported by other researchers for nanoparticle-reinforced epoxy systems, confirming that moderate filler loading improves mechanical strength, while excessive addition leads to aggregation and property degradation. Therefore, it can be concluded that alumina reinforcement up to 0.5% significantly enhances the flexural strength of LY556 epoxy composites, validating the data for publication and practical composite design applications.

5 Shear Test of Epoxy - Alumina composite:

5.1 Experimental Procedure of Epoxy - Alumina composite:

The dynamic shear test was conducted in accordance with the ASTM E1876 - Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. This method determines the elastic properties of materials by measuring the natural resonance frequencies of test specimens subjected to mechanical excitation. Shear and dynamic characterization was performed according to ASTM E1876 on rectangular specimens measuring 150 mm in length, 50 mm in width, and 5 mm in thickness. For each composition (0%, 0.25%, 0.5%, 0.75%, and 1% Al_2O_3), one specimen was prepared, resulting in a total of five samples. Each specimen was tested twice to obtain two flexural resonance frequencies and two torsional resonance frequencies, ensuring repeatability and reducing measurement error. The composites were fabricated using LY556 epoxy resin and HY951 hardener mixed in a 10:1 ratio, which is essential to maintain proper cross-linking and achieve consistent elastic behaviour. The mixture was poured into moulds after careful stirring and degassing, and cured at room temperature for 24 hours. Accurate control of the mixing ratio and curing conditions is critical, as deviations can alter stiffness, affect resonance behaviour, and lead to inaccurate computation of Dynamic Young's modulus, Shear modulus, and Poisson's ratio. Each specimen was supported in a free-free boundary condition, meaning both ends were unrestrained to allow natural vibration modes. The setup was carefully arranged to prevent any external damping or constraint effects. An impact hammer was used to excite the specimen by delivering a light mechanical tap, initiating vibration in both flexural and torsional modes. The vibration response was recorded using a sensitive microphone connected to a Data Acquisition (DAQ) system interfaced with specialized vibration analysis software. The fundamental flexural frequency (f_x) and fundamental torsional frequency (f_t) were extracted from the recorded signal. Using these frequencies along with the specimen's mass density (ρ) and geometrical dimensions (length, width, and thickness), the Dynamic Young's Modulus (E) and Shear Modulus (G) were calculated using standard equations provided in ASTM E1876. The Poisson's ratio (ν) was then derived from the relationship between E and G:

$$\nu = (E / 2G) - 1$$

Each composition of composite material (0%, 0.25%, 0.5%, 0.75%, and 1% Al_2O_3) was tested twice to ensure repeatability, and the average values of resonance frequencies were considered for final calculations. The testing method was completely non-destructive, allowing the same specimen to be used for further mechanical characterization. This dynamic testing approach provides high accuracy and sensitivity for evaluating the elastic and shear behaviour of polymer composites, enabling detailed assessment of stiffness improvement with increasing Al_2O_3 nanoparticle content.

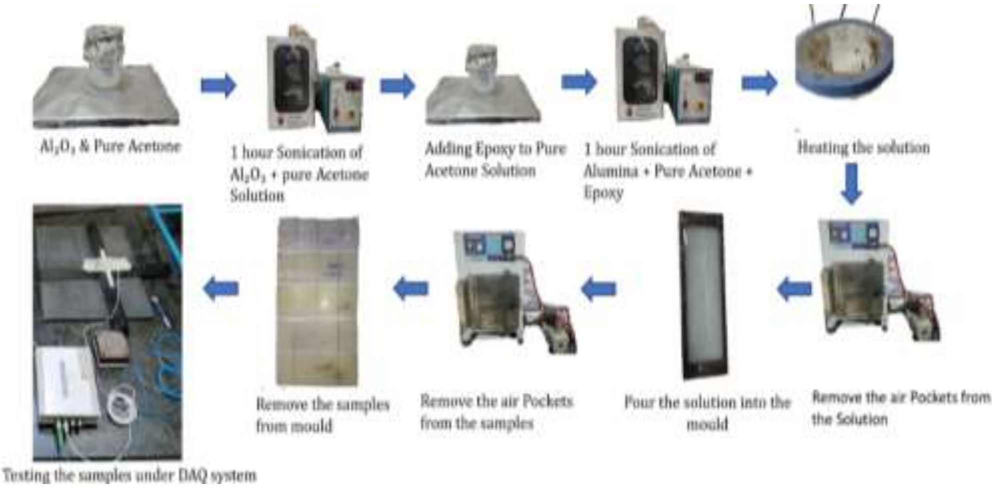


Fig. 3.1 Experimental procedure for determining dynamic and shear properties of epoxy- Al_2O_3 composites as per ASTM E1876, including specimen preparation, support arrangement, and measurement of resonance frequencies for modulus calculation.

