JJMIE

Volume 19, Number 4, Dec. 2025
ISSN 1995-6665
Pages 749– 761
https://doi.org/10.59038/jjmie/190405
Editor-in-Chief: Prof. Faris M. AL-Oqla

Jordan Journal of Mechanical and Industrial Engineering

Impact and Flexural Response of Hybrid Composite Consisting of Waste Flex Banner and Glass Fiber

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Received 16 April 2025 Accepted 8 September 2025

Abstract

The study assesses the mechanical performance of composites that contain a mixture of glass fiber (G) and waste flex banners (F) at different proportions and orientations relative to the polyester matrix testing. The mechanical properties of the composite were investigated through impact strength, flexural strength and elastic modulus testing of the samples, while researchers studied fiber composition and orientation effects. Sample C7 (0^0/flex/0^0/0^0/flex/0^0) represented the optimum impact strength outcome, where it achieved 19.2 J energy absorption and 0.406 J/mm² impact strength range because appropriate fiber alignment enhances material impact performance. C7 also produced the strong flexural strength of 431.199 MPa and elastic modulus of 21.638 GPa, establishing it as the premier composite for bending capacity. C10 (Polyester) sample demonstrates inferior flexural strength (81.99 MPa) together with the lowest elastic modulus (4.382 GPa) because using plain matrix material does not supply adequate structural integrity. Fiber type and its arrangement pattern control how well a composite material performs as a result of this research. The research enables quantitative assessments for optimal composite material designs that exhibit exceptional bending strength, stiffness, and impact tolerance. This significant increase confirms the potential of using flex banner waste as a reinforcement in environmentally friendly composite materials.

Keywords: Composite, flexural strength, modulus of elasticity, impact strength, glass fiber, polyester matrix, fiber orientation.

1. Introduction

Members of the composite family continue gaining popularity across aerospace and construction sectors and transportation applications because of their beneficial properties. Composite materials demonstrate useful properties because they achieve strong weight ratios at minimal densities. Low-density materials are particularly attractive for weight reduction in their applications[1,2], such as in the aerospace, automotive, and aviation industries [3–7]. Composite materials also exhibit high resistance to corrosion and wear, which can extend the lifespan of the products. Additionally, composites offer superior fatigue life and creep resistance, making them suitable for applications where durability is essential. However, composite materials have drawbacks[8–10]. Regarding the environmental aspect, these materials rely on non-renewable, fossil-fuel-derived resources. The production of the resins and fibers used in conventional composites often involves energy-intensive processes and the release of greenhouse gases. Furthermore, the disposal of composite materials at the end of their life cycle can pose significant challenges, as they are typically non-biodegradable and difficult to recycle[11,12].

In this modern era, practical and fast technology has been used in various fields, including the printing industry. Printing companies are now present in almost every city and village to meet the increasing needs of society. One of the printing media used is flex banners. The public usually uses these media for campaigns and promotion in several activities, such as student activities, business promotions, and politics. The principal compiler of flex banners is plastic, so recycling is challenging and will produce waste detrimental to the environment[13]. There is a need for a solution to process waste from flex banner waste, one of which is using it to make a composite material[14,15].

Plastic waste poses a significant environmental challenge due to its non-biodegradable nature and the large volumes generated globally annually[16–20]. However, recent research has demonstrated the potential for waste plastic to be studied as a valuable resource. Specifically, incorporating waste plastic as a partial replacement for

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traditional aggregates in composite materials has shown promising results regarding both environmental and engineering benefits[21]. Reusing flex banners is one method to reduce the potential for damage. One promising approach to addressing this issue is using waste plastic as a reinforcement in the material composite[14,15,22–25].

In pursuing sustainable and eco-friendly composite materials, incorporating waste materials as reinforcement has garnered significant attention[26–29]. Although extensive research has been conducted on glass fiber-based composites, studies on waste flex banners as reinforcing materials are still minimal. This is despite waste flex banners being a type of plastic that is difficult to decompose and their volume continues to increase. This research offers a novel contribution by combining waste flex banners and glass fibers in a polyester matrix, optimizing mechanical properties through a sustainable hybrid composite design.Hybridizing fiber reinforcements in polymer composites has offered synergistic enhancements in mechanical performance[30–34]. The experimental investigation will focus on assessing the impact and flexural properties of the developed composite. Impact testing will provide insights into the energy absorption capabilities of the material. In contrast, flexural testing will reveal its load-bearing and deformation characteristics. The research findings will contribute to understanding this innovative composite material's performance and potential applications.

