Journal of Techniques, ISSN: 2708-8383, Vol. 5, No. 2, 2023, Pages 52-60
DOI: https://doi.org/10.51173/jt.v5i2.1176

JOURNAL OF TECHNIQUES

Journal homepage: http://journal.mtu.edu.iq

RESEARCH ARTICLE - ENGINEERING

Mechanical Properties of Multi-Layer Woven E-Glass/Epoxy in Variable Fiber-Mat Directions

Saif Aldeen Ghafel H.[1*], Nasri Salh M. Namer[1], Abdul Jabbar H. Ali[2]

[1] Engineering Technical College - Baghdad, Middle Technical University, Baghdad, Iraq

[2] Al-khawarizmi College of Engineering, University of Baghdad, Baghdad, Iraq

[*] Corresponding author E-mail: aldeensaif524@gmail.com

Article Info.

Article history:

Received
11 January 2023

Accepted
26 March 2023

Publishing
30 June 2023

Abstract

In this research, the epoxy resin was reinforced by (16 layers) of E-glass fiber woven mat (0^°/90^°) with 50% weight fraction and total thickness (3mm). Using 16 layers was due to the absence of any previous study that used this number of layers at this thickness. It is considered a modern study of this style because of the rapid development in modern engineering industries that required lightweight composite materials with high strength and small thickness, which are used in the aerospace industry aviation and other precision engineering industries. The composite material was cut into angles (0^°,5^°,15^°,30^°,45^°) by using CNC water jet culling machine. The tensile test was used to determine the strength of a material ratio to the fiber's direction and by using Vickers hardness to determine the hardness of composite and pure epoxy. The result of pure epoxy (matrix) has the lowest value in tensile strength (σ_{UTS}), Yong's modulus (E), 0.2% proof yield stress (σ_(0.2%)), modulus of toughness and toughness when compared with a composite material with adding 16 layers of "E-glass fibers". The direction of the fibers with (5^°) of composite has the highest strength, Young's modulus, and 0.2% proof yield stress when compared with (0^°,15^°,30^°,45^°) and pure epoxy. The improvement strength (10.8, 11.8, 9.8, 8.5, 8.3 times) at (0^°,5^°,15^°,30^°,45^°) respectively when compared with pure epoxy. The hardness of composite material improved (220%) relative to pure epoxy. The results show that the best improvement of composite material with fiber's angle (5^°) has the highest results compared with pure epoxy.

Publisher: Middle Technical University

Keywords: Multi-Layer; Woven; E-Glass/Epoxy; Fiber-Mat Directions.

1. Introduction

During the last years, demands for composite materials are increased due to the many advantages they possess [1, 2]. Composite materials are rapidly substituted materials used traditionally, with the rate of their increasing dramatically[3]. although the area of composites is very broad, fiber-reinforced polymer matrix composites are an area of greater interest [4]. The properties of composite materials depend on several factors, including the properties of the reinforcing elements, their geometry, shape, forms, quantity of the reinforcing elements (fiber weight fraction), fabrication technique, and properties of the matrix [5, 6]. In composite materials, glass fibers are one of the most widely used synthetic fibers, due to some factors; one of them is good resistance to chemical attack, second is good insulating properties, third is no moisture absorption, and fourth is inexpensive and has high tensile strength. The glass fibers are shaped into filaments, a mat of short fibers, woven filaments, etc. [7-9]. A composite material is two or more materials with distinct chemical, mechanical, and physical properties, classified as (matrix), and (reinforcement) fused in a way to act in concert while remaining separate and distinct at some level so they do not fully blend or dissolve into one another [10, 11].

If the weight of the compound, in any structural application, is taken into account rather than its strength and rigidity, it is the polymeric materials woven with fibers that take the first place as a compound with good properties. Polymer madly materials are light weighted materials and they are not very strong materials in their pure form, fiber woven mats are added to enhance their mechanical properties and are called composite materials [12].

Reinforcement and matrix are essential components of any compound, they are insoluble in each other; It possesses better mechanical properties than individual entities. The matrix transfers the loads to the fibers while fiber is an essential component in carrying loads, epoxy composites are reinforced with "E-glass fibers" with a scientific, industrial, and commercial appearance that is clear to the attention. [13], epoxy resins belong to the group of thermosetting resins, "E-glass fibers" has been used as reinforcement in matrix epoxy compounds, in a wide range because its wettability, adhesion to the glass fiber slow, low density, dimensional stability, low shrinkage, corrosion resistance, and good strength, etc. due to their unique properties. These compounds have been widely used in [14-16].