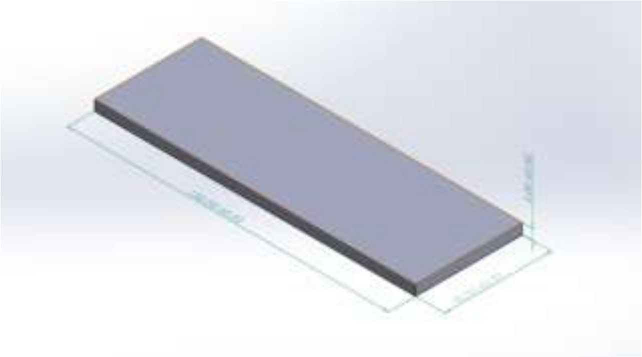


Fig. 3.2 Shear test specimen used for dynamic testing (ASTM E1876)

Fig. 3.3 Set up for Torsional

Fig. 3.4 Set up for flexural

Dynamic mechanical properties of the epoxy-alumina composites were evaluated in accordance with ASTM E1876, Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. Rectangular bar specimens (length = 0.15 m, width = 0.05 m, thickness = 0.005 m) were tested under flexural and torsional vibration modes to determine the natural frequencies. The Dynamic Young's modulus (E) and shear modulus (G) were calculated from the fundamental flexural and torsional frequencies using the standard relations prescribed in ASTM E1876 as follows:

The Dynamic Young's modulus (E) determined from:

$$E = 0.9465\left(\frac{mf_f^2}{b}\right)\left(\frac{L^3}{t^3}\right)T_1 \qquad \text{(Eq.1)}$$

The determined shear modulus (G) from:

$$G = \frac{4\,Lmf_t^{\,2}}{bt}R \qquad \text{(Eq.2)}$$

The correction factors were estimated using the standard approximations:

$$T_1 = \left[1.000 + 6.585\left(\frac{t}{L}\right)^2\right] \qquad \text{(Eq.3)}$$

$$R = \left[\frac{1+\left(\frac{b}{t}\right)^2}{4 - 2.521\frac{t}{b}\left(1 - \frac{1.991}{e^{\pi\frac{b}{t}}+1}\right)}\right]\left[1+\frac{0.00851n^2b^2}{L^2}\right] - 0.060\left(\frac{nb}{L}\right)^{\frac{3}{2}}\left(\frac{b}{t}-1\right)^2 \quad (\qquad \text{(Eq.4)}$$

The Poisson's ratio (ν) determined from

$$\mu = \left(\frac{E}{2G}\right) - 1 \qquad \text{(Eq.5)}$$

where:

E = Dynamic Young's modulus, GPa
m = mass of the bar, g
b = width of the bar, mm
L = length of the bar, mm
t = thickness of the bar, mm
f_f = fundamental resonant frequency of bar in flexure, Hz
T_1 = correction factor for fundamental flexural mode to account for finite thickness of bar, Poisson's ratio, and so forth.
n = the order of the resonance (n = 1,2,3…)
G = dynamic shear modulus, GPa
f_t = fundamental torsional resonant frequency of bar, Hz
ν = Poisson's ratio

The measured flexural and torsional frequencies, along with the composite densities, were substituted into these equations to obtain the values of Dynamic Young's modulus, shear modulus, and Poisson's ratio summarized in Table 3.

5.2 Result and Discussion:

The dynamic shear test conducted as per ASTM E1876 provided the fundamental flexural and torsional resonance frequencies, which were used to calculate the Dynamic Young's Modulus (E), Shear Modulus (G), and Poisson's ratio (ν) of the epoxy-alumina composites. The obtained results are summarized in Table 3. The values of E, G, and ν were determined using the standard relationships and equations prescribed in ASTM E1876, which relate the specimen's geometry, density, and resonance frequencies to its elastic constants. A consistent increase in both flexural and torsional frequencies was observed with the addition of alumina (Al_2O_3) filler. The flexural frequency increased from 415.63 Hz for pure epoxy to 444.53 Hz for 1 wt.% Al_2O_3, while the torsional frequency increased from 697.65 Hz to 744.53 Hz. This indicates that the inclusion of alumina particles enhances the stiffness and rigidity of the composite material. Correspondingly, the Dynamic Young's Modulus (E) and Shear Modulus (G) exhibited a noticeable improvement with increasing filler content. The value of E increased from 3.84 GPa for neat epoxy to 4.46 GPa for 1% Al_2O_3, while G rose from 1.39 GPa to 1.63 GPa. This enhancement can be attributed to the superior stiffness and high modulus of alumina particles, which act as effective load-bearing reinforcements within the epoxy matrix. The uniform dispersion of Al_2O_3 particles likely improved stress transfer efficiency between the matrix and filler, reducing localized deformation under dynamic loading. The Poisson's ratio values ranged between 0.37 and 0.43, which are within the acceptable limits for epoxy-based composite materials. These values confirm that the addition of Al_2O_3 does not significantly alter the material's elastic deformation behaviour, thereby maintaining structural integrity while enhancing stiffness. Overall, the results clearly demonstrate that the addition of Al_2O_3 nanoparticles improves the dynamic mechanical properties of the epoxy matrix. The simultaneous increase in E and G reflects an overall improvement in the composite's resistance to deformation under both bending and shear vibrations. Hence, the incorporation of up to 1% alumina enhances the stiffness and rigidity of the composite without compromising its elastic characteristics, making it suitable for applications requiring high strength-to-weight ratio and improved vibration resistance.

