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The Effect of Ceramic Additives on the Mechanical Behavior of Carbon or Epoxy Composites

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Abstract

The investigation of Carbon/Epoxy (C-E) composites reinforced with alumina micro fillers at varying weight fractions (0%, 2.5%, 5%, and 7.5%) for its mechanical features were carried out. The composites were produced by mechanical stirring, hand layup, and compression molding to ensure uniform filler distribution. Filler analysis was conducted using SEM and EDAX to examine the filler dispersion and microstructure. Mechanical testing, including tensile, ILSS, flexural, impact, hardness, and density, was performed according to ASTM standards. Results showed that a specific alumina loading enhanced the composites mechanical properties. This research highlights the role of alumina in improving C-E composites in newer emerging material's world.

Major Findings: *The study found that 7.5% alumina enhanced tensile strength and ILSS in Carbon/Epoxy (C-E) composites. SEM and EDAX analysis showed improved filler dispersion and stronger interfacial bonds. Higher alumina content reduced impact strength, indicating a trade-off between strength and energy absorption. Alumina-filled C-E composites show promise for applications requiring higher strength and toughness.*

Keywords: *Alumina Filler, Carbon Fiber, Epoxy, EDAX, SEM*

1.0 Introduction

Carbon fiber holds immense significance in the current modern world across various industries due to exclusive amalgamation of properties. In essence, carbon fiber's significance lies in its capacity to provide a strong, lightweight, and durable alternative to old materials. Its claims span over various industries, enabling advancements in technology, energy efficiency, performance, and sustainability. Carbon fibers are composed of thin, carbon atoms which are tightly packed or arranged in a crystalline structure. These fibers are characteristically consequent from precursor materials like Polyacrylonitrile (PAN), pitch, or rayon[1]. Carbon fibers are incomparably having toughness, strength, light weight, high stiffness, and tremendous thermal and electrical conductivity. These properties stem from the unique arrangement of atoms made out of carbon in a strong and rigid lattice. The epoxy resin bonds with the carbon fibers, creating a resilient interface between the two materials. The abilities of the composite are inclined by the quality of this interface[2]. Proper impregnation and curing are crucial to achieve optimal adhesion and load transfer. The carbon and its types of fibers provide strength and toughness, while the epoxy as a bonding agent of polymer matrix helps to distribute loads and

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shield the fibers from ecological aspects such as moisture and impacts[3]. Alumina fillers, often in the form of alumina nanoparticles or micro-sized particles, are commonly used in composite materials to enhance certain properties. These fillers are typically added to a polymer matrix to produce a composite material with enriched enactment features. The incorporation of alumina particles into a polymer ground can meaningfully boost the tensile and compressive abilities, and stiffness of the resulting composite. This is particularly valuable in usages where high mechanical abilities are required, such as aerospace components and structural materials[4].

Alumina fillers in composites depend on factors such as the particle size, loading level, dispersion, and the specific polymer matrix used. Proper dispersal of the alumina particles in matrix is vital to accomplish the desired improvements in properties. Research has likely explored how the amalgamation of alumina nanoparticles or micro-sized particles into C-E composites affects characteristic features such as ILSS, flexural and tensile strength and impact resistance. The mixture of alumina's inherent high-strength characteristics of carbon fiber could lead to composite materials with superior wholly mechanical performance[5].

The study focuses on characterizing the mechanical anisotropy in these composites, highlighting variations in material behavior based on fiber orientation. Additionally, the research investigates the relation of fiber or epoxy, shedding light on the composite's overall performance[6]. Carbon fibers exhibit a highly ordered, crystalline structure with consistent alignment, contributing to their exceptional strength. In contrast, CFRP demonstrated a complex microstructure characterized by resin-rich regions and fiber-matrix interfaces. The study's results emphasize the significance of understanding CFRP's microstructure for optimizing its mechanical things and durability[7].