Nomenclature & Symbols			
E	Young's Modulus	vm	Volume Fraction of Matrix
σ_{UTS}	Ultimate tensile strength	σ	Stress
$\sigma_{0.2\%}$	0.2% Proof Yield Stress	A	Area
UD	Unidirectional	ε	Strain
SEM	Scanning Electron Microscope	Hv	Vickers Hardness
3D	Three Dimensional	E-glass	Electrical-Glass (Low Electrical Conductivity)
vF	Volume Fraction	PMCs	Polymer Matric Composite
vc	Volume Fraction of Composite Material	FRP	Fiber-Reinforced Polymer
vf	Volume Fraction of Fibre		

Fiber-reinforced composite materials have been widely used in the industries of aerospace, defense, automobiles, marine, and aviation. Several factors affect the composite materials' reinforcements with fiber from them, type of fibers, the orientation of fibers, the ratio of matrix to fibers, physical links between the fibers and the matrix, and fibers diameter, etc. [17, 18].

Lamon, F, et. al., 2023; Evaluation is done on how the reinforcing design affects the tensile strength and fatigue behaviour of woven composites. E-glass/epoxy laminates with the woven layer at $[0^{\circ}/90^{\circ}]$ and $[\mp 45]$ were created using the stacking sequence unidirectional UD - woven - unidirectional UD. The same matrix and fibers were utilized for both plain and twill textiles. The results of the tensile test and the fatigue test showed that the best strength of the composite material with woven E-glass fiber/epoxy $[0^{\circ}/90^{\circ}]$ two layers unidirectional according to model calculations [19].

Mahboob, Z et. al., 2022; This study used flex fiber and glass fiber reinforcement by fatigue test under constant strain amplitude. Two glass epoxy crossly configurations $([0^{\circ}/90^{\circ}]_{3s}, [\pm 45^{\circ}]_{3s})$ are tested alongside four commonly studied flax/epoxy layups $([0^{\circ}]_{16}, [0^{\circ}/90^{\circ}]_{4s}, [\pm 45^{\circ}]_{4s})$. Quasi Isotropic $([0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ}]_{2s})$. The evaluation of several mechanical properties as (stiffness), elasticity, peak stress, and strength) are evaluated as potential indicators of progressive damage correlated with (SEM) observed microstructure cracking. The study showed that flax samples are better in fatigue endurance the glass samples because of the high elasticity of flax fibers. [20].

Liu, C, Wu, X, and Gao, X., 2021; This article presents experimental results comparing the tensile test and tensile fatigue characteristics of biaxial warp woven glass fiber composites $[0^{\circ}, 30^{\circ}, 45^{\circ}, 90^{\circ}]$ with those of 3D orthogonal woven composite. The stress-strain curves, S-N curve, and stiffness degradation curves were acquired using a tensile test and a tension-tension fatigue test. According to the findings, stress is highest in the woven glass fiber with $[0^{\circ}]$ [21].

Venkatesha et. al., 2020; This research investigates the effect of a multilayer stacking sequence of woven bamboo and E-glass fiber with epoxy resin composite under tensile test. (6 layers) of bamboo fiber and (7 layers) of "E-glass fibers", two types of samples were produced by hand lay-up technique with (0°, 90°) and (∓45°), and the maximum tensile strength was applied to the composite samples. Studies have shown that the best angle for fibers at (∓45°) [22].

Marín et al., 2019; In this research, the direction of the fibers and the number of layers constituting the composite material were studied, and the effect of mechanical properties such as tensile, compressive and shear on the composite material, in research two types of fibers were used, woven glass fiber and woven carbon fiber with epoxy resin with 40% weight fraction to form a composite material consisting of four layers of glass fiber and four layers of carbon fiber with fiber direction at (5°, 10°, 15°, 20°) and the results of the research showed that the best strength with fiber direction at (5°) [23].

Seshaiah & Reddy, 2018; This study demonstrates the effect of the stacking sequence lay-up configuration on the tension, compression, and bending of glass fiber-reinforced epoxy composites. The following laminates were produced by hand lay-up technique with vacuum assistance for this study (0°)s, (90°)s (0°/90°)s and randomly oriented (45°/45°)s with fiber volume fraction (Vf=56.7%). The results showed that the best strength is with (0°) [24].

