

Characterization and Computational Analysis of Mechanical and Physical Properties of fly ash filled Coir/Glass-Epoxy Hybrid Composites

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Abstract: The physical and mechanical properties of hybrid coir and glass fiber reinforced epoxy composites filled with fly ash powder were studied in this study. Three different composite variants were fabricated by manual hand lay-up technique by varying the Fly ash filler content (0 wt.%, 5 wt.% and 10 wt.%) keeping the weight percentages of E-glass fiber (20 wt.%) and coir fiber (10 wt.%) constant. The experimental results reveal that the incorporation of Fly ash filler has a significant influence on the physical, mechanical and water resistance properties of the hybrid composites. The overall density and micro-hardness of the composites increases continuously with increase in Fly ash content with 10 wt.% composition showing the maximum hardness. Further, the strength of the filler is also effective in reducing the internal voids, leading to a significant decrease in moisture uptake rate. The 10 wt.% sample showed the lowest water absorption after 24 hours. On the other hand, optimum values of tensile, flexural and impact performance are obtained only at a threshold of 5 wt.% Fly ash loading. However, at 10 wt.% concentration a clear strength degradation takes place beyond this limit which is attributed to particle agglomeration, poor mixing of matrix-reinforcement and reduced interfacial adhesion.

Keywords: Hybrid composites, Coir fiber, Epoxy resin, Hand lay-up technique, Tensile strength, Water absorption

1. Introduction

In the past few decades, the material science has shifted from conventional metals to advanced polymer matrix composites (PMCs) due to their low cost of production, easy fabrication and high strength to weight ratios [1]. PMCs are extensively employed in high performance industries such as aerospace and automotive engineering. The most common synthetic reinforcement is woven E-glass fiber, which has high tensile strength, insulating properties and chemical resistance. Modern research is focusing on sustainable natural fibres such as jute, sisal, bamboo and coir as low-cost biodegradable alternatives [2]. Many researchers have studied natural fiber reinforced polymer composites. Gupta et al. [3] studied epoxy composites of bamboo fiber and observed the increase in tensile strength with fiber loading and maximum at 40 wt.% while flexural strength was maximum at 20 wt.%. Coir fiber polyester composites were explored by Monteiro et al. [4] and they found that the reinforcement efficiency was poor because of the low elasticity of coir fibers compared to polyester resin. Harish et al. [5] studied lignin as a compatibilizer in coconut fiber-polypropylene composites and observed enhancement in flexural strength with little improvement in tensile properties. Goud et al. [6] evaluated the tensile properties of Roystonea regia fiber epoxy composites and stated that the tensile properties increased with an increase in fiber amount and the values were highest at 20 wt.%. Luo et al. [7] studied the pineapple leaf fiber epoxy composites and observed that, with the increase in fiber content, the tensile strength was enhanced in the longitudinal direction and decreased in the transverse direction. Alamri et al. [8] studied recycled cellulose fiber epoxy composites and found that water absorption increased with fiber loading and that it decreased flexural properties and fracture toughness due to fiber-matrix degradation. Hu et al. [9] studied the jute fiber-polylactic



composites, where they observed a three-stage process of moisture absorption and no saturation was observed during the test. Havstad et al. [10] studied the effect of sodium bicarbonate treated coir fibers on epoxy composites, and discovered that the mechanical properties are significantly affected by the immersion time. The best performance was observed at 10% fibre content, 15% solution concentration and 5 days of immersion.

Many researchers have investigated the mechanical behavior of synthetic fiber-reinforced polymer composites using different fiber types. Cho and Jung [11] investigated aramid fibers and reported good thermal stability with small changes in mechanical properties. Chauhan et al. [12] have studied the fiber reinforced vinyl ester composites and found the influence of fiber loading on density and wear behavior. Kevlar aramid fibers. They noticed that fiber orientation and mechanical properties were strongly affected by processing parameters. Gururaja et al. [14], the flexural strength of carbon fiber reinforced epoxy composites was decreased because of water absorption and high temperatures. Turaka et al. [15] examined the impact of fiber orientation on mechanical characteristics of unidirectional glass fiber reinforced epoxy composites fabricated by vacuum bagging. The results indicated that 0° fiber orientation provided the highest tensile, compressive, flexural and interlaminar shear strength compared to the other orientations. The fracture analysis revealed the mechanisms of fiber pull-out and matrix damage and the numerical simulations were in good alignment with the findings of the experimental results.