Incorporation of carbon micro- and nano-fillers led to notable enhancements in the composite's stiffness, strength, and fracture toughness. Additionally, the study demonstrated that nanofillers had a more pronounced effect on improving mechanical properties associated to micro fillers. These findings have some engineering applications where lightweight, high-strength composites are essential, particularly in aerospace and automotive industries[8]. Fluorinated polymers enhanced the fracture toughness and impact resistance of the composites. But, modified composites retained their stiffness. These findings underscore the potential of fluorinated poly (etherimide) as effective toughening agents for enhancing the performance of carbon fiber or epoxy composites[9]. Substantial improvement in the mechanical stuffs of the composites, including increased tensile strength and modulus, as well as enhanced interfacial adhesion amongst fibers and epoxy. These findings highlight the potential of polyethyleneimine functionalized carbon fiber fabric as a valuable reinforcement for enhancing the mechanical things of epoxy laminated composites[10].

Surface modification with the help of carbon black led to increase in adhesion between the carbon-epoxy matrix, resulting in improved t_s and modulus. Additionally, the same material exhibited enhanced impact resistance[11]. Increase in mechanical resistance, highlighting the potential for MWCNTs to reinforce composite materials. These results showed improved strength and sturdiness are crucial. However, further investigations into the optimal MWCNT concentration and manufacturing processes are warranted for practical implementation[12].

Mechanical abilities and fracture toughness associated to epoxy composites. Additionally, the morphological analysis showed failure and interactions carbon fibers and the altered epoxy matrix[13,14]. A synergistic enhancement in mechanical properties, including increased tensile, flexural and impact resistance, showcasing the potential of this hybrid approach[15]. The impacts of micro scaleoil penetration on both the chemical and mechanical features of CFR epoxy composites. The outcomes reveal a noteworthy reduction in tensile and flexural possessions, suggesting that oil intrusion compromises the structural integrity of the material system. Furthermore, the alterations in chemical properties, indicating potential degradation of the epoxy matrix. This research underscores the importance of protecting composite materials from oil exposure in solicitations where mechanical strength and chemical stability are crucial[16].

Fillers of alumina-type, titanium dioxide, and silicon carbide helps in reinforcing the composites, thus demanding in increased strength and durability. However, further studies may be needed to optimize filler concentrations for specific applications[17]. Substantial improvement in tensile and flexural strength, as well as enhanced stiffness, suggesting synergistic reinforcement effects from both fibers and nanoparticles. This hybrid approach offers capable opportunities for high-

performance applications in aerospace industries, where lightweight and durable materials are essential[18].

Impact resistance and toughness due to these modifications, making the composites s requiring improved durability. Additionally, the study highlights a minimal impact on thermal properties, ensuring the materials remain suitable for high-temperature environments[19]. Mechanical abilities for validating the efficacy of carbon fiber reinforcement. Results thus provide implications for industries requiring high-performance materials. However, additional research may be needed to optimize the engineering process for practical applications[20].

Results demonstrate that variations in these parameters significantly affect tensile and flexural properties. An optimal combination of ply count and fiber content can yield superior mechanical performance. Furthermore, the introduction of angle-ply layers provides enhanced stiffness and strength in specific orientations[21]. Notable improvements in both tensile strength and thermal stability, indicating enhanced binding ability of filler and epoxy matrix. It synthesizes a wealth of research findings on various types of fibers and fillers, their effects mechanical properties. The review highlights the versatility of these additives in tailoring composite for specific claims across multiple industries[22]. Basic mechanical abilities and toughness due to the addition of these nanomaterials. The combination of carbon fibers or CNT and graphene shows promising synergistic effects. Additionally, numerical simulations validate the experimental findings, further enhancing the credibility of the study. Resin exhibits promising mechanical properties, including enhanced tensile and impact resistance when compared to traditional epoxy resins[23]. Thermal conductivity and tensile due to the amalgamation of MWCNTs. This study underscores the potential for MWCNTs to reinforce composites, useful for high-stress applications like aerospace and automotive[24].

Improvement in interlaminar shear strength and delamination resistance due to MWCNT reinforcement. These findings are of great significance for aerospace and structural applications where composite materials require increased durability. However, further research may be needed to optimize MWCNT content and processing techniques for practical implementation[25]. The present research is aimed at exploring the mechanical behaviors of the Al_2O_3 filled with CF reinforced or epoxy composite.

