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Experimental analysis of epoxy-based functionally graded composite materials

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ABSTRACT

Functionally graded materials (FGMs) are crucial in the mechanical and aerospace industries for improving material quality by combining distinct qualities to create composite substances with desired properties. Using the layer-by-layer hand-laying technology in the casting process, samples with dimensions calculated according to international standards (ASTM) were created in a glass mold. Several fine fillers, such as alumina (Al_2O_3) and silicon carbide (SiC) microparticles, were added to the epoxy resin. Tensile, bending, and impact tests were performed on samples from the five layers of FGM. The experimental test results showed that the fracture toughness of functionally graded samples slightly improved, with the highest value reaching 13.63865 $MNm^{3/2}$ in the Al_2O_3-reinforced epoxy sample. The ultimate tensile stress of the functionally graded epoxy sample reinforced by Al_2O_3 is 15.572 MPa, and the ultimate value of tensile stress of the functionally graded epoxy sample fortified with SiC is 19.4198 MPa. In comparison, the ultimate value of tensile stress of the pure epoxy sample is 21.247 MPa. The results show that pure epoxy samples have high stress levels. The increase in SiC percentage in the functionally graded sample enhanced the mechanical properties in the bending tests, giving the best results. The pure epoxy sample has the ultimate bending stress of 1.974 MPa, while the ultimate bending stress in the functionally graded material sample of Al_2O_3-reinforced epoxy is 1.9558 MPa. The ultimate bending stress of the functionally graded sample of SiC-reinforced epoxy is 2.924 MPa, and the ultimate bending stress value in the SiC-reinforced epoxy sample was 2.924 MPa. The functionally graded sample of epoxy and SiC yielded the best result in terms of durability. The maximum load applied on the sample of epoxy and SiC was 150 N; this indicates that the functionally graded material has significantly reduced the material's deformation and increased the mechanical properties of the material in terms of strength, durability, and resistance. It was found that the maximum load applied on the pure epoxy sample was 91 N, while the maximum load applied on the functionally graded sample of epoxy and Al_2O_3 was 126 N.

Keywords: *Functionally graded material (FGM), Epoxy, Silicon carbide (SiC), Alumina (Al_2O_3), Mechanical properties*