Yang et al. [16] reported that the tensile strength of polyurethane composite foam was improved by the reinforcement of SiO₂, glass fiber and carbon fiber. Goud et al. [17] reported that with increase in glass fiber content, tensile, flexural, impact and hardness properties were improved while electrical properties were decreased. The curaua-glass hybrid composites showed better density, hardness and impact strength due to better adhesion of the glass fiber [18]. Bledzki et al. [19] reported that the dynamic mechanical properties increased with increasing fiber content, where the flax fiber composites provided better strength than jute. Kim et al. [20] discovered that moisture absorption reduced the flexural strength and flexural modulus of basalt/CNT/epoxy composites due to weakened interfacial bonding. Zamri et al. [21] and Silva et al. [22] reported that hybridization of natural and glass fibers reduced moisture absorption and improved mechanical properties. Jahani et al. [23] observed that modified polypropylene improved tensile strength and reduced moisture absorption in wood flour composites, while Dixit et al. [24] concluded that hybridization of coir, sisal, and jute fibers significantly enhanced tensile properties.

A filler that merely increases the bulk volume, reducing the price, is called an extender filler, while a filler that increases mechanical strength is called a reinforcing filler. Plastics industries use millions of metric tons of fillers and reinforcements each year. The utilization of these additives in plastics is expected to increase as enhanced compounding agents facilitate the incorporation of fillers and reinforcements at elevated levels [25, 26].

2. Material and methods

2.1 Matrix material

Polymer matrices are widely used because they are cost-effective, easy to fabricate, and possess excellent room-temperature properties. Among thermosetting resins (such as polyester, vinyl ester, and polyurethane), epoxy—chemically known as Bisphenol-A-Diglycidyl-Ether—is preferred for composites due to its superior fiber adhesion, high mechanical and electrical performance, good thermal and chemical resistance, and low curing shrinkage [27]. Consequently, epoxy was selected as the matrix for this study.

2.2 Reinforcement material

Coir fiber, extracted from abundant coconut husks, is highly robust due to its high lignin content. Thanks to advantages like low density, biodegradability, and low cost, coir-reinforced composites are increasingly used to improve fuel efficiency in automobiles, railway coaches, and buses, as well as in building construction [28, 29]. Conversely, synthetic E-glass fiber is widely utilized in polymer matrix composites due to its excellent insulating qualities, low cost, high strength, and chemical resistance. [30, 31].

2.3 Filler material

Fly ash is a by-product of coal combustion and is widely used as a filler in polymer composites because of its low density, low cost, and higher silica content. The addition of fly ash improves stiffness, hardness, thermal stability, and mechanical properties, while also promoting sustainable utilization of industrial waste [32, 33]. Table 1 and Table 2 represents the physical characteristics and chemical composition of fly ash respectively.

Table 1: Physical characteristics of fly ash

Density (g/cm ³)	2.18
Bulk density (g/cm ³)	1.29
Melting point (°C)	>1200 °C
Moisture content	% 1.7
Colour	Gray

Table 2: Chemical composition of fly ash

Compound	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	SO ₃	Na ₂ O	K ₂ O
Composition (wt. %)	51.13	25.45	4.65	1.22	3.17	0.53	0.22	0.89

2.4 Composite fabrication

The low-temperature curing epoxy resin and its associated hardener are combined in a weight ratio of 10:1. The composite sheets are cast using a 210 x 210 x 3 mm³ mold. The fly ash powder is mixed with epoxy resin before adding the hardener by the simple mechanical stirring. Fly ash is used in three different weight percentages, while glass fiber content is maintained at 20 weight percent by using a simple hand lay-up technique. A detailed description and designation of the composite samples are mentioned in Table 3. For each composite, a load of approximately 20 kg is applied for 24 hours before the casting is removed from the mould cavity. Once these sample are taken out of the mould cavity, they are post-cured for another 24 hours in the air. Following curing, appropriately sized pieces are cut for mechanical and physical testing.

Table 3: Designation of different Composites fabricated

Notation for composite	Composition of composites
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (5wt. %)
C3	Epoxy (60wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (10wt. %)

2.5 Density Measurement

The density of the composite is obtained by using the principle of Archimedes. This principle asserts that the weight of bodies submerged in a liquid equals the weight of the liquid displaced by the bodies. The density of composites was determined by Archimedes drainage method according to equation (1).

$$\rho_E = \frac{m}{(m - m_w)} \rho_w (1)$$

Where ρ_E is the experimental density of the composites, m_w is the mass of the composites in distilled water, m is the mass of the composites in air and ρ_w is the density of distilled water. The density of distilled water at 20°C is 998 kg/m³.