2.0 Materials and Methods

2.1 Materials

The carbon fiber of 220 gsm used is in twill form as

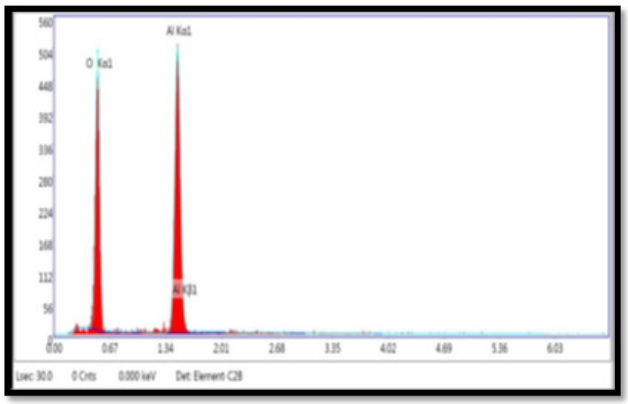


Figure 1. EDAX result of alumina filler.

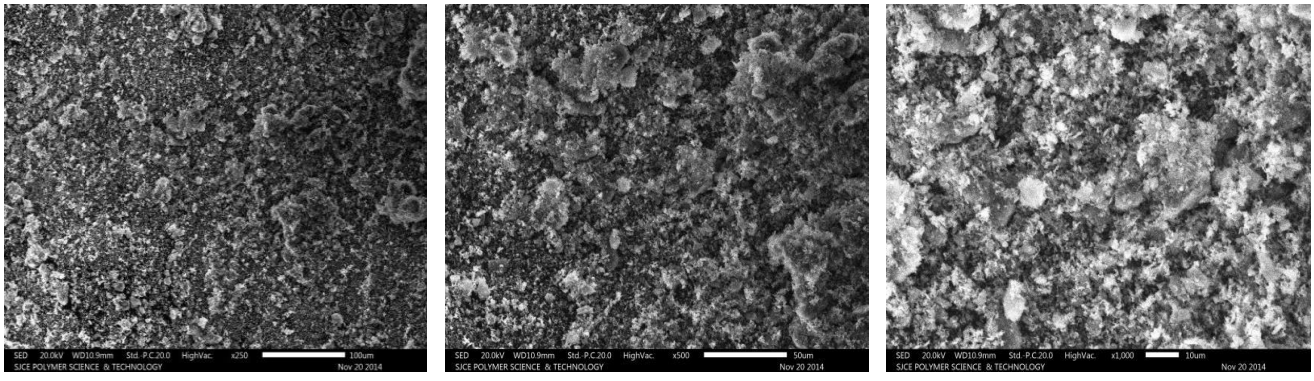


Figure 2. SEM images of alumina filler (magnification levels 250x, 500x and 1000x).

primary reinforcing material in combination with secondary reinforcement as alumina filler of 45-micron sized inorganic based being reinforced with polymer matrix, epoxy resin of Lapox L-12 grade and hardener, K-6 category in a ratio of 100:10 is used to prepare the composite laminates. To ensure the purity of alumina filler used for investigation, EDAX analysis was carried out. The EDAX results reveal that the Al constituted the highest percentage in the filler received from the manufacturer along with some traces of O as shown in Figure 1 and SEM pictures were used to understand the particle geometry of the alumina filler for composite preparation as illustrated in Figure 2, which revealed that the particles are highly irregular in their shape with approximate size 45-micron size at different magnification levels.

2.2 Methods

Hand layup and compression molding techniques were adopted to prepare quality laminates for the study. The laminates were made-up in variations of filler loading starting with 0%, 2.5%, 5% and 7.5% wt. percentage with carbon fiber-epoxy as thermoset polymer composites are shown in Table 1. Samples as per ASTM geometry were cut by Abrasive jet machining technique and later moisture intake was neutralized by oven drying illustrated in Figure 3.