Al-Alkawi et al., 2012; This research is conducted to study the effect of E-glass fiber mat on mechanical behaviour (tensile test) of composite which is made up of E-glass fiber/ polyester (woven and chopped strand mat) as a laminate with a fixed fiber volume fraction of (33%). The results showed that the laminate reinforced of "E-glass fibers woven" (0°/90°, ∓45°, 0°/90°) and (0°/90°)4 where laminate made up of E-glass fiber (0°/90°, ∓45°, 0°/90°) have lower ultimate tensile strength than the laminates reinforced with E-glass fiber (0°/90°)4, the tensile strength the best laminate was (0°/90°)4 [25].

Khelifa and Al-Shukri, 2008; Study the experimental and theoretical mechanical behaviour of composite materials manufactured by stacking sequence (4 layers) of E-glass fiber in different angle directions (0°, +45°, –45°, 0°/90°) and four layers of (0°/90°) immersed in polyester resin with total thickness 4mm. the test under two types of load (tension and compression load) and the results showed that the best strength was (0°/90°) [26].

The aim of the study, Study the effect of the direction of the glass fibers on the mechanical properties (tensile strength (σ_{UTS}), Young's modulus (E), 0.2% proof yield stress $(\sigma_{0.2\%})$, modulus of toughness, toughness, and hardness) of the samples of pure epoxy reinforced by woven "E-glass fibers" compared with pure epoxy (matrix).

2. Experimental Work

2.1. Material and method

The composite materials used in this work consist of a 16-layer woven mat made of (0°/90°) E-glass/epoxy with a 50% weight fraction. It is used in a variety of life applications, including automobiles, planes, and wind turbine blades. Table 1 lists the mechanical and physical properties of epoxy resin and Table 2 lists the chemical composition of E-glass fiber.

The mechanical and physical properties of epoxy resin shown in Table 3 are tested in the material engineering department/University of Technology. The result is compared with the standard results of epoxy resin shown in Table 1. It shows that there is a slight difference between the two.

Table 1. Mechanical and Physical Properties of Epoxy Resin [27]

Property	Unit	Value	Standard of Test
viscosity 25c	cps	200	ASTM 445
density kg/litre	Kg/litter	1.1	ASTM D4052
flexural strength	MPa	61	DIN 53452
E-modulus	GPa	1.8	DIN 53452
Tensile Strength	MPa	37	ISO 527

Table 2. Chemical Composition of E-glass fiber [27]

Sio_2	MgO	Al_20_3	CaO	B_2O_3	TiO_2	Na_2O	Fe_2O_3	K_2O	F_2	ZrO_2
52-56	0.4-4	12-15	21-23	4-6	0.2-0.5	0-1	0.2-0.4	Trace	0.2-0.7	0.2-0.5

Table 3. Mechanical and Physical Properties of Epoxy Resin

Property	Unit	Value	Standard of Test
viscosity 25c	cps	198	ASTM 445
density kg/litre	Kg/litter	1.15 ± 0.1	ASTM D4052
flexural strength	MPa	60	DIN 53452
E-modulus	GPa	1.65 ± 0.1	DIN 53452
Tensile Strength	MPa	33	ISO 527

2.2. Tensile Test

This test was carried out by (ASTM D-638) standardization (Fig. 1). The specimens were cut to (0˚,5˚,15˚,30˚,45˚) according to fiber direction with gauge length (50 mm) by a CNC water jet cutting machine (Fig. 2). The test was performed in the University Technology / the materials engineering department using (LARYEE UE 34 XX series tensile test machine), and the tensile specimen before and after testing in Fig. 3.

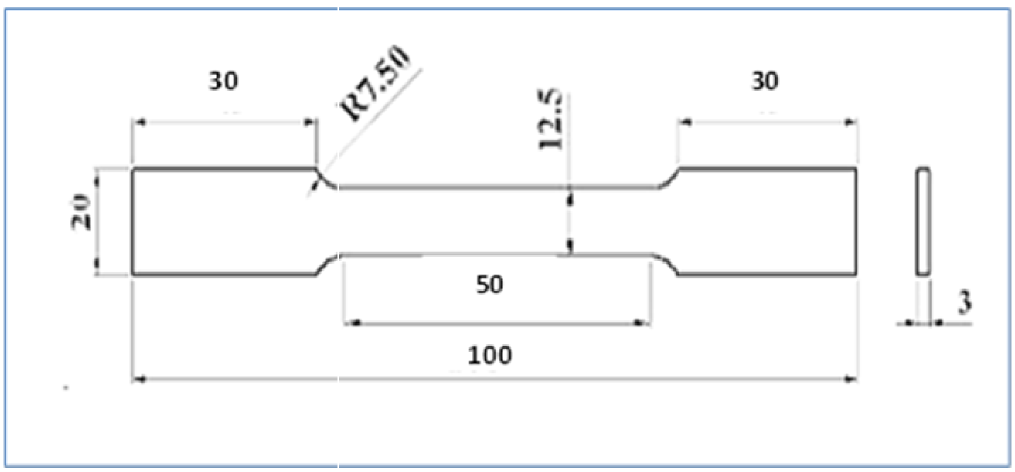

Fig. 1. Schematic of Tensile Specimen according to ASTM D-638 (All Dimension in mm)