2.6 Water absorption test

Moisture absorption test was conducted as per ASTM D 570-98. The specimens are made in the form of a disk of 50.8 mm diameter. The specimens are dried in an oven for a $52 \pm 3^\circ\text{C}$ temperature. The samples were cooled to normal water (23°C) and the weight recorded. The specimens were removed from the wet environment after 24 h of exposure. Surface moisture was removed from the specimens using a clean, dry cloth or tissue paper. The moisture absorption level was determined by difference in weight of specimens. The percentage gain in weight of the specimens was calculated for different time intervals using the equation (2):

$$\%M = [(W_t - W_0) / W_0] \times 100 \quad (2)$$

Where W_t is the weight of specimen at a given immersion time and W_0 is the oven-dried weight.

2.7 Tensile Test

The Universal Testing Machine Instron 3382 is used for composites testing for tensile strength with an accuracy up to $\pm 0.66\%$ as per the ASTM D638-01 test standards. The test specimen used in the experiment had a gauge length (L) of 50 mm, a width (D) of 13 mm and a thickness of 3 mm. The cross-head speed was maintained at 2 mm/min at a temperature 28°C . Figure 1 shows the specimens for tensile test. Figure 1 represents the specification of tension test specimen.

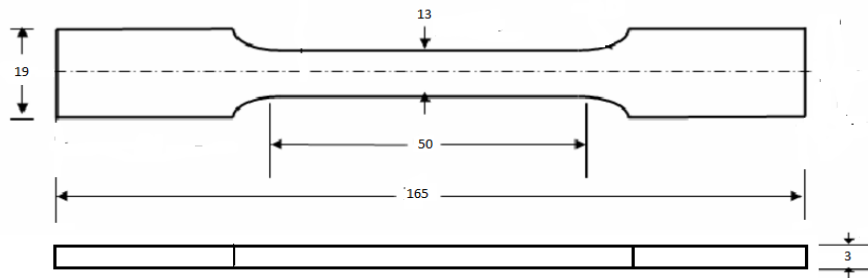


Figure 1: Specification of tension test specimen [all dimensions are in mm]

2.8 Flexural Test

Flexural strength is the strength of material to resist the bending loads exerted upon it. The 3-point bending test is used to assess the flexural strength of the composites according to ASTM D790-03 on Universal Testing Machine Instron 3382 having accuracy up to $\pm 0.66\%$. The flexural test maintains a span of 43 mm and a cross head speed of 2 mm/min at a temperature 28°C . Three samples of each composition are tested and the mean value is considered. Figure 2 represents the specification of flexural test specimen.

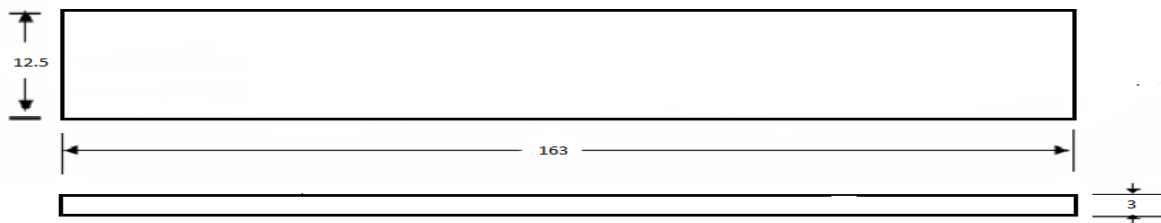


Figure 2: Specification of flexural test specimen [all dimensions are in mm]

2.9 Impact Test

Impact strength test of composite is performed using izod test. The test is conducted as per ASTM D 256 using impact testing machine Tinius Olsen having working range 0-25 joule and accuracy 0.015 joule. Three specimens of each composite are tested and the mean value is taken.

2.10 Hardness Test

Hardness is a mechanical property of material, which is characterized by the resistance of substance to penetration and scratching. It is the distance of indentation and recovery when the indenter is passed into the surface under uniform load. Shore D hardness test was used for hardness measurement.

3. Result and discussion

3.1 Density of fabricated composites

The experimental density of composite components is determined based on Archimedes' Principle. The density of the composites increases with increasing weight percent of reinforcement. Experimental densities of composites are shown in Table 4.

Composites	Composition	Density (gm/cc)
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	1.162± 0.015
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (5wt. %)	1.173± 0.017
C3	Epoxy (60wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (10wt. %)	1.195± 0.016