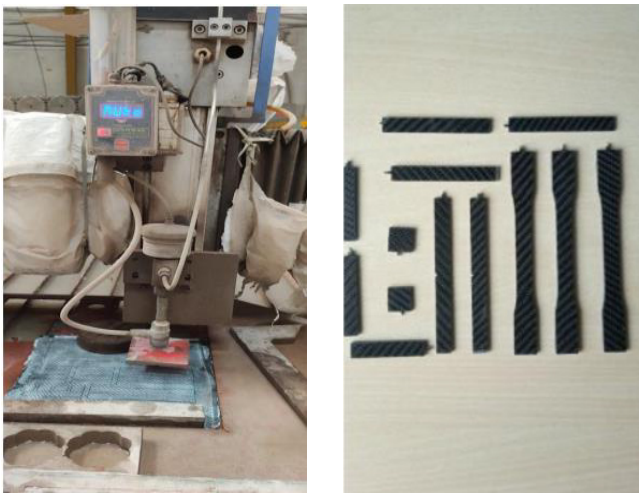


Figure 3. AJM and samples.

3.0 Mechanical Characterization

The mechanical evaluation was conducted at specific testing conditions on the samples produced. Tensile test [ASTM D638], with the cross speed load of 5 mm/min maintaining span length of 57 mm, flexural [ASTM D790], with span length of 60 mm at cross load of 10 mm/min while inter laminar shear strength [ASTM D2344] of the composites was tested at cross loading rate of 5 mm/min with span length of 30 mm. Shore D hardness [ASTM D2240], Density [ASTM D792], Izod [ASTM D256] and Charpy Impact [ASTM D6110] examinations were also performed according standard testing conditions using universally accepted testing equipment's[26-32].

4.0 Results and Discussion

In Tables 2 to 6 highlights of mechanical properties determined and obtained after investigations were conducted as per ASTM.

Comparing themechanical capacity of the composites is illustrated in Figure 4 and 5. Tensile strength of the C-E composite filled with alumina filler of 7.5% wt. is the highest amongst all the samples tested with 362.10 MPa. The tensile strength increases when fillers are added in all cases, and this improvement is even greater in hybrid

Table 1. Material compositions of composites

S. No	Material Configuration			Sample Code
	Carbon Fiber (wt. %)	Alumina Filler (wt. %)	Epoxy (wt. %)	
1	55	0	45	C-E
2	52.5	2.5	45	C-E-Al_2O_3- 2.5%
3	50	5	45	C-E-Al_2O_3- 5%
4	47.5	7.5	45	C-E-Al_2O_3- 7.5%

Table 2. Tensile characters of composites

S. No	Sample Code	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)
1	C-E	283.3	14.92
2	C-E-Al_2O_3-2.5%	303.2	15.45
3	C-E-Al_2O_3- 5%	355.9	18.71
4	C-E-Al_2O_3-7.5%	362.1	23.35

Table 3. Flexural and ILSS features of composites

S. No	Sample Code	Flexural Strength (MPa)	Flexural Modulus (GPa)	ILSS (MPa)
1	C-E	260.45	11.35	21.50
2	C-E-Al_2O_3-2.5%	281.56	13.41	30.10
3	C-E-Al_2O_3-5%	332.81	15.55	37.50
4	C-E-Al_2O_3-7.5%	386.07	16.32	44.90

Table 4. Density and hardness properties of composites

S. No	Sample Code	Shore D Hardness	Density
1	C-E	72	1.32
2	C-E-Al_2O_3-2.5%	74	1.36
3	C-E-Al_2O_3- 5%	76	1.43
4	C-E-Al_2O_3-7.5%	84	1.46

composites. The upsurge in tensile strength is mainly by alumina dispersion and stronger bonding of interfacial amongst the particles and matrix in composites. When cracks spread quickly and branch out, they absorb more energy, which helps delay the failure of the composite material, consuming a greater amount of energy. The

Table 5. Impact strength of composites

S. No	Sample Code	Charpy Impact Strength (kJ/m²)	Izod Impact Strength (J/m)
1	C-E	22.67	386.70
2	C-E-Al_2O_3-2.5%	19.59	214.5
3	C-E-Al_2O_3- 5%	18.37	204.5
4	C-E-Al_2O_3-7.5%	17.01	200.9

