Engineering and Technology Journal 43 (12) (2025) 1084-1095

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Investigations of flexural and impact properties of bio-epoxy-based composites for bone plate application

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HIGHLIGHTS

- Hybrid fracture fixation composites were fabricated using the hand lay-up technique.
- The type of reinforcement significantly affects the composite's mechanical properties.
- Increasing fiber layers improved strength, toughness, shear stress, and surface smoothness.
- These composites show strong potential as future bone implant materials.

Keywords:
Bio-composite
Bone plate
Bio epoxy
Flexural strength
Impact strength
Flexural modulus

ABSTRACT

Bone plates are necessary for bone fracture healing since they adapt the bio-mechanical micro-environment at the fracture location to provide the essential mechanical fixation for the fracture fragments. This research concentrates on decreasing the influence of stress shielding that takes place owing to an incompatibility between the metallic plate and the cortical bone by using a composite material based on biopolymer bio-epoxy thermosetting material reinforced by natural pumpkin powder at a fixed weight fraction (2 wt.%) for all lamination sample in addition to fiber reinforcement which involves different layers of flax woven fabrics mainly in addition to woven Carbon fibers, woven Glass fibers, as laminates which prepared by hand layup technique. Thus, the prepared specimens were exposed to the flexural max shear stress, impact, and surface roughness tests. The results manifested an improvement in composite properties (the flexural strength, flexural modulus, impact strength, fracture toughness, max: shear stress, and surface roughness) by the addition of flax fibers. Also, hybrid laminate bio-composites with natural and synthetic reinforcement recorded the best results among other composites. Also, the (2% pumpkin powder + 4-layer flax/2 layers Carbon fiber) biocomposites have the best result in terms of flexural strength, flexural modulus, and maximum. Shear stress and impact strength values rise from (62.5 MPa), (2.1 GPa), (4.37 MPa), and (5.6 KJ/m^2) to reach (210 MPa), (5.27 GPa), (12.18 MPa), and (94.37 KJ/m2), respectively. The SPSS program was also used to analyze the results of this study statistically. According to the current study, Laminate fiber-reinforced composites are the materials most recently probed as possible candidates for internal fracture fixation implants by placing different woven fabric reinforcements.

1. Introduction

When a human bone sustains a fracture, internal fixation devices, such as bone plates, are applied at the site of the fracture to stabilize and support the structural integrity of the bone. Characteristically, the interior fixation is conducted by open surgery employing wires, plates, and screws [1]. Different substances can be utilized as bone plates, including ceramics, polymer-based composites, and metals. Metallic materials, like pure titanium (Ti) and its alloys, stainless steel (SS) alloys, and cobalt (Co) alloys, are too broadly utilized as internal fixation for lengthy bone fractures due to their exceptional mechanical properties. Nevertheless, such apparatuses are not appropriate for application as the plates of interior fixation in the skin for lengthy periods owing to the many restrictions. the big discrepancy in the elasticity between the bone and the metals causes the outcomes of stress shielding in plate loosening, osteoporosis, osteopenia, and postponement of the period of healing; in addition to that, the metallic plates of bone are mismatched with living tissue, bio-active, magnates influence, lower fabric ability, and elevated price. Though ceramics, like ZrO_2 and Al_2O_3, have been regarded as inert, the elevated level of hardness, brittleness, and elevated modulus of elasticity resulted in the influence of stress shield, creating its inappropriate application as plates of bone [2]. Polymer-based composites, which have reduced stiffness for bone plate fixations, can be used as an alternative to metal materials to solve these problems. Today, many classes of polymers are utilized in all fields of medicine. The selection of a polymer is primarily based on its engineering properties like elasticity, tensile strength, stiffness, and other related properties, like toxicity

http://doi.org/10.30684/etj.2025.159004.1936
Received 10 April 2025; Received in revised form 03 June 2025; Accepted 19 June 2025; Available online 22 September 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

and bio-compatibility. The polymer-based materials, like poly (ether ether ketone) (PEEK), poly (glycolic acid) (PGA), poly (lactic acid) (PLA), and poly (hydroxyl butyrate) (PHB), are used for orthopedic uses. Also, the core problems connected with the polymer's usage are insufficient tribological wear and other mechanical properties [3]. To improve the polymers' tribological response and mechanical properties, reinforcements of fibers and fillers are integrated into the polymer. Researchers are exploring polymer-based composites for bone implants, experimenting with various fibers to enhance their strength, including unidirectional lamina, natural fibers, short fibers, discontinuous fibers, and plaited fibers [4]. Nevertheless, their achievement relies upon the fibers, matrix, and biocompatibility. Furthermore, regarding matrix, epoxy is the most widely used polymer in dentistry and orthopedics [3]. Moreover, epoxy resins possess brilliant chemical and mechanical properties that support them as a substitute for other materials, like ceramics and metals. Performance epoxy can be enhanced via the filler materials supplement, like pumpkin powder, which strengthens the construction [5].