1. INTRODUCTION

Functionally graded materials (FGMs) are innovative materials that exhibit a gradual change in their properties with their dimensions. This collection of materials demonstrates a significant enhancement over the composite materials that were previously employed. Functionally graded material (FGM) is a technique that involves using two or more materials together to create specific qualities for a particular application [1]. Functionally gradient materials were developed to solve the issue of delamination, or the separation between the layers, which can cause composite materials to fail in harsh working environments. Delamination is the process of fibers separating from the matrix [2]. The idea of structural gradient (FGM) was first applied to polymeric materials in 1972 [3]. To imitate and manufacture FGMs with similar behavior and structure to functionally gradient materials found in nature, such as bones, teeth [4], and bamboo trees [5]. A research study conducted by Bever studied material characteristics and graded composites, citing Shen's 1972 explanation of supramolecular structure, molecular makeup, and chemical composition variations as factors affecting polymeric material gradation [6]. In 1984, FGMs were first proposed by scientists in Sendai. For thermal barrier creation. In 1987, SiC-C FGM nose cone samples were made as part of a national project focused on researching the fundamental technology for the development of functionally gradient materials that can alleviate thermal stress. The project continues to advance diverse functional materials [7]. N. Misra *et al*. created silica-reinforced epoxy with quartz fabric, conducting thermal and mechanical tests. Increasing insulation decreased the strength and modulus of strong functionally graded material composites [8]. Aldosari *et al*. studied enhanced composite structure performance to fill the knowledge gap on nanomaterials by adding nanoparticles to epoxy resin. Nine advanced materials, including nanocomposite materials, quasi-isotropic laminates, unidirectional laminates, and control panels, were developed [9]. Mona Megahed and Ahmed Abou El-Wafa Megahed examined the mechanical characteristics of sequentially graded and non-graded hybrid nanocomposites, revealing that adding nanoclay enhances the surface hardness of neat glass fibers, with the highest hardness increase achieved [10]. Rangasreenivasulu & Reddy emphasize the importance of managing residual stress in FGMs post-manufacturing, particularly in aerospace, biomedical, and engine components. Where FGMs combine metal and ceramic properties to create parts with improved strength, toughness, and resistance to heat, wear, and corrosion. They analyze thermal stresses in cylindrical metal-ceramic FGMs using ANSYS, examining the impact of layers and dimensional changes on distribution [11]. The study by Muslim *et al*. focused on the impact of adding wollastonite particles to epoxy, both separately and as a functionally graded composite. The addition of wollastonite improved the fracture toughness of the composite but had negative effects on the tensile strength and flexural modulus. However, the hardness increased with the higher filler content. A coating layer of epoxy/Stear amide was applied to enhance surface performance. It was found that when the amount of Stear amide increased, the coefficient of friction dropped [12]. Hamzah, Al-Kawaz, & Hunain examined the deformation response of a polymeric composite with a mode functionally graded using finite element analysis and classical laminated theory. The tests were carried out on square plates with static homogeneous tension, and the results showed that the FGM composite had less stiffness than the laminate composite [13]. The usage of PMMA microcapsules containing Bisphenol-A epoxy in a self-healing epoxy coating for anti-corrosion reasons is investigated by Mohammed *et al*. The findings indicate that incorporating microcapsules into the epoxy matrix enhances performance and self-healing capabilities [14]. Hassan & Kurgan discussed and evaluated various techniques for using Mechanical APDL to model FGMs in ANSYS software. These techniques include employing user-defined fields, stacking components or layers, and imposing a fictive heat load. The paper also briefly mentions further advanced approaches that require recompilation of the ANSYS executable. The implemented modelling [15]. Njim, Bakhy, & Al-Waily analyzed highly porous polymeric structures called functionally graded nanobeams with porosity (PFGM) suitable for various applications in engineering and biomaterials. Tensile and flexural 3D printing were used to prepare the specimens and 5% (Al/Al_2O_3) nanomaterial. Numerical solutions and simulations were conducted using finite element methods and ANSYS software. The study found that the metrics of porosity and gradient index significantly affect the static behavior of PFGM. Moreover, nanoparticles improve bending resistance [16]. Abdulmajeed & Hamzah investigated the synthesis of FGMs using a centrifugal technique. Different parameters were varied to create the FGMs, and tribological characteristics, including hardness, were described. The findings revealed adding Al_2O_3 nanoparticles enhanced the wear resistance and sliding hardness of the graded composites. The FGMs exhibited better sliding wear performance than homogeneous composites [17]. Musafir, Abdul Ameer, & Hamzah discussed experimental testing on carbon fiber-reinforced laminates to determine fracture toughness in both Mode-I and Mode-II. The study compares various techniques for determining the hardness of fractures in each mode. Slip and stick behavior is observed in the Mode-I test. The results demonstrate that the modified beam theory method is compatible with the industry-standard ASTM protocol for Mode-I fracture toughness. The Compliance-Based Beam Method is identified as a suitable method for evaluating Mode-II fracture toughness without the need for crack length monitoring [18]. Fierro & Caisalitín discussed producing a FGM using particles of silicon carbide (SiC) and aluminum. The researchers used the method of horizontal centrifugal casting and defined various factors such as mold rotation speed and temperature and weight % of SiC particles. They used an Al 365 alloy molten as the matrix material and poured it into a rotating mold. The FGM was then characterized using metallographic analysis and microhardness testing [19]. Abdul Majeed & Hamzah synthesized functionally graded material using a centrifugal technique with varying amounts of alumina (Al_2O_3) nanoparticles. Mechanical tests demonstrated that including Al_2O_3 nanoparticles enhanced the Young's modulus, impact strength, and flexural strength of the FGMs as opposed to pure epoxy. The greatest improvement in impact strength was observed at a 1% volume fraction of Al_2O_3 nanoparticles. Loading the FGMs from the Al_2O_3-rich side increased the Young's modulus and flexural strength, while loading from the side of the epoxy decreased bending resistance but improved bending modulus [20]. Karabulut *et al*. examined Al6061 composites that are functionally graded and reinforced with B_4C, SiC, and Al_2O_3. The composites were made by centrifugal casting and stir methods and then hot-rolled. The microhardness, density, ballistic resistance, and tensile strength were analyzed, along with microstructural properties. The results showed that the ceramic particles were distributed from the interior to the exterior with centrifugal acceleration. B4C-reinforced composites had a more even particle distribution compared to SiC and Al_2O_3. B_4C-reinforced composites had the lowest density and highest microhardness [21]. Boggarapu *et al*. created an aluminum-copper metal composite with five layers using powder metallurgy. Erosion wear tests revealed that wear decreases as the copper content increases. The Al_2Cu phase that forms during sintering improved erosion resistance. Abrasive wear tests showed that the specific wear rate increases with higher loads. The wear on a P2000 grit surface was lower compared to P120 and P800 [22]. AbdulRazaq, Hassan, & Jasim focused on creating and testing a FGM made of SiO_2-reinforced epoxy resin particles. Various tests were conducted on specimens with different weight percentages of silicon dioxide. The results showed that the ratio of silicon dioxide will increase and improve the mechanical characteristics of the FGM, with a higher modulus of elasticity, tensile and flexural strengths, and impact resistance. The thermal conductivity also improved with the addition of silicon dioxide [23].