Fig. 2. CNC Water Jet Cutting Machine (flow 45o CNC Water Jet Cutting Machine)

(a) Before Testing (b) After Testing

Fig. 3. Imaging of Tensile Test Specimen with Glass Fiber Direction (0˚,5˚,15˚,30˚,45˚)

The tensile test was performed as another static stress test, for three reasons:

- To determine ultimate tensile strength (UTS).
- To evaluate the interface strength.
- To investigate whether deboning would occur before failure or not.

2.3. Vickers Hardness Test s

The durometers type (Vickers hardness) like many other hardness measurements (ISO 6507/ASTM 384) measures the depth of an indentation in the sample durometer is an instrument for determining the strength of the material, most metals, polymers, and elastomers. The final Vickers hardness value is determined by the depth of the indenter after it has been added to the substance for (15 seconds). The test was performed using (UE/LARYEE) in the material engineering department/University of Technology, as shown in Fig. 4.

Fig. 4. Vickers Hardness Instrument (UE/Laryee)

This method involves indenting the test material with a diamond indenter in the shape of a pyramid with a square base and an angle of 136˚ between opposite faces as shown in Fig. 5. Normally, the full load is applied for 10 to 15 seconds. The advanced hardness device gives direct results.

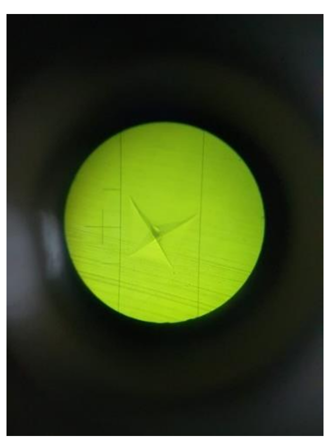

Fig. 5. Indenter image of Vickers Hardness

3. Results and Discussion

3.1. Hardness

Three samples of pure epoxy and composite material were examined and the average for each was calculated at (100 gr) or (1N) applied load and 15 sec dwell time. The hardness of composite material is 22.57 HV with an improved 220% relative to 10.3 HV for pure epoxy. The hardness is the resistance of the material to deformation, wear, and corrosion. The result showed that the hardness of composite material reinforced with woven fiber was higher when compared with pure epoxy.

3.2. Tensile Test

The tensile test is one of the most common mechanical tests; it is a destructive test that provides information about the material's tensile strength, 0.2% proof yield stress, ductility, and modulus of elasticity. The data of the test is recorded on a computer as applied load vs. elongation. Tensile tests can be represented by load-extension or stress-strain curves.

Fig. 6 illustrates the stress-strain curves of pure epoxy substance and all orientations of the composite material when the composite, material was cut by using a water jet cutting machine at angles (0˚,5˚,15˚,30˚,45˚) relative to the direction of the E-glass fibers. Three samples of pure epoxy substance were tested in tensile test and three samples of fiberglass for each of the above angles were tested in tensile test to determine the best fiber direction and high tensile strength resistance. These curves were drawn after taking the average readings of three test specimens for each fiberglass direction. The result showed high tensile strength with woven fiberglass (5˚).