Pumpkins are a plant commonly obtained worldwide and can be employed to strengthen the polymer matrix. Always use plant fibers containing cellulose, lignin, and hemicellulose for coloring. Plants are lightweight with elevated strength, are ecologically friendly, and are cheap. Also, all such characteristics create a selection to improve the epoxy properties [6]. Numerous investigators have altered the epoxy properties by supplementing various natural and synthetic fibers to reach good properties for the final composite to be used in a specific application. Qahtan Adnan and Mayyadah S. Abed utilized the pumpkin and thyme nanoparticles leaf with the weight ratios of (0, 0.5, 1, 1.5, and 2%) for increasing the epoxy's compressive strength and impact [7]. Also, epoxy properties can be improved using natural and synthetic fibers, such as woven fabric reinforcement, as a laminate. Natural fibers (NFs) such as Flax were presented as substitutes for inorganic ones in plastic since they've virtuous biochemical and mechanical properties, are non-hazardous, possess low density, come from renewable resources that are sustainable and eco-friendly, and are biodegradable, are resistant to moisture [8]. Synthetic fibers like carbon fiber have high impact resistance, toughness, and tensile strength. The fibers are also lightweight, corrosion-resistant, and wear-resistant [9].

In a study by all researchers below, they used epoxy as a matrix reinforced by different fibers or particles. They studied the Effect of different reinforcements on the mechanical properties of the final composite. Bagheri et al. [10], and Kureemun et al. [11], tested the hybrid composite's mechanical properties prepared from Carbon Fiber/Flax/Epoxy (Sandwich construction). They studied it for orthopedic implants as a substitute for metallic and alloy plates. The outcomes evinced elevated mechanical properties in bending compared to the sandwich construction influence. Solehuddin et al. [12], prepared a Compression Plate (LCP) for curing the tibia fracture by using cold pressed, which comprises bamboo as well as glass fiber hybrid laminas and they found that new material of plate was (66%) nearer to the cortical bone; therefore, the phenomenon of stress shielding can be reduced, and the “stress-shielding”; decreased, so enhanced the procedure of the bone healing of tibia fracture. Soundhar and Jayakrishna [13], synthesized the composites strengthened by the nanoparticles of CTS for bone plate uses. It was obtained that supplementing the CTS enhanced the strengths, making it appropriate for orthopedic uses. Virupaksha et al. and Hashim [2,14], studied composite's mechanical properties (compression, tensile, compact tension, and bending), where Virupaksha et al. reinforced with (Kenaf/Hemp) as reinforcement materials, considering Al_2O_3 as filler material. They found that the mechanical properties will be increased with an increasing proportion of fiber in composites. The properties of the prepared composite will match the femur Bone, and it is appropriate for orthopedic implants. Kabiri et al. [15], developed glass fiber and polypropylene composites reinforced with three types of fibers for fixation plates. They investigated how factors such as glass type, fiber orientation, and production method affected the mechanical properties of the plates. Their findings indicated that the strength and stiffness of the plates are suitable for use as bone implants in fracture repair.

In a previous study, researchers created metal fixing plates from titanium and cobalt-chromium alloy, causing the load to shift from bone to plate due to differing stiffness. They later experimented with magnesium for the bone plate, but issues with breakdown products remained unresolved. In a recent study, researchers employed thermoplastic polymers like Polylactic acid and ultra-high molecular weight polyethylene to manufacture fixing plates because they rated degradation and biocompatibility; however, they had trouble with the manufacturing process. We aimed to create new bone plate fixation which combine advantages of metals and biocompatibility properties based on new polymer matrix material (bio epoxy) that is widely used in medical applications and study the effect of different reinforcements, like particles (pumpkin) and fibers (flax, carbon and glass) on the material's properties, including modulus, flexural strength, maximum shear stress, and impact strength. The bone plate could fix fractures, facilitate fracture healing, and exist inside the body.

2. Experimental part

2.1 Materials

Used materials in the plate fixation of femoral bone for the study are liquid bio-epoxy resins with Equivalent Weight (182 – 192) (g/eq), density (1.16) (g/cm^3), from the (Dow Chemical Company/China) as matrix materials which supplies as resin powder and a liquid hardener, pumpkin powder (with an average particle size of 1.5 Mm) as a material for strengthening. The powder substances were weighed using a (2%) weight fraction. In addition to reinforcement using flax fibers spun into a mat produced by Changzhou Doris Textil Co., Ltd., carbon fiber (arranged in a unidirectional alignment for full-length reinforcement) and glass fiber (synthesized by Otto Bock Corporation) were also used, as shown in Figure 1 (a-c). The reinforcement fibers (flax, carbon, glass) used in this study have the tensile strength of (300-1500 MPa), (2900 MPa), (2000 MPa), young modulus of (24-80 GPa), (525 GPa), (80 GPa), density (1.28-1. g/cm^3), (1.85 g/cm^3), (2.58 g/cm^3) respectively [16,17].

(a) **(b)** **(c)**

Figure 1: Materials used in the present study are a) Flax woven fabric, b) Glass woven fabric, and c) Carbon woven fabric

2.2 Preparation of pumpkin powder

Pumpkin was first bought from the local market and then washed and peeled into thin slices. The pumpkin peel and the vegetable waste will be cleaned manually twice or thrice. These were dried for 8 days to free the moisture present and then dried in the furnace for three hours at 70 °C, then milled in a mill for thirty minutes, dehydrated, and milled once more. Moreover, such a procedure was repeated (3) times to achieve the optimal fine powder [18]. Then, they will be ground to a powder of 1.5 microns, as shown in Figure 2.