Table 4 – Experimental densities of composites

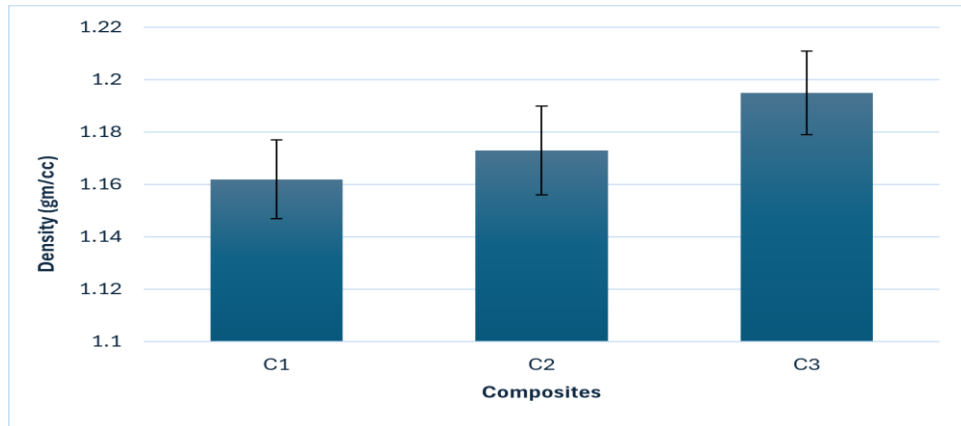


Figure 3: Variation of density with different composition of composites

Figure 3 indicates a gradual increase in composite density with an increase in filler concentration. The density of the composites was observed to increase gradually from 1.162 g/cc for C1 to 1.195 g/cc for C3 with increasing fly ash content. The increase in density can be attributed to the replacement of a portion of epoxy resin with fly ash particles, which possess higher density than the polymer matrix. Furthermore, the incorporation of fly ash particles fills the voids present within the composite structure and enhances particle packing, resulting in a denser composite material [34]. Therefore, increasing fly ash content from 5 wt.% to 10 wt.% led to a corresponding increase in the

overall density of the hybrid composite. The density increased by approximately 2.8% from C1 to C3 due to the addition of fly ash filler.

3.2 Microhardness analysis

As shown in Table 5 and Figure 4, the microhardness of the composites increased with increasing filler content. Compared to C1, the hardness of C2 increased by 8.1%, while C3 showed an increase of 16.2%. The increase in hardness is attributed to the presence of rigid fly ash particles within the epoxy matrix, which improve resistance to localized plastic deformation and enhance load transfer between the matrix and reinforcement. The fly ash particles also reduce matrix mobility and fill micro voids in the composite structure, resulting in improved surface hardness. Therefore, increasing fly ash content significantly enhanced the hardness characteristics of the hybrid composites [35,36].

Table 5 – Microhardness of Composites

Composite	Composition	Hardness
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	74 ± 1.2
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (5wt. %)	80 ± 1.3
C3	Epoxy (60wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (10wt. %)	86 ± 1.5

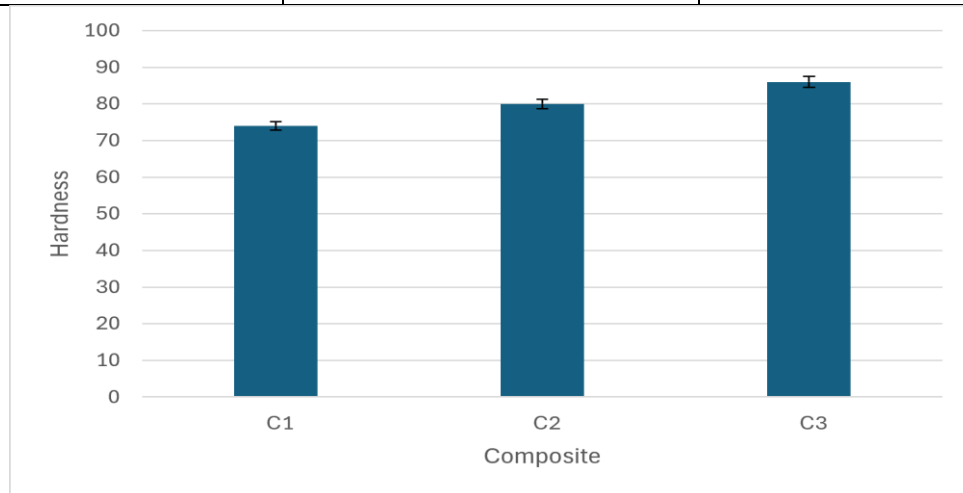


Figure 4: Effect of filler material on the hardness of composites

3.3 Water Absorption Test

The water absorption of the hybrid composites decreased with increasing fly ash content as shown in table 6 and figure 5. Compared to C1, C2 showed a 50.0% reduction, while C3 exhibited a 77.8% reduction in water absorption. This reduction can be attributed to the incorporation of fly ash particles, which fill micro voids and improve fiber–matrix interfacial bonding, thereby restricting moisture penetration into the composite structure [37].