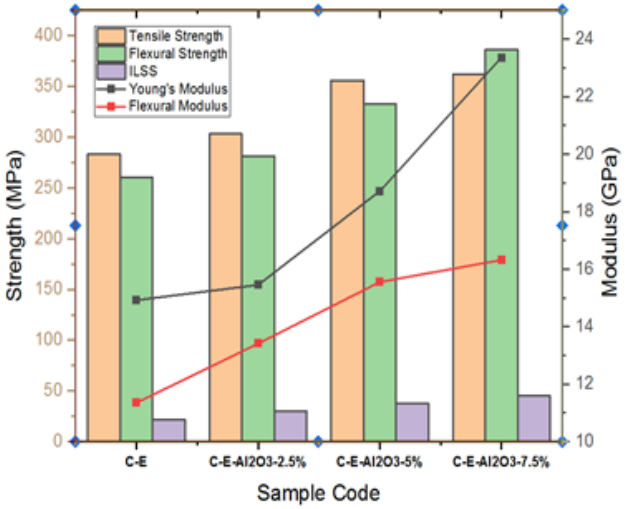


Figure 4. Comparison of tensile, flexural and ILSS properties of composites.

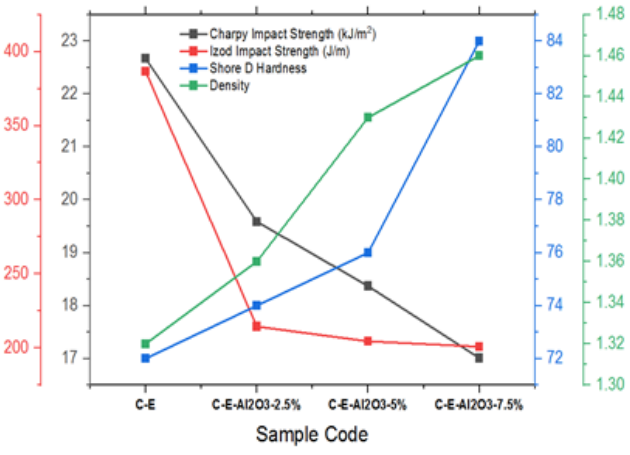


Figure 5. Comparison of density, hardness and impact values of composites.

impact strength in composites decreased with upper filler content significantly compared to other composites. An increase in the addition of Al_2O_3 into the composites led to surge in hardness number due to enhanced adhesion among matrix and reinforcement, and lessens porosity. Increasing particle loading in matrix has decreased the inter-particle distance and increased resistance to indentation. The sample without alumina filler had the lowest impact strength.

The filler didn't improve the impact strength of the composite by increasing the energy it absorbs before cracking, nor did it reduce how deep the impact penetrates the surface. Inter Laminar Shear Strength (ILSS) is an important interfacial aspect of filler based fibrous composites. ILSS was assessed by means of a Short Beam Shear (SBS) test as per standard and the outcomes showed that the ILSS of the carbon-epoxy composite filled with alumina filler of 7.5% wt. is 44.9 MPa very optimal to other composites. The higher ILSS is owed to the covalently- united filler which inhibits the dissemination of micro or pin cracks. The material's density increased steadily as the amount of fillers added went up.

4.1 Fractography

SEM images reveal the failure of tensile tested sample. The analysis reveals that fiber pullouts, fibers breakage, fiber matrix breakage, debonding of filler or matrix, and some voids are shown in Figure 6.

5.0 Conclusion

In conclusion, the mechanical properties of Carbon-Epoxy (C-E) composites with alumina fillers were carefully studied, revealing key insights into the impact of alumina content on performance. The composite with 7.5% alumina filler exhibited the highest tensile strength at 362.10 MPa, demonstrating the effectiveness of alumina in enhancing strength. This improvement is attributed to better alumina dispersion and stronger interfacial bonds, which help absorb energy and delay crack propagation.