Figure 2: Steps to prepare pumpkin powder

2.3 Preparation of fibers

All woven mat Fibers (flax, carbon, glass) used in this research were cut according to the dimensions of the mold, 25×25 cm, using Special scissors for cutting fibers after computing the dimensions using a digital Vernier.

2.4 Silane treatment (ST) of NFs (flax)

Natural plant fibers, made of lignin, cellulose, and hemicellulose, do not bond well with hydrophobic plastics. To enhance this bond and improve product quality, modifying the fibers through physical or chemical methods is essential. The common method for this modification is the ST [19]. Before the ST, the flax fibers were cleansed with deionized water many times to remove the contamination from the surface. Then, ST was conducted via fibers soaking into the Silane solution with concentrations (Silane weight compared to fiber weight) of 3% (w/w). Moreover, the Silane solution was ready via diluting triethoxyvinylsilane into the water and ethanol mix with an (80/20) w/w ratio and hydrolyzed for three hours. We adjusted the mixture's pH to 4-5 with acetic acid before adding Silanes. Flax fibers were soaked in the Silane solution at 0.03 grams per milliliter for three hours, then rinsed with distilled water to remove unreacted Silane. Lastly, these fibers were naturally dehydrated for 72 hours in the furnace at 50 °C for thirty minutes before making the composite. The triethoxyvinylsilane solution was provided via the Co. of Sigma-Aldrich Chemicals, Ltd [20].

2.5 Fabrication of laminate composites

The following procedures were utilized to perform composite all bio laminations

1) The mold, made of glass with a flat and smooth surface and dimensions of 25 cm x 25 cm x 0.4cm, is prepared.
2) A layer of nylon (nylon thermal paper) was used to cover the inner face of the mold to ensure no resin adhered to it.
3) A digital balance was used to measure the amount of resin, hardener, and the mass of the prepared powder for the fabrication composite samples according to the specified weight fractions (2%).
4) The hand layup technique is used to fabricate laminated composite material.
5) Mix the matrix resin with prepared natural powder (pumpkin powder) with a weight fraction of 2% and mix them well before adding hardener to avoid powder agglomeration with the resin. Then, a hardener was added, taking the matrix resin and hardener mixing ratio of 100: 43.
6) After that, the combination thin layer was poured gradually into the molds and distributed manually across the entire mold area. Then, the first layer of fibers was put in, the matrix material was poured, and the fibers were distributed manually. The second layer of fibers was put in, the matrix material was poured, and the fibers were distributed manually until the mandatory number of layers was reached according to the required laminate. Moreover, such a process was conducted on all laminations.
7) The laminates are left for 48 hours to become ready, and then they are cut by a water jet machine for precise cutting to the required dimensions to obtain specimens for experimental tests. Table 1 shows the prepared laminated composite material

in this research, taking into account that a standard (reference) specimen consists of bio-epoxy with (2%wt.) pumpkin powder.

Table 1: Type of laminated composite material

Lamination No.	Total layers No.	Symbol of the layer	Processes of lamination layup
Laminate 1	Bio epoxy + pumpkin powder+ flax fibers	2% P+1 Flax (1F)	
Laminate 2		2% P+2 Flax (2F)	
Laminate 3		2% P+3 Flax (3F)	
Laminate 4		2% P+4 Flax (4F)	
Laminate 5	Bio epoxy + pumpkin powder+ flax fibers+ Carbon fiber	2% P+4 flax (4F) + 1 Carbon (1C)	2F+ 1C+ 2F
Laminate 6		2% P+4 flax (4F) + 2 Carbon (2C)	2F+ 2C+ 2F
Laminate 7	Bio epoxy + pumpkin powder + flax fibers+ Glass fiber	2% P+4 flax (4F) + 1 Glass (1G)	2F+ 1G+ 2F
Laminate 8		2% P+4 flax (4F) + 2 Glass (2G)	2F+ 2G+ 2F

3. Tests

3.1 Flexural test

The flexural test can define the homogeneous stress distribution and the number of loads inside the interface. It can also forecast the materials' stiffness and resistance to break under the flexural load. The test was also performed according to the ASTM (D-790), and the samples have dimensions of (100 mm) length, (10 mm width), and thickness (4.8mm). In addition, the whole data was gathered employing a 3-point bending test machine at a (5 mm/min) crosshead speed (strain rate) and a (5KN) till the breakage of ample. The flexural test can be used to calculate the elastic flexural modulus and flexural strength for a rectangular cross-section from the following Equations (1-5) [21] :

$$\text{Flexural Strength } \sigma f = \frac{3PL}{2bd^2} \tag{1}$$

where, σf: The flexural strength, MPa, P: The bending load, N, L: The support span, mm [22].

$$\text{Flexural modulus } EF = \frac{L^3 P}{4bd^3 \delta} \tag{2}$$

where, EB: The flexural modulus, MPa, δ: The deflection of the beam, P: The load, N: The support span (mm), b: The width of the specimen (mm), d: The thickness of the specimen (mm) [23].

3.2 Test of maximum shear stress

The shear test follows ASTM D-2344, using the Leybold Harris No. 36110 hydraulic press [24]. It involves specimens measuring 35 mm x 10 mm x 5 mm. Maximum shear stress (τ max) is calculated using the equation [25]:

$$\tau \max = 0.75 \times \frac{p}{bd} \tag{3}$$

where, p: Rupture load (N), andτ max: Is the Maximum Shear Stress (MPa).