Table 6: Water absorption (%) of coir and glass fiber reinforced epoxy-based composite with different weight % of Fly ash filler

Composite	Composition	Water Absorption (%)
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C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	1.26 ± 0.4
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (5wt. %)	0.63 ± 0.8
C3	Epoxy (60wt %) +Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (10wt. %)	0.28 ± 0.7

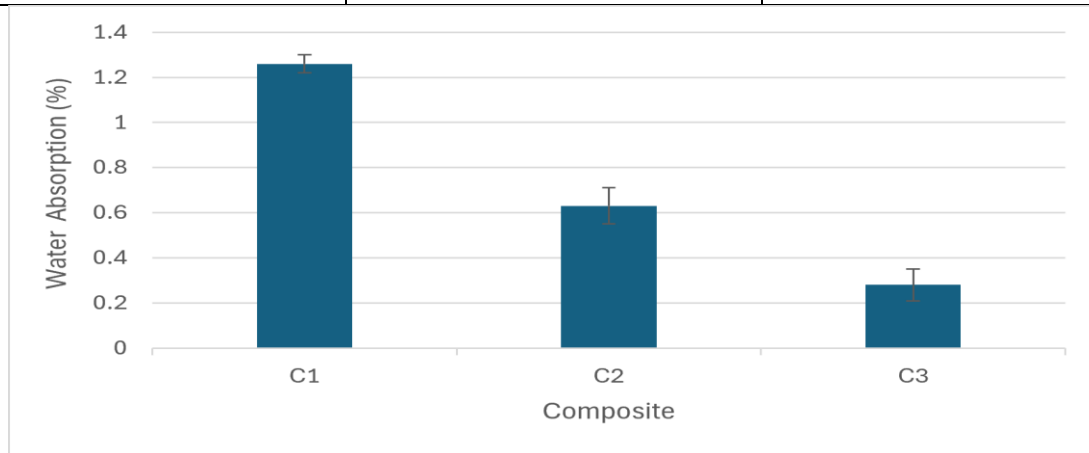


Figure 5: Effect of filler material on the water absorption % of composites

3.4 Tensile strength

The tensile behavior of the developed hybrid composites exhibited a significant dependence on the incorporation of fly ash filler as shown in table 7 and figure 6 and 7. The maximum tensile load increased by 9.2% for C2 and decreased by 20.4% for C3, while the tensile strength increased by 8.5% for C2 and reduced by 14.4% for C3 compared to C1. Initially, the addition of fly ash improved the tensile properties of the composite because of the better stress transfer mechanisms between the reinforcing fibers and epoxy matrix. The uniform distribution of filler particles improved the interfacial adhesion and reduced stress concentration in the matrix, thereby improving the composite's ability to withstand higher loads under tensile conditions [38].

Also, the increase in stiffness of the matrix phase could be related to the increase in tensile strength and tensile modulus in the lower filler content. The fly ash particles act as reinforcers, which restrict the molecular motion of the polymer chains and improve the resistance to deformation under applied loadings. The effective bonding between the fibers, fillers and matrix plays a major role in improving the tensile performance in hybrid composites with natural and synthetic fibers [37].

However, at higher fly ash loading a reduction in tensile properties was observed. The decrease can be ascribed to the agglomeration of filler particles and their non-uniform distribution in the matrix. The high filler concentration might generate some local stress concentration zones and weak zones at the interface, which hinder the effective load transfer from the matrix to the reinforcement fibers. Further, the increase in the filler loading can induce microvoids and defects during the composite fabrication, leading to early crack initiation and propagation under tensile loading [39].

Table 7: Tensile strength and tensile modulus of composites

Composit e	Composition	Maximum Tensile	Extension	Tensile	Tensile Modulus
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		Load (N)	(mm)	Strength@ Max Load (N/mm2)	(N/mm2)
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	2022.33 ± 21.5	4.02 ± 0.08	63.57 ± 1.13	2329.31 ± 27.7
C2	Epoxy (65wt %) + Glass Fiber (20wt. %) +Coir Fiber Mat (10wt %) + Fly ash (5wt. %)	2209.08 ± 23.9	4.47 ± 0.07	68.97 ± 1.25	2510.74 ± 30.6
C3	Epoxy (60wt %) +Glass Fiber Mat (20wt. %) +Coir Fiber(10wt %) + Fly ash (10wt. %)	1609.78 ± 18.9	4.71 ± 0.06	54.41 ± 0.98	1803.88 ± 25.8