However, higher filler percentage led to a reduction in impact ability, as the increased filler load hindered energy absorption. Notably, the composite without alumina

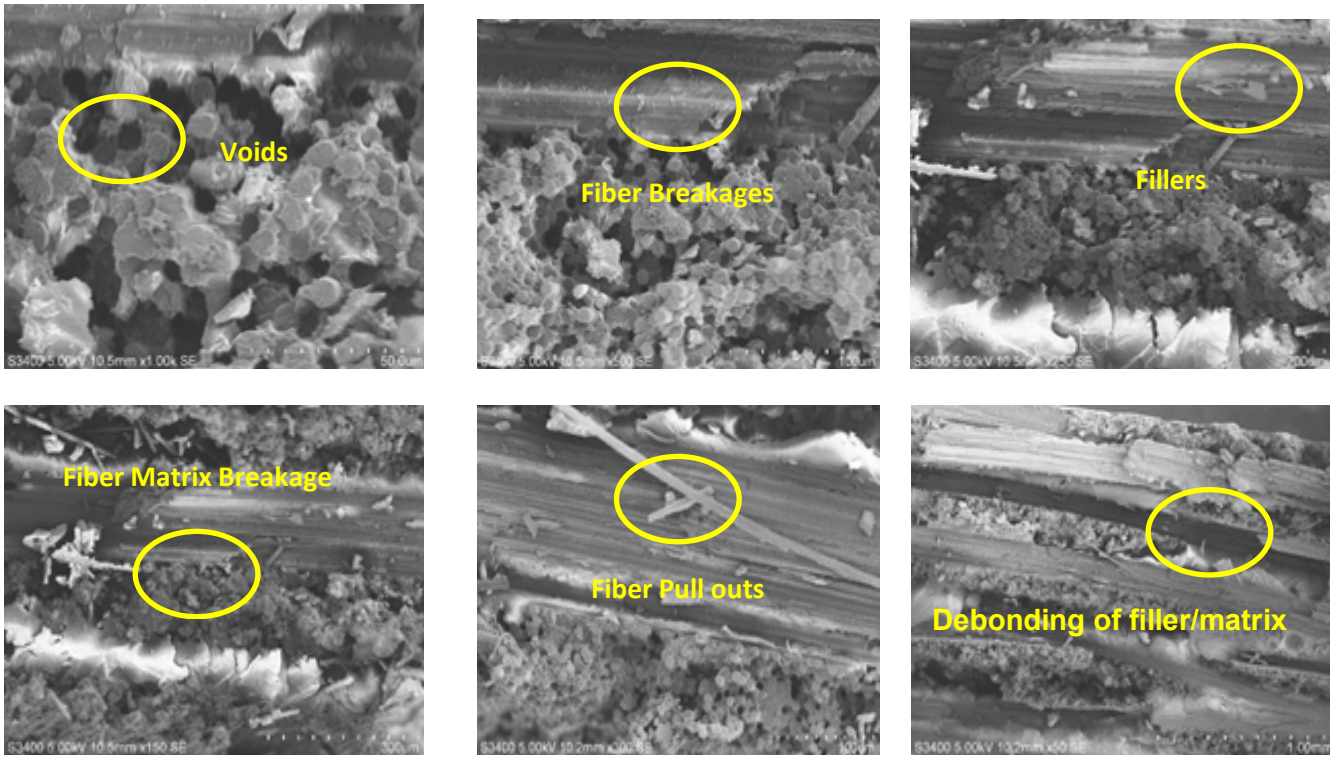


Figure 6. SEM pictures of tensile tested sample.

presented the lowest impact strength, underscoring the importance of filler incorporation.

The composite with 7.5% alumina also achieved the highest Inter Laminar Shear Strength (ILSS) of 44.9 MPa, attributed to strong covalent bonding between filler and matrix, which prevents microcrack propagation. Density increased linearly with filler content, further illustrating the effect of alumina on material properties.

Overall, the study highlights the potential of alumina-filled C-E composites for applications requiring higher strength and toughness. Further research into higher filler levels could clarify the optimal alumina content for balancing mechanical properties, as benefits may diminish beyond a certain threshold.

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