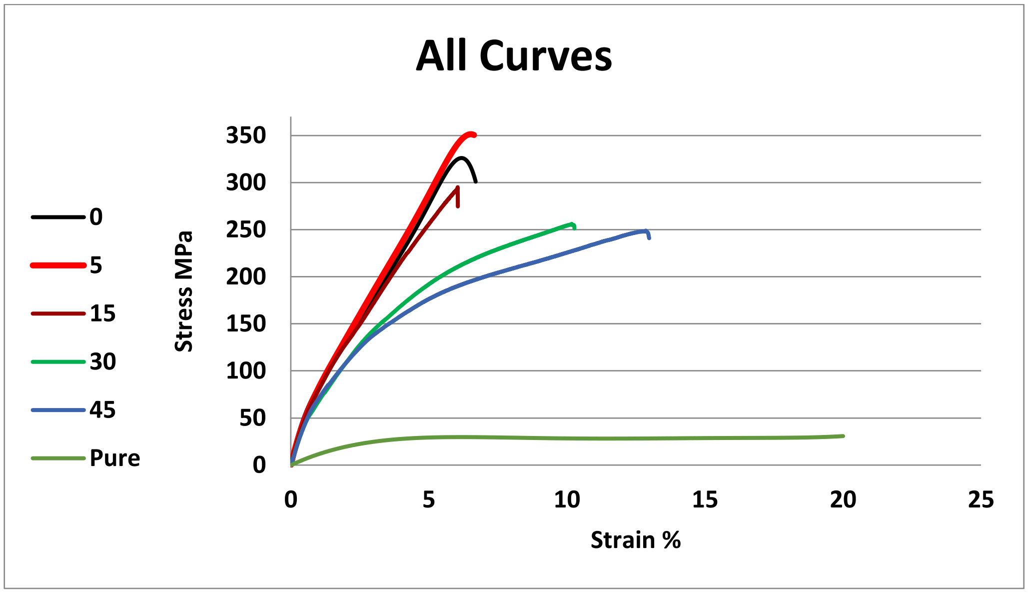

Fig. 6. Stress-Strain Curves of Composite Material and Pure Epoxy

The results listed in Table 4 are obtained and calculated from the experimental stress-strain and load-elongation curves. Pure epoxy (matrix) has the lowest value in Tensile strength **(σ_{UTS})**, Young's modulus **(E)**, 0.2% proof yield stress **($\sigma_{0.2\%}$)**, and Modulus of toughness and Toughness. they are low values and coefficients when compared with the as it is composite materials at (0°) as a result of adding 16-layers of "E-glass fibers". Significantly, as for the composite material, the angle of the fibers (5°) has the highest results because the strength comes from the stability of bearing the main loads during the test, and the high bonding between the fibers and the matrix at this degree especially when the fibers are in shape woven, at this slight angle deviation in the direction of the applied load. It plays a major role in bearing loads and absorbing energy. The effect is a simple deflection of the fibers with (5˚). It is suitable for absorbing tensile loads and force applied to the composite material, and the angle of the fiber with (5˚) in the tensile test. It worked to dispersions the shear stress within the multiple plates of the composite material, therefore the slight deviation in the angle of the fibers contributed significantly to reducing the intensity of the tensile stress applied on the composite material more than other angles with (0˚, 15˚, 30˚, 45˚). It leads to an increase in the strength of the composite material at this angle, in woven mat the fiber rovings are interlaced in two mutually orthogonal directions to one another which promotes the strength composite and the distribution of loads in two directions. The result agrees with the reference [23].

Table 2. Tensile Test Parameters

Matrix & Composites	Tensile Strength (MPa)	Young's Modulus (MPa)	0.2% Proof Yield Stress (MPa)	Modulus of Toughness (MN.m/m^3)	Toughness (N.m)
Comp. 0°	324	11126	70	1171.82	20.22
Comp. 5°	353	11940	74	1393.22	25.70
Comp. 15°	295	10506	69	1053.13	18.83
Comp. 30°	256	8463	67	1798.41	32.91
Comp. 45°	249	7838	66	2297.47	42.04
Epoxy	30	1178	18	532.61	12.25

From Table 5 the addition of 16 layers of fibers with a 50% weight fraction to the pure epoxy led to increasing the tensile strength by 10.8 times with fiber direction at (0˚). This indicated that the cutting angle relative to the direction of the fibers was proportional to the applied load and had played a key role in bearing the applied stress when the angle of the fibers was in the direction of the applied load. It absorbed energy and increased the strength of a composite material.

The maximum increase was reached at (5°) by 11.8 times relative to pure epoxy. The effect of the cutting angle relative to the direction of the fibers on tensile strength is presented in (Fig. 7). It appears to decrease after (5°) but almost increases (9.8, 8.5, and 8.3) times at (15°, 30°, 45°) respectively to the matrix (pure epoxy). Between (0° to 5°) an increase in strength comes from stability to carry more than 99% of the major loads during a test, while the decrease in tensile strength values was shown in Table 4 fiber angle with (15°, 30°, 45°) because increase the lateral component of the applied load on the fibers and decrease the bonded between fibers and matrix from (353 MPa to 249 MPa).