3.3 Impact strength

Izod impact is defined as the required kinetic energy to initiate and sustain a fracture until failure. We conducted the impact test as outlined in (ISO-180). The specimen, supported by a cantilever beam, broke after receiving an impact energy of 5.5 J at 3.5 m/s. We averaged the force measurements from five tests after the pendulum struck the specimen [26]. The specimens measured 80 mm in length, 10 mm in width, and 4.8 mm in thickness. The following equation is used to calculate the Impact strength [27]:

$$G_c = \frac{U_c}{A} \tag{4}$$

where, A: Cross-sectional area of the sample (m^2), Gc: Impact strength,(J/m^{2}), and Uc: Required energy for the sample's fracture (J). Fracture toughness indicates how well a cracked material resists breaking and can be determined through [28]:

$$K_c = EF.\sqrt{G_c} \tag{5}$$

where, E_F: The Flexural modulus of material (MPa), and K_c: The Fracture toughness of material ($MPa.m^{1/2}$)

3.4 Surface roughness

The surface texture characterization of laminate composites is a complex feature due to its heterogeneous Structure and the different stratified surface properties. Different reinforcement layer properties highly impact profile roughness parameters, and their distributions are relatively spread out. Moreover, we tested surface roughness with a TR 200 tester, which uses a sensor to measure the surface. The sensor's movements are converted into electrical signals, amplified, and digitized. Each sample was tested three times at different spots, and we used the average for our results [29, 30].

4. Results and discussion

4.1 Flexural test

Figure 3 shows the flexural strength of the laminates manufactured from bio-epoxy with 2% pumpkin powder and flax fibers, as well as the hybrid laminates to which layers of carbon fibers or glass fibers were added. The figure shows that the increase in the number of flax fiber layers enhances the flexural strength values. This improvement results from an increase in the percentage of fibers, which have a higher resistance to bending than the matrix [31]. Also, adding synthetic woven fabric (glass or carbon) to the woven flax fiber gives higher flexural strength values than those for samples with 1, 2, 3, or 4 layers of flax fibers. This is due to supplementing such kinds of fabricated fibers, which possess higher flexural properties and improve the mechanical properties [32,33]. Also, from the results, note that the hybrid laminates that contain carbon fibers have a higher strength than the rest of the other laminates that include glass fibers or that contain only flax fibers. This is because carbon fibers have a high ability to resist a load during the flexural test due to their high tensile strength, high Young's modulus, and high compression strength in the tensile and compression test where the flexural test causes compression force on the side on which the load is applied and a tensile force on the opposite side [34]. Also, the laminated samples reinforced with (4flax /2 carbon fibers) possess the highest flexural strength properties (210 MPa) compared to the standard specimen (bio epoxy 2% pumpkin powder) (62.5 MPa) [35].

Table 2 represents descriptive statistics for the flexural strength (Std. error, Std. deviation, Mean, Maximum, Minimum, and One-way ANOVA (p-value between groups)). At the same time, the statistical outcomes manifested that the highest value was determined with a sample strengthened via (2% wt pumpkin powder+4 flax+2C). In addition, the sets have revealed a too-elevated important discrepancy (VHS) ($p \leq 0.001$) in raising the no. of layers of flax fibers.

Figure 4 reveals flexural modulus values of bio-composite samples reinforced with flax fiber and hybrid composite with carbon or glass fibers for internal bone plates fixation. When pumpkin powder was added to bio-epoxy bio-composite materials, this helped bear the load exerted upon the bio-composite samples in a manner that matches their form, nature, and mechanical properties. In addition, the homogenous distribution of particles inside the bio epoxy matrix creates a strong bond and strengthens the material, as well as all the values of the flexural modulus improved in the bio-composite samples [36]. Increasing the number of flax layers raises the flexural modulus because the stiffer fibers can carry more load than the matrix, aligning with the reference [37]. The figure also shows an improvement in flexural modulus in the hybrid laminates when adding glass fibers or carbon fibers compared with the laminates consisting of flax fibers alone. The improvement when adding carbon fibers was better when compared with laminates that contain glass fibers or laminates manufactured from woven flax alone. The reason behind it was the ability of carbon fibers to withstand bending, which is higher than that of glass and flax fibers [38]. The best class in this examination was (4F+2C) lamination with a flexural modulus reached (5.2 GPa). Compared with a metal plate, the hybrid bio-composite bone plate fixation can considerably reduce stress shielding to such results [39]. The proposed composite fixation plates are ideal for orthopedic use due to their stiffness, which promotes inter-fragmentary strains during healing, thereby accelerating recovery [1]. Their flexibility enables better fitting with unstable or multi-fractured bones [40].

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Table 3 clarifies the flexural modulus outcomes statistically, into which the descriptive statistics (Std. error, Std. deviation, Mean, Maximum, Minimum, and One-way ANOVA (p-value between groups)) were characterized. The data indicates that the average values for all samples exceed those of the standard sample (Bio epoxy+2 % pumpkin powder), and the sample reinforced by (2% wt pumpkin powder+4 flax+2C) elucidated that the greatest value. Also, the groups portrayed a too elevated important discrepancy (VHS) ($p \leq 0.001$) in raising the no. of layers of flax fibers.