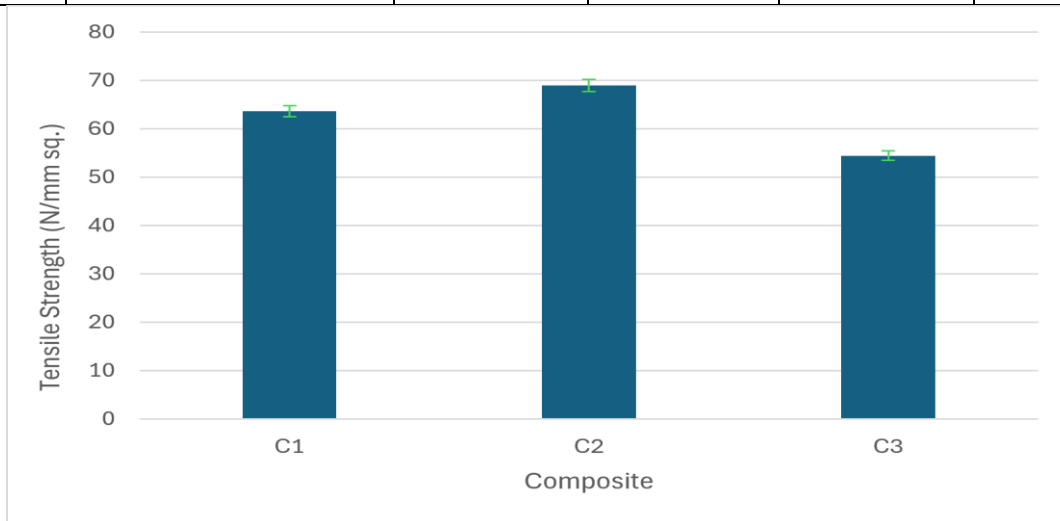


Figure 6: Effect of filler material on Tensile strength of composites

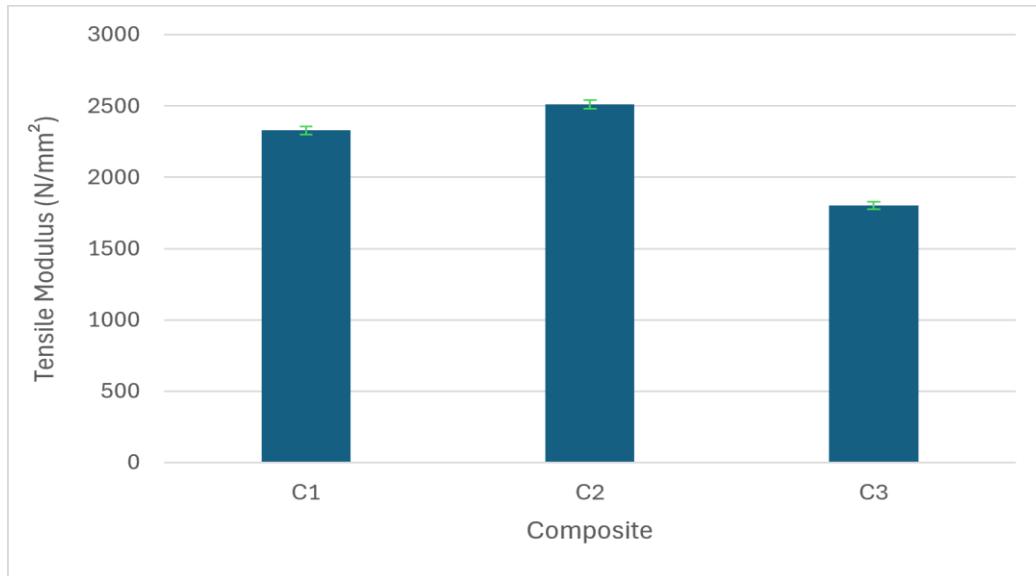


Figure 7: Effect of filler material on Tensile Modulus of composites

3.5 Flexural Strength

The flexural properties of the fabricated composites are summarized in Table 8. Figure 8 and figure 9 represent effect of filler material on flexural strength and flexural modulus of composites respectively. C2 shows an increase of 24.6%, 24.8%, and 29.0% in flexural load, flexural strength, and flexural modulus respectively, while flexural elongation decreases by 4.1%. Compared with C1, flexural load, strength and modulus of C3 increase by 13.0%, 15.7% and 11.7% respectively, while flexural elongation decreases by 32.9%. The addition of Fly ash filler has significantly affected the flexural performance of hybrid composites. At low filler content, the flexural properties are improved due to uniform dispersion of the hard ceramic particles in the epoxy matrix, enhancing the stiffness and providing efficient stress transfer between the matrix and the reinforcing fibers. The rigid particles restrict the deformation of the matrix under bending loads and thus increase the resistance to the flexural failure. Literature has widely reported improvements in stiffness and strength with particulate reinforcement in polymer composites [40].