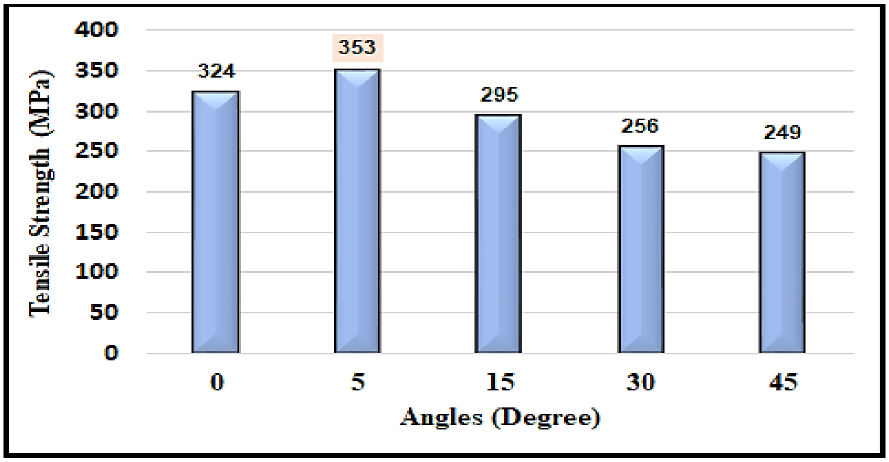

Fig. 7. Ultimate Tensile Strength at variable cutting angles relative to the direction of the fibers

The previous behaviour will repeat in 0.2 proof yield stress, modulus of elasticity (Young's modulus), and toughness as shown in Figs. 8 and 9, and Table 4.

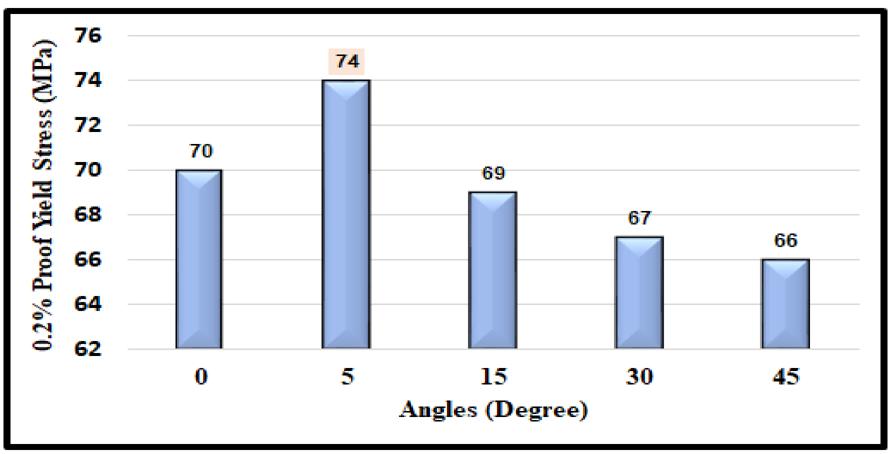

Fig. 8. 0.2% Proof yield stress at variable cutting angles relative to the direction of the fibers

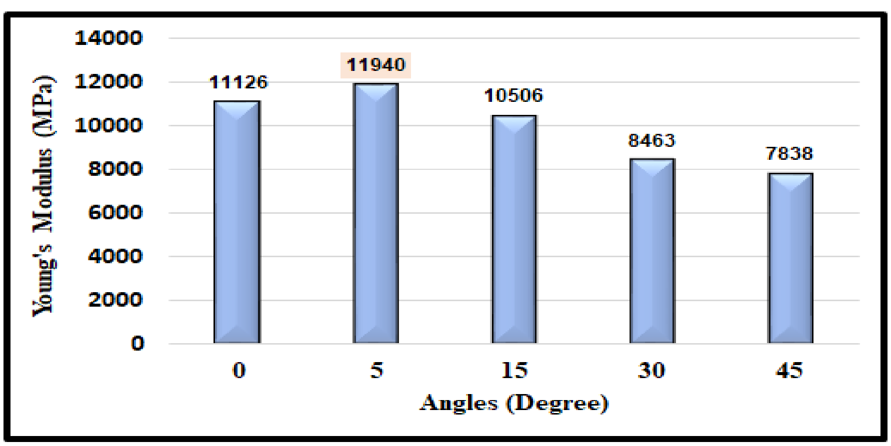

Fig. 9. Young's Modulus at variable cutting angles relative to the direction of the fibers

Table 3. Improvement Times in Tensile Test Parameters

Matrix & Composites	Tensile Strength		02% Proof Yield Stress		Modulus of Elasticity		Toughness		Modulus of Toughness	
	(MPa)	Times	(MPa)	Times	(MPa)	Times	(N.m)	Times	(mn.m/m)	Times
Comp. 0°	324	10.80	70	3.89	11126	9.44	20.22	1.65	1171.82	2.2
Comp. 5°	353	11.77	74	4.11	11940	10.13	25.70	2.09	1393.22	2.61
Comp. 15°	295	9.83	69	3.83	10506	8.92	18.83	1.53	1053.13	1.97
Comp. 30°	256	8.53	67	3.72	8463	7.18	32.91	2.68	1798.41	3.37
Comp. 45°	249	8.30	66	3.67	7838	6.65	42.04	3.43	2297.47	4.31
Epoxy	30		18		1178		12.25		532.61	