The research aims to create a durable material that eliminates brittleness and interphase problems in epoxy, making it suitable for various applications; create functionally graded composite materials from SiC and Al_2O_3 with epoxy by using the layer-by-layer hand layup technique in a casting process; and assess by comparison of graded and non-graded composites and mechanical.

2. MATERIAL AND METHODS

2.1. Material Used

The materials used in preparing the samples consist of epoxy; the polymer used was a low-viscosity epoxy resin from Sika Saudi Arabia Co. Ltd., as per Type I, Grade 1, Class B+C, ASTM C881-78. Table 1 shows the properties of the epoxy used. Silicon Carbide Ltd., C) from Sigma-Aldrich: Table 2 provides information on the properties of SiC, a material with the size of particles of 14–36 µm. We also used aluminum oxide (Al_2O_3) from Dentify GmbH, where Table 3 displays the properties of Al_2O_3, also known as alumina, with a particle size of 25 µm.

2.2. The FGM Sample's Preparation

As demonstrated in Table 4, the layer-by-layer manual casting process was utilized to construct FGM by the filler's weight gradient. First, different weight ratios of SiC and Al_2O_3 (0, 10, 15, 20, and 25 wt.%) were prepared as shown in Figure 1. Secondly, epoxy resin was combined in various weight ratios of SiC or Al_2O_3 for twenty minutes by using a magnetic stirrer, then the hardener was added (in a 1:2 ratio) and manually mixed with a wooden rod for 4–5 minutes until homogeneous. The mold was cleaned, and a suitable lubricant was placed on the mold wall to prevent gluing between the samples and the mold. The mixture was put into a mold that had certain measurements of (200 × 100 × 5) mm, where the mold was partly filled with the first level of epoxy combined with a particular weight percentage of SiC or Al_2O_3. Furthermore, in another step, the second level of epoxy mixed with different SiC or Al_2O_3 weight content was poured on the first partially hardened level, with five levels of thickness, each level 1 mm. Levels of 0–25 were arranged by the weight of SiC or Al_2O_3. When the levels are completed, the concentration of the reinforcement phase in it varies according to the location inside a foundation. Last but not least, the sample spent two hours in the oven at 110°C to ensure an adequate curing process. The reinforced epoxy composite plate with SiC or Al_2O_3 Particles was divided into samples with appropriate sizes and shapes for testing. Particles were divided into samples with appropriate sizes and shapes for testing.