Table. 3 Dynamic Young's modulus, shear modulus, and Poisson's ratio of epoxy-Al_2O_3 composites (ASTM E1876).

Alumina %	**Density (kg/m³)**	**Avg. Flexural Frequency (Hz)**	**Avg. Torsional Frequency (Hz)**	**Dynamic Young's Modulus (GPa)**	**Shear Modulus (GPa)**	**Poisson Ratio**
0	1150	415.6255	697.6565	3.84	1.39	0.38
0.25	1157	422.6565	705.4698	3.99	1.44	0.39
0.5	1164	429.8675	713.2815	4.13	1.47	0.41
0.75	1170	441.4065	724.2190	4.38	1.53	0.43
1	1178	444.5315	744.5315	4.46	1.63	0.37

Recent studies (2023–2025) on epoxy-based nanocomposites reinforced with hybrid or surface-functionalized fillers show that combining Al_2O_3 with other nanomaterials or functionalizing the filler surface can significantly enhance mechanical performance compared to plain Al_2O_3/epoxy systems. For example, Enhanced Mechanical Properties of Epoxy Composites Reinforced with Silane-Modified Al_2O_3 Nanoparticles: An Experimental Study reports that silane-modified Al_2O_3 nanoparticles improved tensile strength by nearly 50% relative to neat epoxy. Meanwhile, Thermo-mechanical behaviours investigation of Nano-Sized Al_2O_3, TiO_2, and Graphene Nanoplatelet Reinforced Epoxy Composites (2024) demonstrated that an epoxy matrix reinforced with a mixture of Al_2O_3, TiO_2 and graphene nanoplatelets (GNP) showed very large improvements not only in tensile strength but also in hardness and thermal conductivity. Compared to these hybrid or functionalized filler systems, the present work using unmodified Al_2O_3 nanoparticles shows a modest but consistent improvement in mechanical properties (tensile/flexural/shear strength) with increasing filler content (up to 1 %). This suggests that while unmodified Al_2O_3 is effective as a reinforcement, further gains might be possible if surface functionalization or hybrid-filler strategies are employed in future studies.

Therefore, our results align with the general trend observed in recent literature: adding rigid ceramic fillers to epoxy improves strength and stiffness; but to maximize filler efficiency and interfacial bonding (and reduce agglomeration) surface modification or hybrid-filler approach appears more effective. Accordingly, future work could focus on silane-treated Al_2O_3 or Al_2O_3 combined with other nanofillers (e.g., TiO_2, GNP) for improved performance.

6 Conclusion:

The mechanical characterization of epoxy - alumina (Al_2O_3) composites was carried out to evaluate the influence of filler loading on tensile, flexural, and shear behaviour. Epoxy LY556 resin was reinforced with varying Al_2O_3 contents (0%, 0.25%, 0.5%, 0.75% and 1%) and tested according to ASTM D638, D790, and E1876 standards. From the tensile test, the tensile strength increased from 34.8 MPa for neat epoxy to a maximum of 50.1 MPa at 0.5% Al_2O_3, followed by a gradual decrease at higher loadings. The Young's modulus also improved from 1.81 GPa to 2.08 GPa, indicating enhanced stiffness due to uniform particle dispersion. Similarly, in the flexural test, the mean flexural strength improved from 80.83 MPa (0%) to 96.18 MPa (0.5%), demonstrating better stress transfer at the matrix filler interface. Beyond 0.5 %, a slight reduction was observed, likely due to particle agglomeration and reduced matrix continuity. Dynamic mechanical analysis through ASTM E1876 showed that the dynamic Young's modulus and shear modulus increased consistently with alumina content, from 3.84 GPa and 1.39 GPa for pure epoxy to 4.46 GPa and 1.63 GPa at 1 % Al_2O_3. The Poisson's ratio ranged between 0.37 - 0.43, confirming stable elastic behaviour. These parameters were computed using the equations provided in ASTM E1876 based on measured flexural and torsional frequencies. Overall, the results reveal that the incorporation of 0.5% Al_2O_3 provides the optimum combination of tensile, flexural, and shear properties. The enhancement is attributed to effective load transfer, improved interfacial bonding, and uniform filler dispersion within the epoxy matrix. Higher alumina additions tend to cause clustering, reducing the overall mechanical performance. Thus, epoxy–alumina composites with moderate filler content exhibit significant potential for structural and industrial applications where improved stiffness and strength are required without compromising weight or processability.

The improvements in mechanical properties observed in this study suggest that epoxy-Al_2O_3 composites have potential applications in lightweight structural panels, vibration-resistant coatings, and aerospace components, where enhanced stiffness and strength are desirable. Moreover, future research could focus on incorporating hybrid fillers, surface-functionalized nanoparticles, or environmentally sustainable epoxy matrices to further improve performance. Investigating additional properties such as thermal stability, wear resistance, and damping behaviour would also provide a more complete understanding of these composites, supporting their application in multifunctional engineering systems.

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