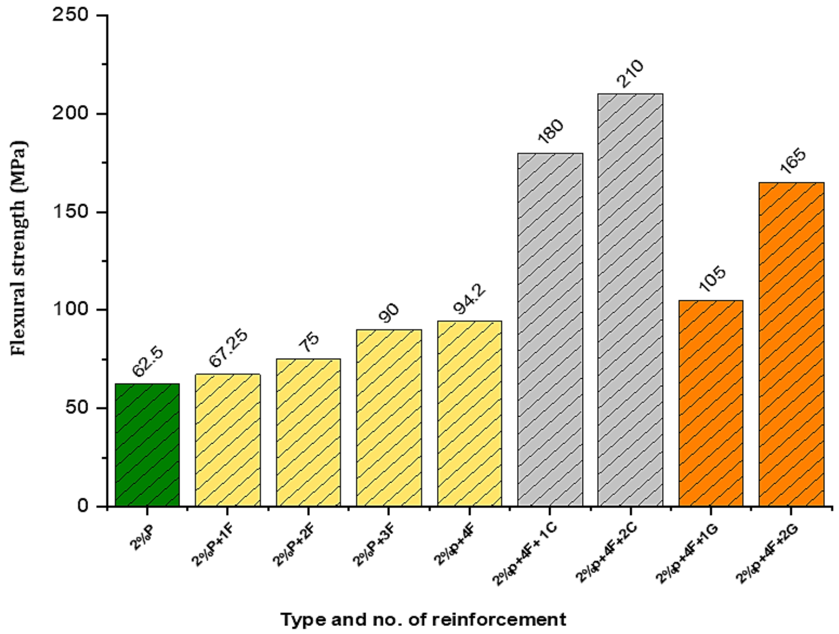
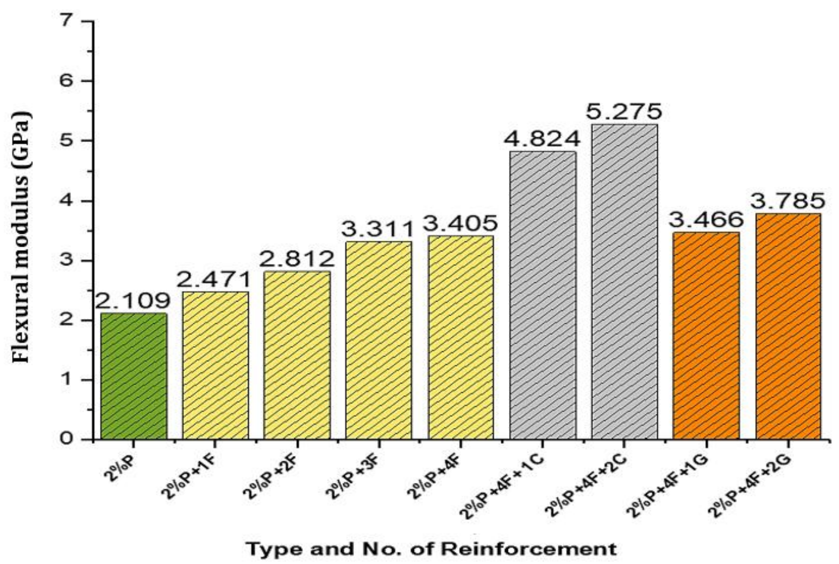


Figure 3: Flexural strength of composites and hybrid laminate composites with different layers of reinforcements

Table 2: One-way ANOVA (p-value between groups) and the descriptive statistics for the flexural modulus

Groups		N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	P values between groups
Flax	Bio epoxy+2%pumpkin powder	3	2.1093333	0.29500904	0.17032355	1.81000	2.40000	0.000 (VHS)
	1 Flax	3	2.4703333	0.23000072	0.13279098	2.24000	2.70000	
	2 Flax	3	2.8186667	0.19402148	0.11201835	2.61300	3.00100	
	3 Flax	3	3.3103333	0.20100083	0.11604788	3.10900	3.51100	
	4 Flax	3	3.4040000	0.30150124	0.17407182	3.10200	3.70500	
	4 Flax+1C	3	4.8240000	0.19354844	0.11174525	4.62300	5.01000	
	4Flax+2C	3	5.2710000	0.26850140	0.15501935	5.00300	5.54000	
	4 Flax +1G	3	3.4686667	0.21509378	0.12418445	3.24000	3.67000	
	4 Flax +2G	3	3.7800000	0.21554350	0.12444410	3.56200	3.99300	



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	3 Flax	3	3.3103333	0.20100083	0.11604788	3.10900	3.51100	
	4 Flax	3	3.4040000	0.30150124	0.17407182	3.10200	3.70500	
	4 Flax+1C	3	4.8240000	0.19354844	0.11174525	4.62300	5.01000	
	4Flax+2C	3	5.2710000	0.26850140	0.15501935	5.00300	5.54000	
	4 Flax +1G	3	3.4686667	0.21509378	0.12418445	3.24000	3.67000	
	4 Flax +2G	3	3.7800000	0.21554350	0.12444410	3.56200	3.99300	

4.2 Test of maximum shear stress

Figure 5 illustrates the association between the type and number of reinforcements used and maximum shear stress. It shows that shear stress rises with the addition of woven flax fiber to the composite. Also, the addition of synthetic fibers (glass or carbon) gives a higher result of maximum shear stress than those with only flax fiber, as well as a hybrid composite with carbon fiber performing better than glass fibers [41]. The highest maximum shear stress value was recorded (12.18 MPa) for the composite containing bioepoxy, 2% pumpkin powder, 4 woven flax fiber, and 2 woven carbon fiber. At the same time, the lowest value (4.3) was recorded for the (bioepoxy, 2% pumpkin powder) composite. Table 4 details the maximum shear stress statistics and indicates that specimens with 4 layers of flax and additional glass or carbon fibers have higher average shear stress compared to those with flax fiber alone.