2. Materials and Methods

2.1. Materials

The materials used in the study are a waste flex banner and fiberglass WR 800 as a reinforcement, shown in Figure 1. The matrix used is Yukulac Polyester BQTN EX-157, and a catalyst is added to the resin mixture to quicken the curing process. The mirror glaze is applied to prevent damage to the composite when released from the mold. Table 1 shows the density of the flex banner, glass fiber, polyester resin, and hardener.

The initial procedure for making a composite is determining the volume fraction of fiber. Prepared the reinforcement, flexbanners are cut in random sizes (Figure 1.b). After that,flex banners and glass fiber are weighed based on the weight following the prescribed volume fraction (30%, 40% and 50%). Another variation is a hybrid composite with the addition of different amounts of fiberglass (G/F/G/F/G/F/G, G/F/G/F/G/F/G/F/G, G/F/G/F/G/F/G/F/G/F/G). The influence of the orientation angle was also studied, where the glass fiber layer was modified in placement based on certain angles (00,450 and 900). All variations of stacking sequences are shown in Figure 2. Fiber and matrix mass calculation is done using a density equation. After that, the fiber is thoroughly combined with the resin and hardener, and the composite is molded using the hand layup technique. The composite needs time to cure in a day. The density and weight of the fiber and matrix are shown in Table 2 and Table 3.

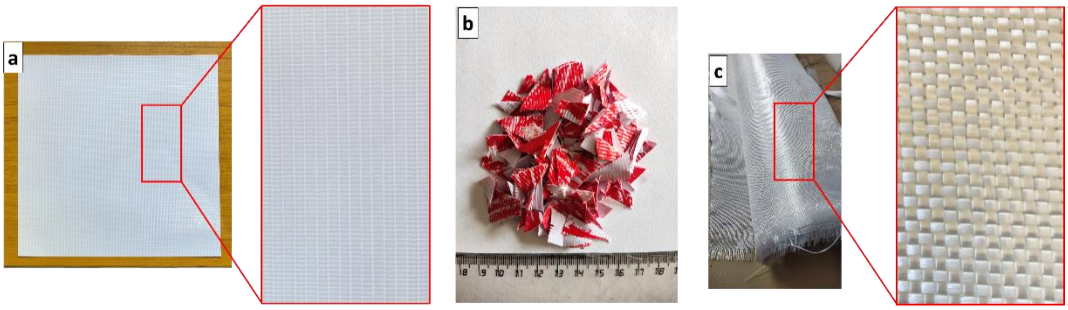

Figure 1. Reinforcement in composite materials (a) Flex banner (b) Randomly sized flex banner (c) Glass fiber

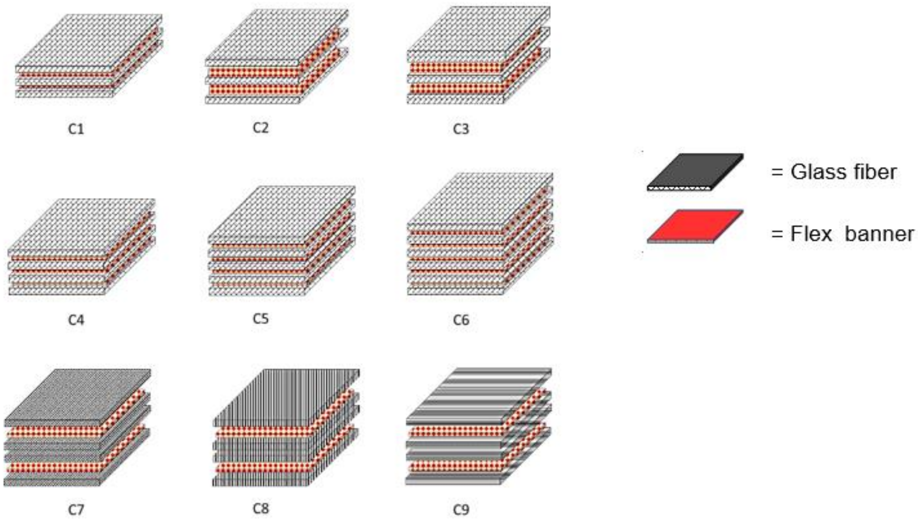

Figure 2. Stacking sequence of composites

Table 1. Density of materials

Material	Density, (g/cm^3)
Flex banner	1.71
Glass fiber	2.54
Polyester	1.12
Hardener	1.17