Table 1. The properties of epoxy based on ASTM C881-78 Type I, Grade 1, from the supplier (Sika)

Property Section A+B Mixed (2:1)	
Density at 20 ˚ C	part(A): 1.1 Kg/L part(B): 1.0 Kg/L Mixed (A+B): 1.1 Kg/L
Color	part(A): yellowish part(B): Brownish Mixed(A+B): Yellowish brownish
Coefficient of Thermal Expansion	$89×10^{-6}$ per °C (from –20°C to +60°C)
Viscosity	˜1000 (mpa. S) at 10°C in normal type ˜500 (mpa. S) at 20°C in normal type ˜250 (mpa. S) at 30°C in normal type
Compressive Strength	53 N/mm² (at 20°C and 65% r.h.)
Tensile Strength	25 N/mm² (at 20°C and 65% r.h.)
Flexural Strength	50 N/mm² (at 20°C and 65% r.h.)
Modulus of Elasticity	1060 N/mm²

Table 2. The properties of SiC, from supplier Sigma-Aldrich

Silicon Carbide Properties	
Physical state	Powder
Color	Light gray
Density	3.22 g/cm³ at 25°C - lit
Color	Black to Gray
Melting Point/freezing point	2700°C - lit
Water solubility	0.01 g/l at 20°C – OECD Test Guideline 105 - insoluble

Table 3. The properties of Al_2O_3 from the Website of Dentify GmbH (Supplier)

Al_2O_3 Properties	**Values**
Hardness	9 Mohs
Grain shape	Angular
Melting Point	Approx, 2050°C
Specific gravity	Approx, 3.9–4.1 g/cm³
Bulk density	Approx, 1.4–2.1 g/cm³
Color	White

2.3. Test Sample Preparation

After removing the final FGM sheets from the mold, the samples were trimmed to the reference specimen's dimensions with two replicates for each test, as specified in Table 5, using a CNC/router machine, as shown in Figure 2.

3. EXPERIMENTS TEST

3.1. Tensile Test

A machine for universal tensile testing, specifically the Bong Shin WDW-SE model, was utilized to perform tensile testing

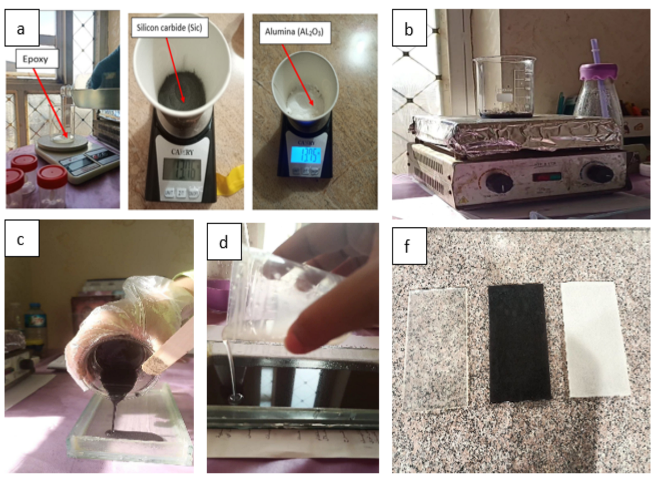


Figure 1. a) Measuring weight percentages of epoxy, SiC, and Al_2O_3; b) using a magnetic stirrer to mix epoxy with filler; c) putting the mixture of epoxy with filler into a mold; d) putting the final level of pure epoxy into a mold; f) the final look is three plates: the first plate is pure epoxy, the second plate is epoxy with SiC, and the third plate is epoxy with Al_2O_3

Table 4. The FGM profile model

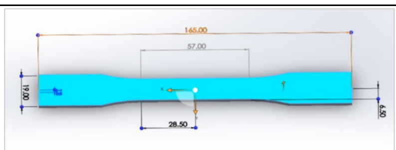
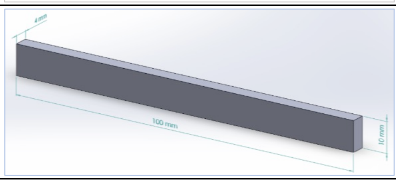
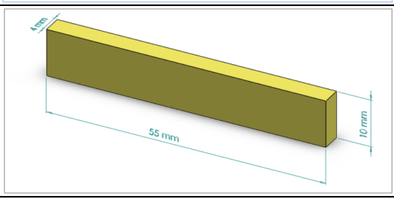
Level no.	The percentage of levels that are made up	Thickness of the level (mm)	Weight of the epoxy mixture (g)	Silicon carbide weight (g)	Alumina weight (g)
1	100% epoxy	1	20	0	0
2	90% epoxy, 10% SiC	1	18	2	0
3	85% epoxy, 15% SiC	1	17	3	0
4	80% epoxy, 20% SiC	1	16	4	0
5	75% epoxy, 25% SiC	1	15	5	0
6	90% epoxy, 10% Al_2O_3	1	18	0	2
7	85% epoxy, 15% Al_2O_3	1	17	0	3
8	80% epoxy, 20% Al_2O_3	1	16	0	4

on the provided material specimens. Specifications for each specimen that is being evaluated under ASTM D638 [24]. The specimens were subjected to failure at a consistent rate of 5 mm every minute. Using Equation (1), a modulus of elasticity plot of the FGM specimens was produced.