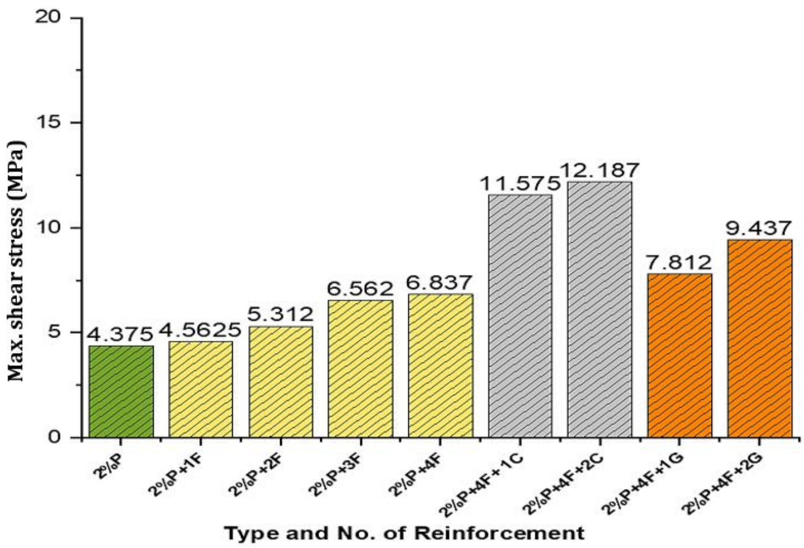

Figure 5: Max. shear stress of composites and hybrid laminate composites with different layers of reinforcements

Table 4: One-Way ANOVA (p-value between groups) and the descriptive statistics for the max. Shear stress

Groups		N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	P values between groups
Flax	Bio epoxy+2%pumpkin powder	3	4.37466667	0.197611572	0.114091094	4.120000	4.509000	0.000 (VHS)
	1 Flax	3	4.56200000	0.302986798	0.174929510	4.201000	4.803000	
	2 Flax	3	5.31200000	0.211000000	0.121820907	5.101000	5.523000	
	3 Flax	3	6.56233333	0.204407273	0.118014594	6.301000	6.704000	
	4 Flax	3	6.83233333	0.120068036	0.069321313	6.710000	6.950000	
	4 Flax+1C	3	11.57066667	0.307903123	0.177767951	11.203000	11.814000	
	4Flax+2C	3	12.18233333	0.250911007	0.144863537	11.900000	12.400000	
	4 Flax +1G	3	7.81400000	0.100239713	0.057873425	7.700000	7.900000	
	4 Flax +2G	3	9.43233333	0.300759594	0.173643633	9.100000	9.700000	

4.3 Impact test

Impact strength is how well a material stands up to a sudden shock or can withstand the stress applied at a very high speed. Figure 6 shows the impact strength values for the various composite specimen groups. The figure shows that the increase in the number of flax layers is directly proportional to the increase in the impact strength. The improvement was due to the increase in thickness after increasing the number of layers. The energy stored in a material increases, enhancing its impact strength and resistance to breaking. The addition of reinforcement layers helps prevent crack growth, consistent with reported findings [42, 43].

As for the hybrid laminates, it has been shown that adding carbon or glass fibers helps to increase impact strength, and adding carbon fibers shows better results than adding glass fibers to specimens reinforced by flax layers because of the high ability of carbon fibers to absorb energy and resist breakage when exposed to a high-speed load [44].In the case of hybrid laminates, adding carbon fiber layers with flax layers produced excellent results and had the highest impact strength of the other layers. The laminate (4F + 2C) exhibited the highest impact strength (94.37 KJ/m^2), significantly greater than all the other lamination. Table 5 represents the descriptive statistics (std. error, std. deviation, mean, maximum, minimum, and one-way ANOVA (p-value between groups)) for impact strength. The results showed that the sample (Bio epoxy+2% pumpkin powder) has a mean value lower than that of the other specimens. Moreover, the largest value was from the specimen (4Flax+2C), with all groups showing significant differences in reinforcing layers ($p \leq 0.001$).