Flexural properties are decreased with increase in Fly ash content. The degradation is mainly attributed to the poor dispersion and agglomeration of particles, which leads to stress concentration sites and weakens the fiber–matrix interface. These defects are responsible for early crack initiation and lower load carrying capacity under bending loads. Moreover, the existence of too much filler can also be prejudicial to the good wetting of the fibers by the resin, and thus, to the efficiency of the interfacial bonding. The same behavior has been reported for particulate-filled polymer systems, where an optimum filler loading is required to balance strength and toughness [38]

Table 8: Flexural strength and flexural modulus of coir and glass fiber epoxy-based composite with different weight % of Fly ash filler

Sample	Composition	Maximum Flexural Load (N)	Flexure Elongation @max load (mm)	Flexural Strength@ Max Load (N/mm²)	Flexural Modulus (N/mm²)
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %)	135.88 ± 3.1	5.16 ± 0.10	94.92 ± 1.7	4715.98 ± 67.4

	+ Coir Fiber (10wt %)				
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (5wt. %)	169.23 ± 3.6	4.95 ± 0.11	118.49 ± 1.3	6083.16 ± 62.5
C3	Epoxy (60wt %) +Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (10wt. %)	153.58 ± 3.4	3.46 ± 0.12	109.88 ± 1.1	5267.88 ± 68.1

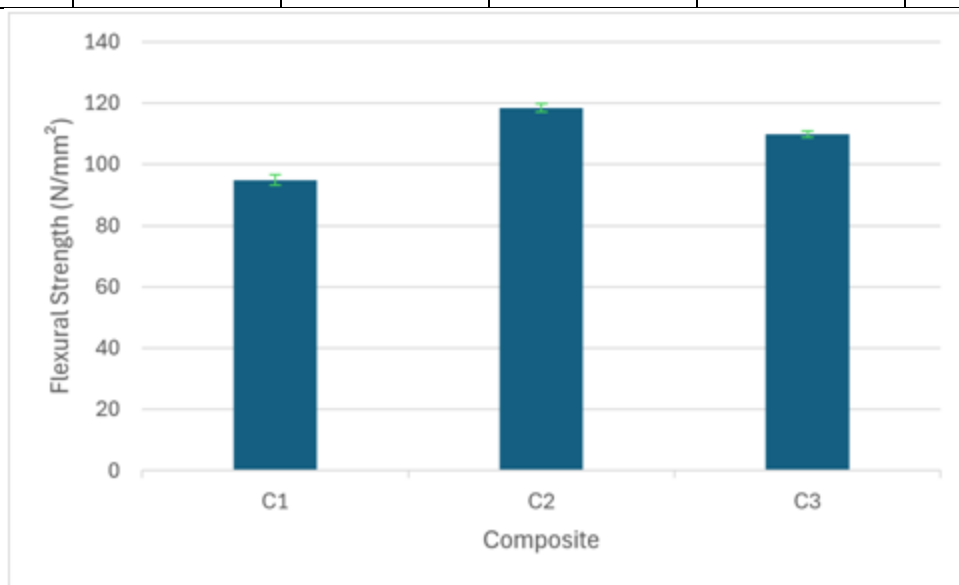


Figure 8: Effect of filler material on Flexural Strength of composites

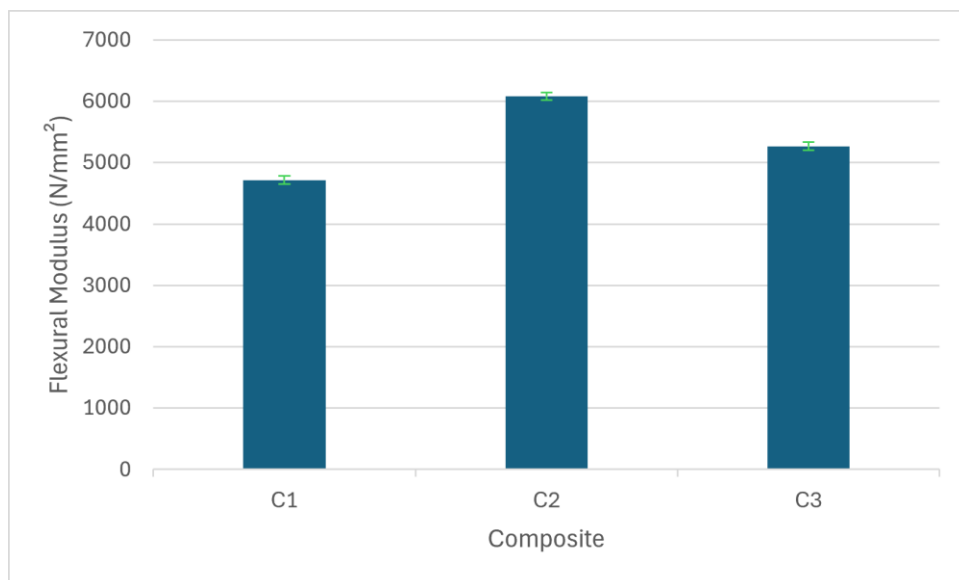


Figure 9: Effect of filler material on Flexural Modulus of composites

The impact strength for the hybrid composites was found to be increasing with addition of fly ash filler as shown in table 9 and figure 10. This showed the improvement in energy absorption capability of material. C2 and C3 showed an increase of 21.9% and 17.2% respectively in comparison to unfilled composite. The improvement in impact strength is attributed to the addition of fly ash particles which improve the stress transfer and interfacial bonding between the epoxy matrix and reinforcing fibers. The filler particles also help in dissipating energy under impact loading by hindering the initiation and propagation of cracks.