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{1}$$

here $\Delta\sigma$ is the strain change, measured in millimeters per millimeter, and E is the tensile modulus of elasticity, expressed in GPa.

Table 5. Standard-sized sample

Test object	Test sample specifications	ASTM standard
Tensile		ASTM D638-03 Type I
Bending		ASTM D790 & ISO 178
Impact		ISO 179-1

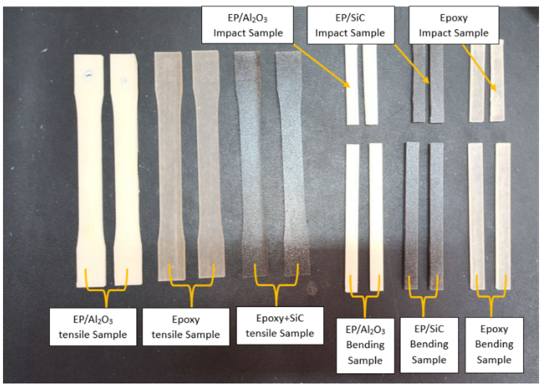


Figure 2. Preparation of the samples to the standard size

3.2. Flexural Test

A machine for universal tensile testing (Bong Shin WDW-SE model) was utilized to perform a flexural test using a three-point test on the provided material specimens. The specification of each sample is evaluated according to the standard adopted in the ASTM D790 bending test [25], where the sample dimensions are 100 mm × 10 mm × 4 mm. The force was applied at a rate of 0.5 mm/min until a fracture occurred.

3.3. Impact Test

Unnotched Charpy impact tests were done with a Pendulum Wp 400. Cut samples were adopted for each sample according to the standard adopted in the ASTM D179 [26] impact test, where the sample dimensions were 55 mm × 10 mm × 4 mm. The Charpy impact strength and fracture toughness calculations can be done by Equations (2) and (3), respectively:

$$I_s = \frac{I_E}{A} \tag{2}$$

where I_S is the impact strength (j/mm^2), I_E is the impact of energy (J), and A is the specimen's cross-sectional area (mm^2).

$$K_{IC} = \sqrt{E_f I_s} \tag{3}$$

where K_{IC} is the Fracture toughness (N.m$^{3/2}$) and E_f is the modulus of elasticity (GPa).

4. RESULTS AND DISCUSSION

4.1. Tensile Test

Figure 3 shows the FGM sample's stress-strain curve. We can see from Figure 3 that the ultimate tensile stress of the functionally graded epoxy sample reinforced by Al_2O_3 is 15.572 MPa, and the ultimate value of the tensile stress value of the functionally graded epoxy sample fortified with SiC is 19.4198 MPa. In comparison, the ultimate value of tensile stress of the pure epoxy sample is 21.247 MPa. The results show that pure epoxy samples have high stress levels compared with FGMs reinforced by Al_2O_3 and SiC, which have low tensile stress. This is due to pure epoxy typically exhibiting higher tensile stress compared to functionally graded epoxy (FGE) due to several key factors:

1. **Homogeneity**: Pure epoxy is a homogeneous material, meaning its properties are consistent throughout. This uniformity allows it to bear tensile loads more effectively without the presence of weaker regions that could act as stress concentrators.
2. **Absence of Fillers**: Functionally graded epoxy often contains fillers or reinforcements that are distributed non-uniformly. These fillers can introduce microstructural defects or voids, which can reduce the overall tensile strength of the material.
3. **Cross-Linking Density**: Pure epoxy resins typically have a high cross-linking density, which contributes to their rigidity and tensile strength. In contrast, the addition of fillers in FGE can disrupt the cross-linking network, leading to a reduction in tensile strength.
4. **Stress Distribution**: In FGMs, the gradation can lead to uneven stress distribution under tensile loading. This uneven distribution can cause localized stress concentrations, which can initiate cracks and reduce the overall tensile strength.
5. **Microstructural Integrity**: The process of creating FGMs can sometimes introduce microstructural inconsistencies, such as voids or weak interfaces between different regions. These inconsistencies can act as points of failure under tensile stress [27]. Functionally graded epoxy with SiC increases tensile stress and less deformation, while Al_2O_3-reinforced epoxy has increased tensile stress and decreased strain. This is because ceramic additives have high hardness, which improves the hardness of the samples. The increase in tensile strength improved the elastic modulus, which is consistent with the work of Sudhir *et al*.

From the observation of Figure 4, it can be explained that when force is applied to a functionally graded material ofAl_2O_3-reinforced epoxy or SiC, a complex reaction occurs that improves the properties of the material, this may be due to the epoxy is a type of thermoplastic epoxy consisting of two basic compounds: resin and hardener react to form a strong durable material either SiC and Al_2O_3 are excellent hardeners that are characterized by their resistance to corrosion and high temperature and that the functionally graded material has a graduated composition of epoxy and SiC or Al_2O_3 where SiC or Al_2O_3 is gradually distributed inside the epoxy and the greater the force applied to the functionally graded material, the greater the internal tension in the material and thanks to the distribution of SiC or Al_2O_3 gradient the deformation resistance improved, as its deformation is relatively reduced with increasing strength which enhances the stability of the material, thus increasing strength leads to improved material properties and reduced deformation, making the functionally graded material more flexible and durable, unlike the pure epoxy sample, where the deformation is high.

4.2. Flexural Test

Figure 5 depicts the flexural modulus of elasticity to compare pure epoxy with a homogenous, functionally graded composite. The Al_2O_3 and epoxy-rich side's flexural modulus of elasticity and the SiC-rich side was calculated. Figure. 5 shows the findings that the flexural modulus of elasticity of the functionally graded material from the SiC-rich side is better than the pure epoxy, while the Al_2O_3-rich side's functionally graded material is better than the pure epoxy. As can be seen from Figure 5 that the introduction of SiC and Al_2O_3 fillers to epoxy led to an increase in elasticity's flexural modulus relative to pure epoxy. Due to the ceramic nature of SiC and Al_2O_3, their surface hardness is much higher [28]. As a result, the epoxy becomes harder when Al_2O_3 and SiC are added.

Figure 6 represents the FGM sample's bending stress-strain curve., From the observation of Figure 6, we can see that the pure epoxy sample has the ultimate bending stress of1.974MPa, while the ultimate bending stress in the functionally graded material sample of Al_2O_3-reinforced