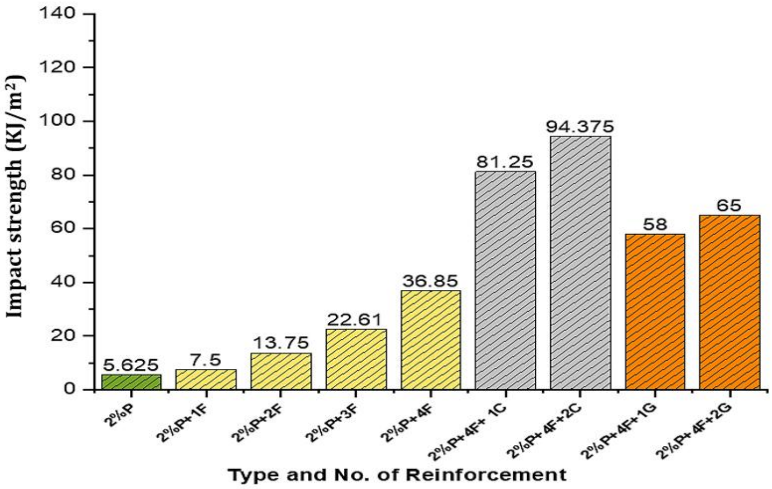

Figure 6: Impact strength of composites and hybrid laminate composites with different layers of reinforcements

Table 5: One-way ANOVA (p-value between groups) and the descriptive statistics for the impact strength

Groups		N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	P values between groups
Flax	Bio epoxy+2%pumpkin powder	3	5.6286667	.19457732	.11233927	5.42100	5.81000	0.000 (VHS)
	1 Flax	3	7.5233333	.08736895	.05044249	7.45000	7.62000	
	2 Flax	3	13.7600000	.23515952	.13576941	13.53000	14.00000	
	3 Flax	3	22.6133333	.30005555	.17323715	22.30000	22.90000	
	4 Flax	3	36.8566667	.91001831	.52539932	35.95000	37.77000	
	4 Flax+1C	3	81.2566667	.98764029	.57021438	80.14000	82.11000	
	4Flax+2C	3	94.3783333	.91529139	.52844373	93.42000	95.25000	
	4 Flax +1G	3	58.0000000	1.00000000	.57735027	57.00000	59.00000	
	4 Flax +2G	3	65.0000000	1.00000000	.57735027	64.00000	66.00000	

Figure 7 illustrates the association between the fracture toughness and the number of reinforcing layers of composite materials. As the layers increase, fracture toughness improves due to enhanced impact strength and flexural modulus provided by the additional layers [45]. Incorporating glass or carbon fibers into a bio-epoxy matrix enhances fracture toughness, with carbon fibers proving more effective than glass. Both types of fibers offer greater strength and durability than the base matrix, and they resist crack growth better than composites made with only natural fibers, resulting in stronger hybrid laminated composites [46]. Specimens with four layers of reinforcing flax fibers and two layers of carbon fibers showed the highest fracture toughness at 22.3 MPa.m$^{1/2}$, outperforming those with fewer layers. The carbon fiber increases the energy required to break the specimen, while the reinforcements slow crack growth, depending on the bond strength between the matrix and reinforcement. In contrast, the control specimen, made with bio epoxy and 2% pumpkin powder, had the lowest fracture toughness at 3.35 MPa.m$^{1/2}$.

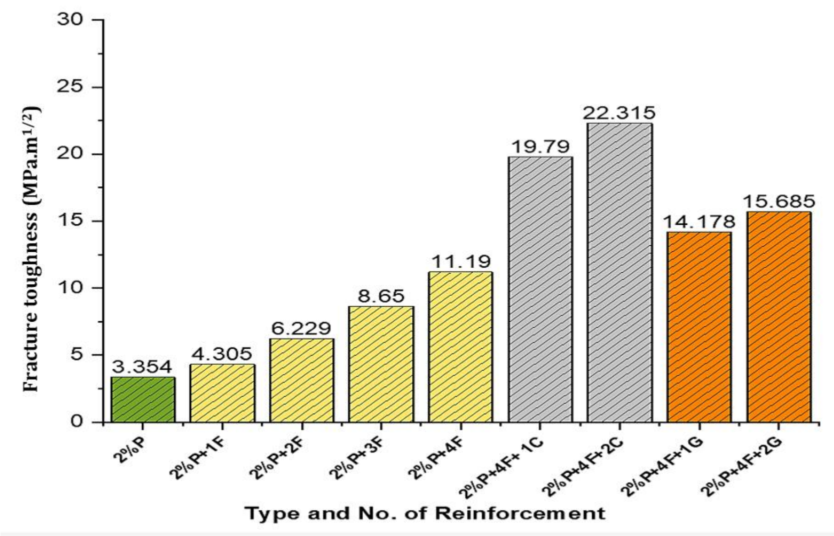

Figure 7: Fracture toughness of composites and hybrid laminate composites with different layers of reinforcements

Table 6 presents fracture toughness statistics, including mean, standard deviation, and one-way ANOVA (p-value). It shows that all sample averages exceed the standard sample (Bio epoxy + 2% pumpkin powder), with the highest value in the specimen reinforced with 2% wt: pumpkin powder, 4 flax fibers, and 2C. A very high important variance (VHS) ($p \leq 0.001$) is observed with more flax fiber layers.