Composites are made using the hand layup method. Metal molds and some equipment must be prepared, such as a glass mold base, mirror glaze, brush, roller, resin cup, and stirring spoon. Waste flex banners are cleaned of dirt and dust using a detergent solution, then rinsed with running water. The ink removal process is done using a dissolution method of 70% ethanol. This step is crucial for better bonding of the polyester matrix to the flex banner fibers.Prepared the reinforcements, each variation is made with six layers of fiber with fiber volume fraction variations of 30%, 40%, and 50%.The arrangement and number of other variations follow the arrangement scheme in Figure 2.

2.2. Fabrication and testing

In fabrication, glass fiber and random-size waste flex are manually placed onto a mold, and resin is applied to bond the layers. The polyester resin is mixed with a hardener and then applied to the reinforcement material using brushes and rollers to ensure complete saturation without excess. Each layer is compacted to eliminate air pockets and achieve uniform flex distribution, which is critical for the strength of the final composite. After building up the required number of layers, the composite is allowed to cure at room temperature. Once cured, the part is de-molded, trimmed, and finished to the desired specifications.

Impact loading of construction components is complicated because design attributes and material properties affect the system's response. Assessing material resistance to abrupt loading requires impact testing because these sudden impacts commonly occur in aviation, automotive, and construction industries. This method evaluates material toughness by measuring its capacity to soak in energy before breaking and testing its behavior in severe temperatures. The assessment of the impact of the manufacturing process and the detection of unseen composite defects are made possible through impact testing. The evaluation process enables designers to modify material, design and forecast progressive failures that users might experience[35]. The impact testing of material helps verify compliance with safety requirements and regulatory standards, boosting user perception of product material reliability. Impact tests with the Charpy method occurred in this study using the GOTECH GT-7045-MDH machine as shown in Figure 3(b). The testing sequence followed ASTM D256[36].

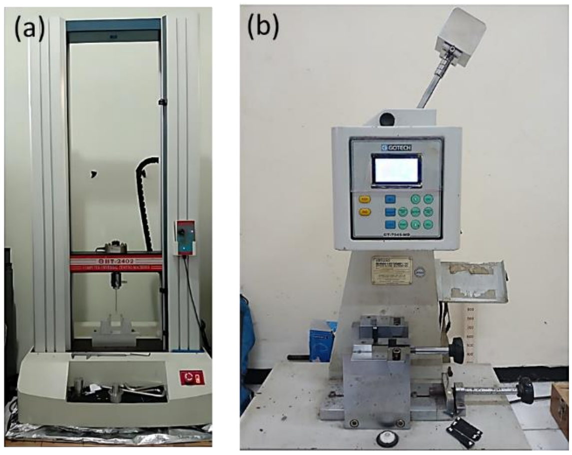

Figure 3. Testing tools include (a) universal testing machine for flexural tests and (b) impact testing machine

Flexural testing of composites is essential to assess how much a material can withstand flexural loads without permanent damage or deformation. This test was performed using the ASTM D790 standard [36,37], and a universal testing machine manufactured by HT-2402 served as the testing equipment. Testing results yield essential data regarding material properties, including strength, elasticity, and pressure and load resistance capacity. Testing outcomes of this kind serve essential requirements in the automotive, aerospace and construction industries for their structural applications. Information from flexural tests reveals how load compression affects composite stress patterns, mechanical deformations, and the material weak points that could lead to failure [6]. The test provides value in material development for assessing performance requirements of specific applications while validating product safety and durability when composite materials are used[37]. Before and after testing specimens are shown in Figures 4 and 5.

Table 2. Composite variation and weight of materials

Composite	Sample code	Weight (g)			
		Glass Fiber	Flex banner	Polyester	Hardener
Fiber : matrix V_f= 30% : 70%	C1	68.88	30.9	116.94	1.22
Fiber : matrix V_f = 40% : 60%	C2	91.8	41.3	100.2	1.053
Fiber : matrix V_f = 50% : 50%	C3	114.8	51.6	83.5	0.8
G/F/G/F/G/F/G	C4	48.20	5.1	144.16	1.49
G/F/G/F/G/F/G/F/G	C5	60.26	5.1	138.97	1.43
G/F/G/F/G/F/G/F/G/F/G	C6	72.31	5.1	133.52	1.39
0^0/flex/0^0/0^0/flex/0^0	C7	141.73	31.8	123.74	1.25
45^0/flex/45^0/45^0/flex/45^0	C8	141.73	31.8	123.74	1.25
90^0/flex/90^0/90^0/flex/90^0	C9	141.73	31.8	123.74	1.25
Polyester	C10	0	0	167.05	1.75