However, a slight decrease in impact strength was observed at higher filler loading as compared to optimum composition. This behavior can be attributed to particle agglomeration and non-uniform filler distribution, which results in localized stress concentration regions in the matrix. Such defects can decrease the efficiency of energy absorption and cause early crack propagation. Similar trends have been observed in particulate filled polymer composites where optimum filler concentration is important to improve impact performance [41].

Table 9: Impact strength of coir and glass fiber reinforced epoxy-based composite with different weight % of Fly ash filler

Sample	Composition	Impact Strength (KJ/m ²)
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	40.11 ± 0.82
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) +Coir Fiber Mat (10wt %) + Fly ash (5wt. %)	48.88 ± 0.78
C3	Epoxy (60wt %) +Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (10wt. %)	46.99 ± 0.80

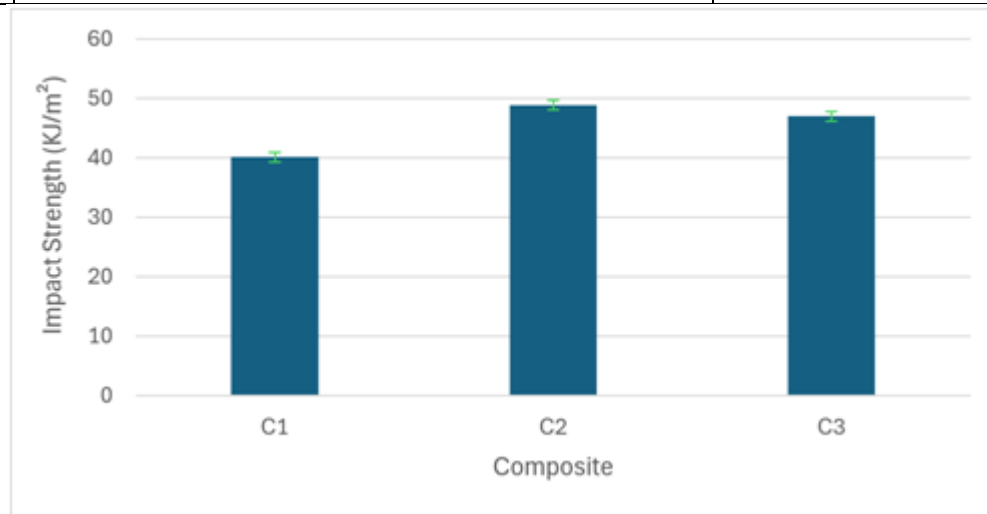


Figure 10: Effect of filler material on the impact strength of composites

4. Conclusions

In the present work, fly ash filler reinforced epoxy hybrid composites with coir fiber and glass fiber were successfully fabricated and their physical and mechanical properties were investigated. The experimental results indicated that the addition of fly ash had a great influence on the composite performance.

- Density of the composites increased with the increase in fly ash content due to the higher density and improved packing effect of fly ash particles.
- The addition of filler increased the hardness values due to the rigid nature of fly ash particles which increased resistance to localized deformation.
- Water absorption was significantly reduced with increasing fly ash content indicating increased moisture resistance with less voids and improved fiber–matrix bonding.
- Enhanced tensile properties with first addition of filler and optimum performance at 5 wt.% fly ash loading. Tensile strength and tensile modulus were increased by 8.5% and 7.8% respectively.
- Improvement in impact strength was observed due to fly ash incorporation showing a maximum increase of about 21.9% which indicates better energy absorption capability.
- Flexural properties improved significantly at optimum filler loading. Flexural strength and flexural modulus increased by ~24.8 and 29.0%, respectively.
- The mechanical properties showed a decrease beyond the optimum fly ash content due to agglomeration of particles, poor dispersion and stress concentration effects.
- The optimum filler concentration of fly ash is 5 wt% for the improved mechanical properties of coir-glass fiber reinforced epoxy hybrid composites.
- The developed hybrid composite can be considered as a lightweight, low cost, and eco-friendly material for structural and engineering applications.

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