The toughness is the ability of the material to absorb energy. The behaviour of toughness and their modules for composites have acceptable results compared to the matrix (epoxy) with an improvement range (1.65 to 3.43) but have not the same tendency of previous parameters as a result of failure strain (extension) that varied as shown in Fig. 10, so the same tendency in failure strain appears in toughness as shown in Fig. 11 and modulus of toughness as shown in Fig. 12.

The modulus of toughness and toughness of cutting angles (0°, 5°, 15°) has good and gradual results according to the angles of the fibers. So, toughness and their modulus of angle (30°, 45°) are higher than the other angles.

Higher toughness is indicated at (30°, 45°) because the composite material behaves like a ductile material and the direction of the fibers is far from the direction of the applied load. The matrix behaviour overcomes fiber behaviour, the matrix worked to absorb the applied load more than the fibers which lead to significant elongation of the material. The results are acceptable, good, and well-proportioned relative to the direction of the fibers of load applied. This is related to the composite material that has behaved like a brittle material, and the fiber's direction is in the direction of the applied load. The behaviour of the fibers overcomes the behaviour of the matrix and the fibers absorbed more energy from the matrix. This agrees with references [28, 29].

Table 6 showed the result of the tensile test of a composite material consisting of four layers of woven E-glass fiber and four layers of woven carbon fiber/epoxy matrix with 40% weight fraction with fiber direction at ($5^\circ, 10^\circ, 15^\circ, 20^\circ$) where the highest strength with fiber direction (5°) [23].

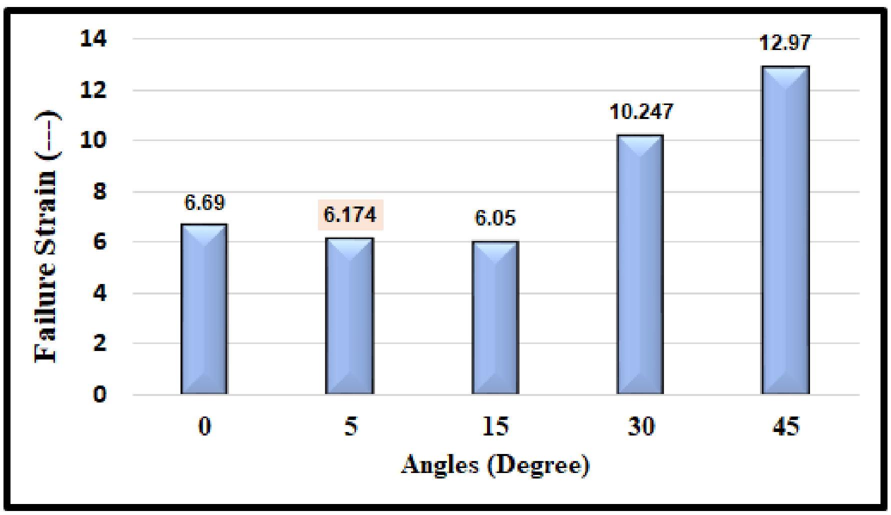

Fig. 10. Failure strain at variable cutting angles relative to the direction of the fibers

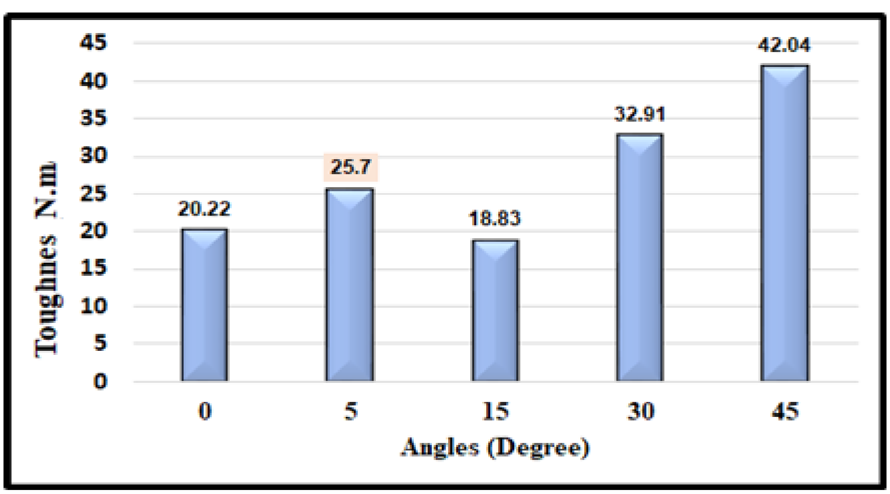

Fig. 11. Toughness at variable cutting angles relative to the direction of the fibers