Figure 4. Before and after impact testing

Figure 5. Before and after flexural testing

3. Results and Discussion

3.1. Impact test

The absorption energy value of composite materials requires impact testing to determine it. The maximum energy level materials can receive from shock loads until they fail constitutes absorption energy in impact testing. Material resistance to shock impact depends heavily on the measured absorption energy levels. Table 3 displays the absorption energy and impact strength of each composite specimen. The graphic and macrograph of the impact test specimen are shown in Figures7 and 10.

Based on the data, most composite specimens have a positive relationship between the E-absorber value and impact strength. Specimen C7 showed the best performance with the highest E-absorber value 19.2 J and the highest impact strength 0.406 J/mm^2, indicating excellent resistance to impact. In contrast, C10 (pure polyester) had the lowest E-absorber 1.30 J and a very low impact strength of 0.031 J/mm^2, indicating its susceptibility to impact damage. The reinforced composite that obtained the lowest value was the C4 specimen, with an E-absorber value of 5.03 J, and the impact strength was 0.123 J/mm^2.

Table 3. The results of the impact tests

Sample code	Sample no.	E-absorber (J)	Impact strength (J/mm^2)	Average impact strength (J/mm^2)
	1	10.56	0.259	
C1	2	8.35	0.205	0.225
	3	8.63	0.212	
	1	9.22	0.193	
C2	2	11.37	0.238	0.195
	3	7.39	0.154	
	1	9.05	0.174	
C3	2	8.25	0.159	0.163
	3	8.04	0.155	
	1	5.19	0.127	
C4	2	4.59	0.112	0.123
	3	5.33	0.131	
	1	5.72	0.125	
C5	2	5.44	0.118	0.123
	3	5.84	0.127	
	1	7.88	0.193	
C6	2	8.45	0.207	0.199
	3	7.97	0.196	
	1	19.91	0.426	
C7	2	18.57	0.388	0.406
	3	19.33	0.404	
	1	10.13	0.216	
C8	2	9.40	0.201	0.203
	3	9.15	0.191	
	1	9.09	0.203	
C9	2	8.10	0.173	0.186
	3	8.49	0.181	
	1	1.30	0.031	
C10	2	1.44	0.035	0.031
	3	1.16	0.028	

High E-absorber in impact test indicates that the composite specimen has good toughness or ability to absorb energy when exposed to impact or sudden load[38]. This shows that the composite material can spread and reduce the impact of energy received, reducing the possibility of significant damage or structural failure. Composites with high E-absorbers usually have good resistance to dynamic and impact conditions. They are more resistant to cracking or breaking[39–41]. This makes the material more reliable in applications involving frequently changing loads or impacts, such as in vehicles, aircraft, or structures that are susceptible to damage due to impact.

As shown in Figure 6, composite C7 variation (0^0/flex/0^0/0^0/flex/0^0) has the highest impact strength value, the composite consists of four glass fiber arrangements with an orientation of 0^0. Composites with unidirectional glass fibers at 0^0orientation have better impact strength because fibers parallel to the load direction can efficiently transfer and withstand direct impact forces. Glass fibers have high tensile strength[42], so this composite can absorb more impact energy without experiencing significant damage. The 0^0orientation maximizes the stiffness and toughness of the material, allowing the composite to distribute impact energy more evenly and reduce the risk of harm or cracks caused by dynamic loads[43]. In addition, using glass fibers in the right direction optimizes stress distribution. It increases material efficiency, making it more impact-resistant than other fiber orientations and variations.