Table 6: One-Way ANOVA (P-Value between Groups) and the Descriptive Statistics for The Fracture Toughness

Groups		N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	P values between groups
Flax	Bio epoxy+2%pumpkin powder	3	3.35133	.370520	.213920	2.950	3.690	0.000 (VHS)
	1 Flax	3	4.30500	.465000	.268468	3.840	4.770	
	2 Flax	3	6.22633	.470128	.271429	5.740	6.680	
	3 Flax	3	8.65000	.290000	.167432	8.360	8.940	
	4 Flax	3	11.19333	.134288	.077531	10.980	11.230	
	4 Flax+1C	3	19.79667	.257747	.148810	19.470	19.980	
	4Flax+2C	3	22.31500	.400094	.230994	21.900	22.700	
	4 Flax +1G	3	14.17600	.100240	.057873	14.090	14.290	
	4 Flax +2G	3	15.68500	.311087	.179606	15.330	15.950	

Figure 8 shows how the type and number of flax fiber layers in a bio-epoxy matrix affect surface roughness, which increases with more layers [47]. This is due to the fact that the test is focused on the exterior surface of specimens rather than the interior surface. Additionally, incorporating woven mats of glass and carbon fibers also raises surface roughness, because of their rough textures [48]. The highest surface roughness recorded was 1.971 µm in composites with four flax layers and two carbon layers. Table 7 provides surface roughness values, including mean, standard deviation, and ANOVA p-values. It shows that the mean surface roughness for samples with four flax layers plus glass or carbon is higher than that of samples with flax fiber alone.

Table 7: One-way ANOVA (P-Value between groups) and the descriptive statistics for the surface roughness

Groups		N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	P values between groups
Flax	Bio epoxy+2%pumpkin powder	3	0.46167	0.090046	0.051988	0.370	0.550	0.000 (VHS)
	1 Flax	3	0.52900	0.110123	0.063579	0.410	0.630	
	2 Flax	3	0.58200	0.082541	0.047655	0.495	0.660	
	3 Flax	3	0.63133	0.090002	0.051963	0.540	0.720	
	4 Flax	3	0.80133	0.099500	0.057447	0.702	0.901	
	4 Flax+1C	3	1.46020	0.190000	0.109697	1.270	1.650	
	4Flax+2C	3	1.77567	0.080052	0.046218	1.690	1.850	
	4 Flax +1G	3	1.09200	0.095974	0.055411	0.980	1.171	
	4 Flax +2G	3	1.28633	0.095002	0.054849	1.190	1.380	

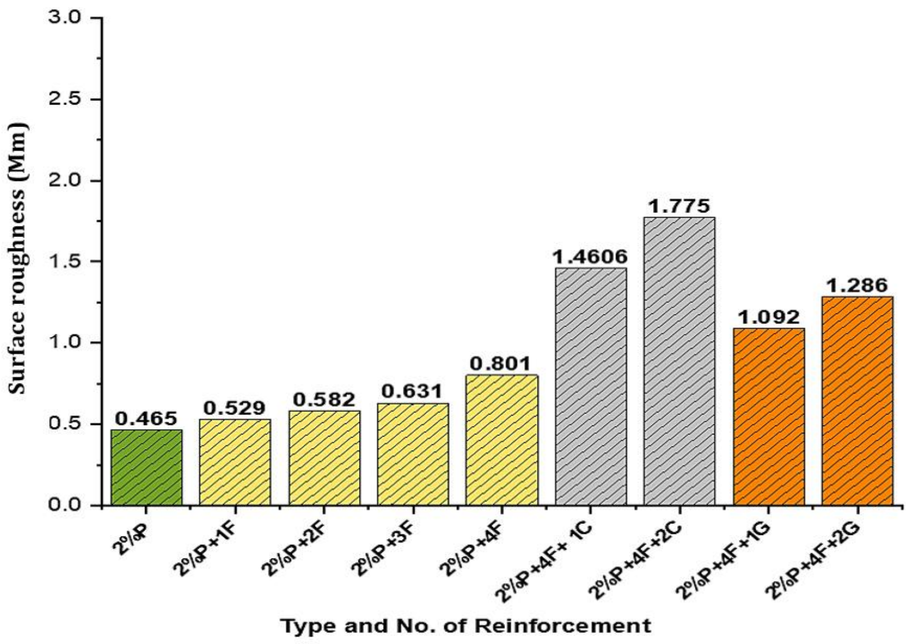

Figure 8: Surface roughness of composites and hybrid laminate composites with different layers of reinforcements

5. Conclusion

Varying the number and type of reinforcements had a significant impact on all lamination groups' characteristics. The optimum value of these characteristics is noticed in specimens of hybrid (natural and synthetic) fiber layers. Adding carbon fibers to the composite produced the best results in contrast to adding glass fibers, which had a small percentage of improvement. The (2% pumpkin powder+4F+2C) was the best laminate from all laminations with enhancement in flexural strength, maximum shear stress, flexural modulus, and impact strength (210 MPa), (12.18 MPa), (5.27 GPa), and (94.37 kJ/m²), respectively. Hybrid bio-composites possess high strength and impact resistance, which makes them ideal for tough conditions, as they incorporate pumpkin powder, flax fiber, and CF into bio-epoxy.

Author contributions

Conceptualization, **H. Fadhil, Q. Hamad** and **J. Oleiwi**; data curation, **H. Fadhil**; formal analysis, **H. Fadhil**; investigation, **H. Fadhil**; methodology, **H. Fadhil**; project administration, **Q. Hamad** and **J. Oleiwi**; resources, **Q. Hamad and J. Oleiwi**; software, **H. Fadhil**; supervision, **Q. Hamad** and **J. Oleiwi**; validation, **Q. Hamad** and **J. Oleiwi**; visualization, **Q. Hamad** and **J. Oleiwi**; writing—original draft preparation, **H. Fadhil**; writing—review and editing, **H. Fadhil, Q. Hamad** and **J. Oleiwi**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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