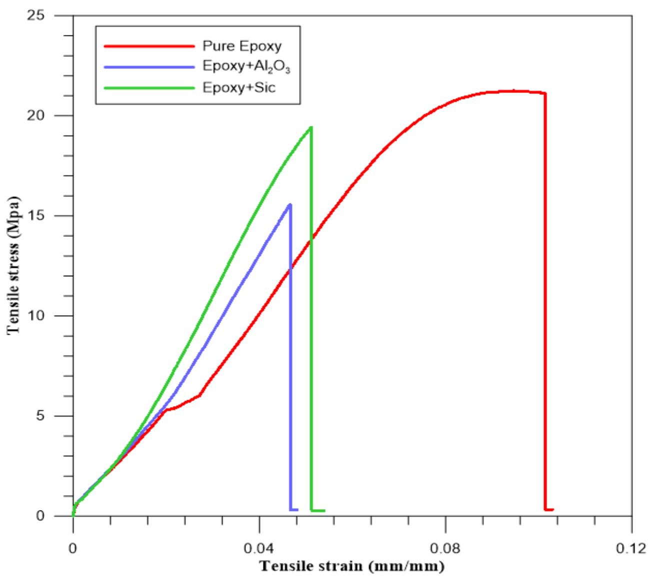


Figure 3. FGM sample's tensile stress-strain curve

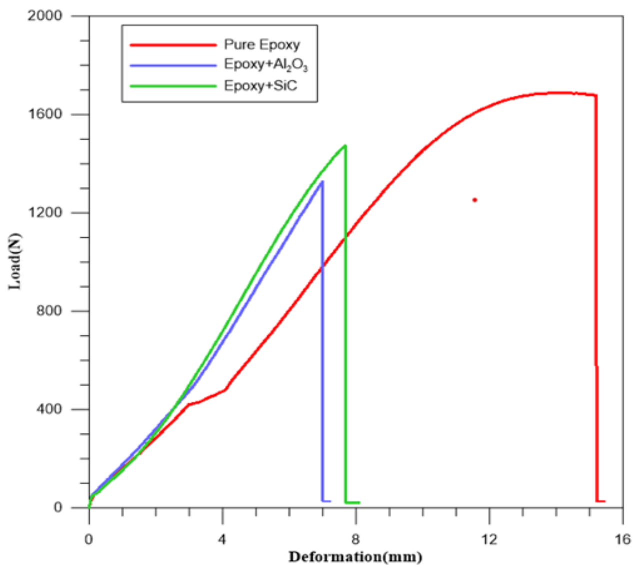


Figure 4. FGM sample's tensile load-deformation curve

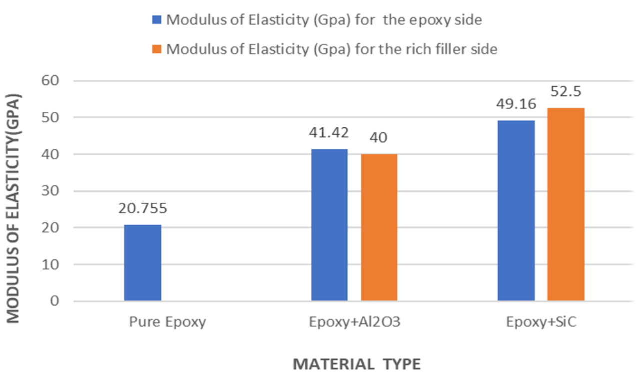


Figure 5. Flexural modulus of elasticity for FGM samples

epoxy is 1.9558 MPa. The ultimate bending stress of the functionally graded sample of SiC-reinforced epoxy is 2.924 MPa.

Figure 6 shows that the use of silicon carbide powder and alumina in the manufacture of functionally graded material has helped improve mechanical properties, increase bending strength, and reduce material deformation, unlike the pure epoxy sample, in which the deformation was high and bending resistance was low and also, note that the functionally graded sample of epoxy and silicon carbide gave better mechanical properties

Figure 7 represents the FGM sample's load-deformation curve. When looking at Figure 7, the functionally graded sample of epoxy and SiC yielded the best result in terms of durability the maximum load applied on the sample of epoxy and SiC was 150 N; this indicates that the functionally graded material has significantly reduced the material's deformation and increased the mechanical properties of the material in terms of strength, durability, and resistance. It was found that the maximum load applied on the pure epoxy sample was 91 N, while the maximum load applied on the functionally graded sample of epoxy and Al_2O_3 was 126 N.

4.3. Impact Test

Equation (2) was used to calculate the impact strength of the FGM composite, and Equation (3) was used to calculate the Fracture Toughness. The impact test results are displayed in Table 6, where it is observed FGMs exhibit somewhat better and higher fracture ductility when compared with the pure epoxy sample.

5. CONCLUSION

This study examined how SiC and Al_2O_3 affect the mechanical properties of epoxy composites, particularly regarding impact, flexural, and tensile strengths. Composite materials consisting of epoxy reinforced with SiC and Al_2O_3 were produced with varying weight percentages of 0, 10, 15, 20, and 25 wt%. The conclusions were derived from the findings of this inquiry.