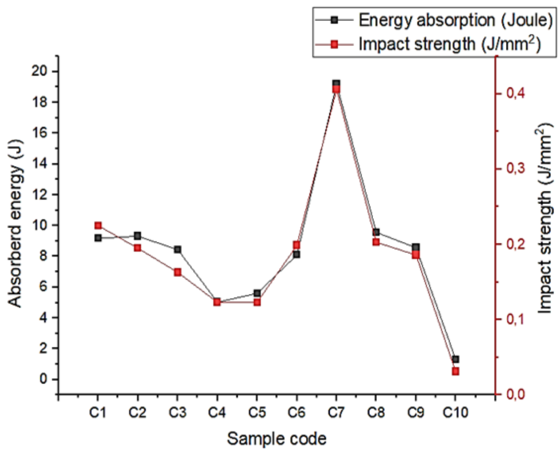

Figure 6. Absorbed energy vs. impact strength

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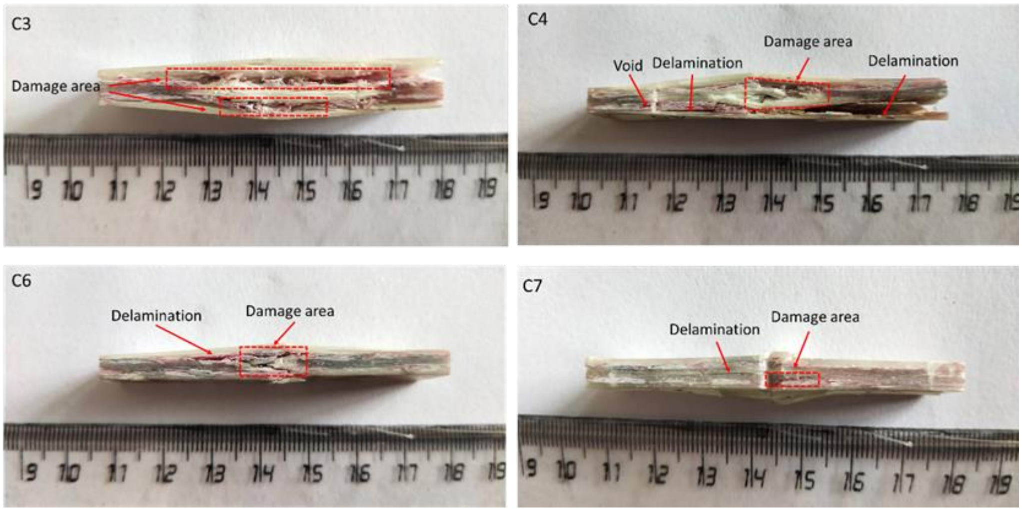

Figure 7. Composite laminates damaged at different variation

Table 2 shows that the fiber content in the C4 variation (48,20 gr glass fiber and 5,1 gr flex banner) is the lowest compared to other variations, which gives this variation the lowest impact strength value. Composites with the lowest reinforcement content will have lower strength in impact testing because the material's ability to absorb impact energy is limited. Reinforcement, such as fibers or particles, increases the material's resistance to loads and impacts. The composite cannot effectively distribute or absorb impact energy with low reinforcement content. The more brittle matrix will absorb most of the impact energy, the more it cannot withstand the load or reinforcement. In addition, the composite's toughness decreases because fewer fibers block crack propagation[44,45], causing the material to be more susceptible to damage or permanent deformation. Therefore, composites with low reinforcement content tend to be more vulnerable to damage and failure in impact testing than composites with higher reinforcement content.

The damaged area after the impact test can be seen in Figure 7. The large area of damage on the specimen indicates that the material's ability to withstand loads is significantly reduced. Composites endure major damage whenever a combination of three main factors exists, such as bond failure between fibers and matrix, uneven force distribution, or substandard production methods. Internal composite structural failure becomes evident when delamination or major fiber failure occurs along with crack propagation, thus rendering affected areas unable to distribute loads efficiently. A big damage zone weakens the composite's stress resistance while raising the possibility of substantial structural collapse[46,47], which weakens the composite's strength (C3 variation).

3.2. Flexural test

Flexural testing for composite materials establishes how much bending strain a material can sustain until it shows irreversible deformation. The testing method provides vital knowledge about composite strength and elasticity when subject to loading that creates bending or deformation. Toughness evaluations of the composite material can be achieved through flexural testing because the test measures the material's ability to absorb energy before breaking. Results from this test support developers and designers of composite materials by helping them determine material strength and elasticity and locate structural weaknesses before commercial application. The testing method identifies whether composite materials match regulatory performance requirements used by various industries. A table and figure show the flexural strength findings for the composite specimens in Table 4 and Figure 8.