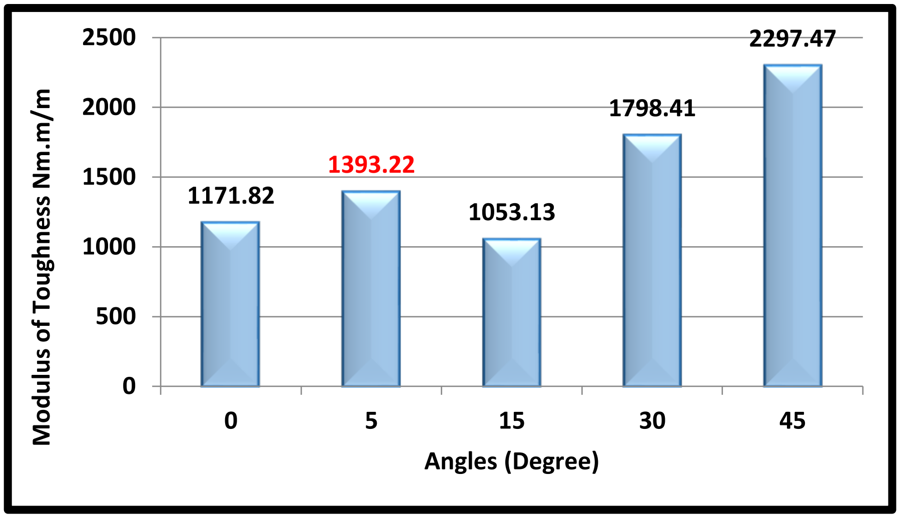

Fig. 12. Modulus of Toughness at Variable Cutting Angles Relative to the Direction of the Fibers

Table 4. Tensile Test Parameters [23]

Matrix & Composites	Tensile Strength (MPa)	Young's Modulus (MPa)
Comp. 5°	279	9681
Comp. 10°	264	9572
Comp. 15°	241	7210
Comp. 20°	218	6315

From Tables 4 and 6 the composite material with woven E-glass fiber with (5°) was the highest tensile strength when compared with other fiber angles ($0^{\circ}, 15^{\circ}, 30^{\circ}, 45^{\circ}$) and improvement (1.26 times) when compared with other previous studies of composite material with fiber angle ($5^{\circ}, 10^{\circ}, 15^{\circ}, 20^{\circ}$) [23].

4. Conclusion

The results show improvement in mechanical properties as (strength, Young's modulus (E), 0.2% proof Yield stress ($\sigma_{0.2\%}$), and hardness) of epoxy reinforced with 16 layers from woven E-glass with 50% weight fraction when compared with pure epoxy (matrix). the significant findings of this research are as follows.

- The improvement of strength for composite materials is (10.8, 11.8, 9.8, 8.5, 8.3 times) at angles (0˚, 5˚, 15˚, 30˚, 45˚) respectively when compared with pure epoxy (matrix).
- The improvement of modulus of elasticity (E) for composite materials is (9.44, 10.13, 8.92, 7.18, 6.65 times) at angles (0˚, 5˚, 15˚, 30˚, 45˚) respectively when compared with pure epoxy (matrix).
- The results showed that the hardness of the composite material improved (220%) relative to pure epoxy.
- The improvement of 0.2% proof yield stress ($\sigma_{0.2\%}$) for composite materials is (3.89, 4.11, 3.83, 3.72, 3.67 times) at angles (0˚, 5˚, 15˚, 30˚, 45˚) respectively when compared with pure epoxy (matrix).
- Increased major load bearing ratio by more than (99%) when fiber direction between (0° to 5°) of composite material.
- The behaviour of toughness and their modules for composite material has acceptable results compared to the pure epoxy (matrix) with an improvement range (1.65 to 3.43 times).
- The toughness indicated at (30°, 45°) is higher from other angles because the composite behaves like a ductile material, and the direction of the fibers is from the direction of the applied load.

Acknowledgment

The authors thank the Engineering Technical College, the University of Technology, Governmental institution, and everyone who contributed to the completion of this research.

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