1. The elastic modulus of elasticity increased significantly for the functionally graded material of

Table 6. The result of impact testing with a standard deviation of about (4%)

Sample No.	Describe sample No.	Impact energy (J)	Impact Strength (J/m^2)	Fracture Toughness (MNm$^{3/2}$)
P1-1	Pure epoxy	0.310	5904.240	12.37655
P2-1	Epoxy + Al_2O_3	0.215	4584.132	13.63865
P3-1	Epoxy + SiC	0.160	3423.485	13.40645

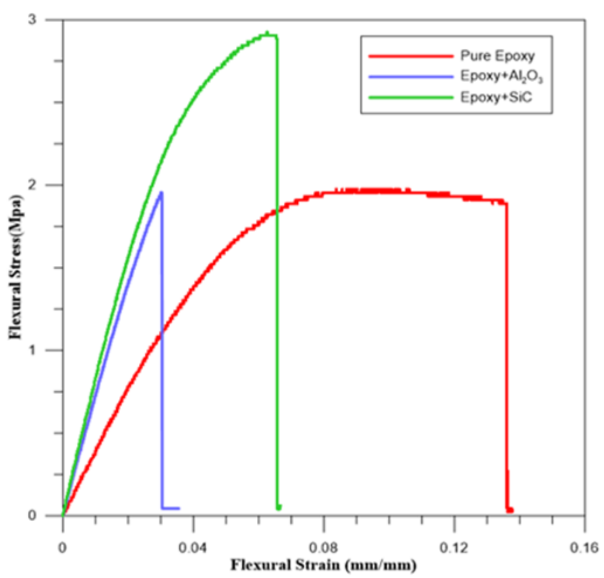


Figure 6. FGM sample's bending stress-strain curve

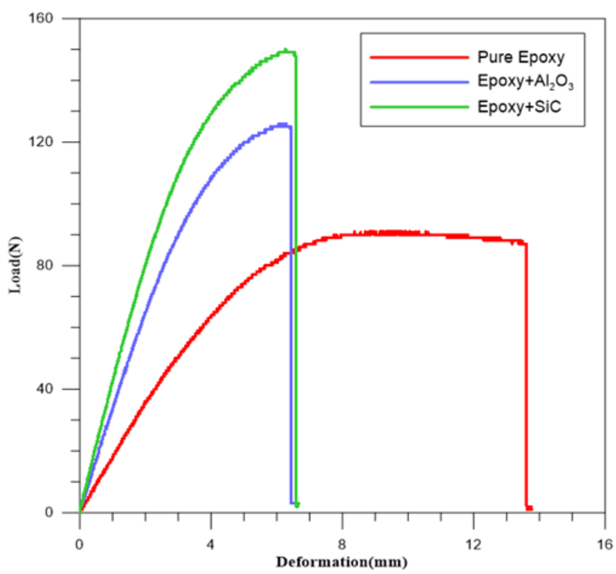


Figure 7. FGM sample's load-deformation curve

epoxy reinforced by SiC, as its value on the epoxy side reached 49 GPa and on the filler-rich side it reached 52.5 GPa.

2. Thus, the improvement in tensile stress and decrease in deformation observed in our study could have been attributed to this increase in hardness. Al_2O_3 and SiC have a much higher surface hardness because it is a ceramic. As a result, adding Al_2O_3 and SiC to the epoxy increases its hardness.
3. The functionally graded material is more flexible and durable, unlike pure epoxy samples, where the deformation is high.
4. The functionally graded sample of epoxy and SiC gave better mechanical properties in the flexural test.
5. Samples loaded by pure epoxy exhibited a maximum bending stress of 1.974 MPa, but samples loaded by SiC had a greater flexural stress of 2.924 MPa.
6. The functionally graded epoxy reinforced by SiC material had a fracture toughness value of 13.40645248 $MNm^{3/2}$, while the functionally graded epoxy reinforced by Al_2O_3 material had a fracture toughness value of 13.63865 $MNm^{3/2}$. These values indicate a slight increase in fracture toughness. The pure epoxy sample has a fracture hardness of 12.37655 $MNm^{3/2}$. The Pure epoxy sample shows high stress and low tensile strength compared to FGMs reinforced with Al_2O_3 and SiC.
7. Tensile strength decreases with decreasing modulus of elasticity, while strain increases due to an inverse relationship with modulus of elasticity.
8. Functionally graded epoxy with SiC increases tensile strength and less deformation, indicating increased modulus of elasticity.
9. Functionally graded epoxy with Al_2O_3 also increases tensile strength and decreases deformation, due to the high hardness of ceramic materials (Al_2O_3, SiC).

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