Table 4. The flexural strength of the composite specimens

Sample code	Sample no.	Flexural strength (MPa)	Average flexural strength (MPa)
	1	260.74	
C1	2	298.26	252.87
	3	199.64	
	1	101.73	
C2	2	106.04	110.33
	3	123.22	
	1	80.62	
C3	2	60.15	71.10
	3	72.56	
	1	218.19	
C4	2	213.53	215.35
	3	214.33	
	1	251.04	
C5	2	259.15	257.14
	3	261.23	
	1	264.42	
C6	2	267.75	266.23
	3	266.55	
	1	424.19	
C7	2	422.02	431.19
	3	447.39	
	1	206.04	
C8	2	206.13	209.93
	3	217.63	
	1	123.21	
C9	2	129.74	125.62
	3	123.94	
	1	80.86	
C10	2	84.68	81.99
	3	80.43	

Based on the flexural strength data, composite C7 showed the highest flexural strength with a value of 431.199 MPa, making it the strongest among the other samples. On the other hand, composites C3 (71.106 MPa) and C10 (81.99 MPa) had the lowest flexural strength, indicating that both were more susceptible to damage when tested under flexural loads. Several other composites, such as C5 (257.14 MPa) and C6 (266.239 MPa), also showed better flexural strength than the C3 variation.

Composites with 0^0 fiber orientation have the best flexural strength because fibers parallel to the load direction can absorb stress more efficiently, maximizing the fiber contribution in increasing the material strength. In this orientation, the fibers work toward the principal stress, increasing the composite's ability to withstand bending forces and reducing the possibility of damage to the matrix. In addition, the 0^0 orientation helps minimize distortion, cracking, and structural failure by inhibiting crack propagation, thereby increasing the overall stability of the composite[48–51].

Composites with 0^0 fiber orientation (C7 variation) tend to have excellent flexural strength because the fibers are aligned parallel to the load direction, maximizing stress absorption efficiency and providing optimal reinforcement in the principal stress direction. However, the disadvantage is that the strength is only focused in one direction and cannot handle loads from other directions. In contrast, woven fibers with $0^0/90^0$ orientation (C1-C6 variation) provide better toughness because the fibers are arranged in a pattern in two or more directions, allowing for more even load distribution and increasing resistance to damage or failure under multidimensional loads[52–54]. Although woven fibers provide a better balance of strength in various directions, their flexural strength is usually lower than that of 0^0 fibers in one direction. Therefore, composites with 0^0 fiber orientation are more suitable for applications that require high flexural strength in one direction. In contrast, woven fibers are ideal for applications that require toughness and resistance to multidimensional loads.

A decrease in flexural strength was observed in the C3 variation, with a value of 71.106 MPa, even lower than the composite specimen without reinforcement (C10 variation), with a value of 81.99 MPa. C3 composite variation consists of a fiber-to-matrix volume fraction ratio of 50% : 50% tends to have lower flexural strength due to the imbalance between the fibers and the matrix. Too much fiber without enough matrix causes the composite to be less flexible and more brittle. Although fibers provide strength, too little matrix cannot distribute the load effectively or absorb impact energy, increasing the risk of damage and failure of the material. In addition, the lack of a matrix reduces the bond strength between the fibers and the matrix, so force transmission between the two is not optimal[55]. As a result, despite the reinforcement from the fibers, these composites cannot withstand long-term flexural loads and are more susceptible to localized cracking or deformation, which ultimately reduces the overall flexural strength.

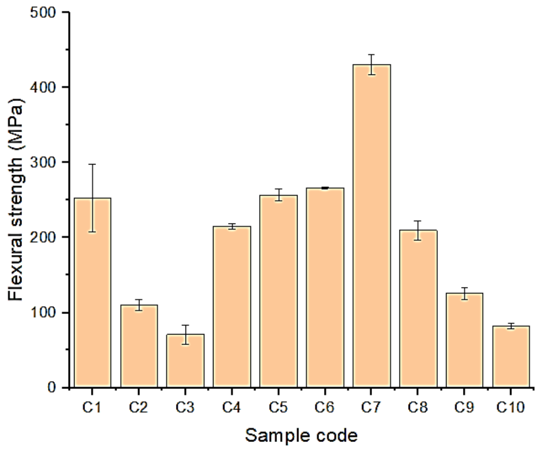

Figure 8. The graphic of the flexural strength of the composite specimens

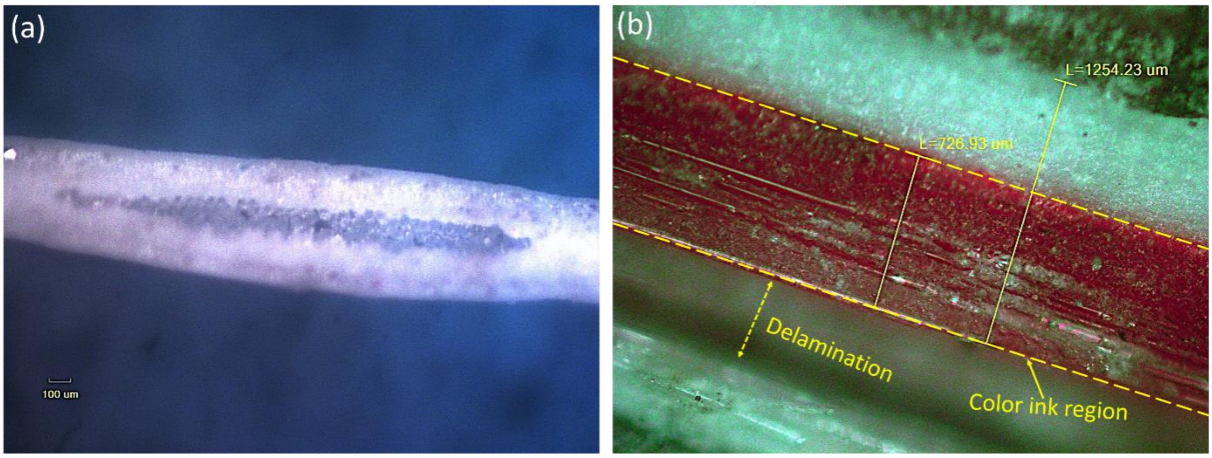

Figure 9. (a) colorless ink flex banner (b) delamination failure on the surface of the color ink area flex banner

The presence of ink on the surface of a flex banner within a composite material may lead to delamination[45]. The ink causes such degradation by creating weak points where the fiber-to-matrix bond weakens, resulting in composite structural failure. The ink develops a protective layer that blocks mechanical contact between surfaces, thus weakening the bond strength and reducing load transfer from the matrix to fibers. The risk of structural failure grows substantially when tension or stress operates on the affected region. Inks with specific chemicals that do not blend well within the matrix and thick coatings that prevent fiber-to-matrix adhesive connections result in delamination, and the condition worsens [56–58], as shown in Figure 9. Therefore, proper ink selection and fiber surface treatment are critical to maintaining the strength and integrity of the composite.

Random-sized reinforcement components have multiple impacts on composite flexural strength generation. The non-uniform distribution of reinforcement material produces strained stress patterns that result in areas of excess strength versus weakness throughout the structure thus decreasing the material's flexural strength potential. The material's toughness improves from random-sized reinforcement through crack blocking properties and enhanced resistance to deformation[50]. However, such disordered reinforcement sizes could result in weaker flexural properties when subjected to heavy loads since unstructured reinforcement lacks adequate strength for bearing weight. Random distribution of reinforcement leads to suboptimal matrix-to-reinforcement interactions, which result in local failure and microcracking[59].

Several elements contribute to the reduced flexural strength of reinforced composites (C3 variation) compared to pure resin (C10 variation). These elements include uneven distribution of reinforcement[60], weak bonding between reinforcement and matrix, and the inability of reinforcement to withstand flexural loads [52]. If reinforcement is distributed randomly or suboptimally, some areas may lack reinforcement, reducing the material's ability to absorb loads effectively. In addition, insufficient bonding between reinforcement and matrix can cause microcracking or delamination[21], random and suboptimal reinforcement distribution weakens parts of the material structure thus reducing its capacity to absorb external loads. The material strength decreases when inadequate bonding exists between reinforcement and matrix or when microcracking and delamination occur [61], reducing the composite's flexural strength even lower than that of pure resin-based composites.

In composites, good bonding between the fibers and the matrix is essential to ensure that the fibers can act as effective reinforcement, distributing the load throughout the material and increasing the overall strength and stiffness of the composite. Suppose the bond between the matrix and the fibers is not strong enough. In that case, when the composite is loaded, the load cannot be distributed properly, which can cause delamination, which reduces the composite's ability to carry the load and leads to premature failure, often with the failure of the weaker matrix layers.

However, if no delamination occurs and the fibers remain well bonded to the matrix, the load can be effectively transferred to the stronger fibers, and the fibers will begin to fail under excessive stress[50]. This failure of the fibers indicates that they can withstand the applied load until their maximum strength is reached. This means that the composite material has been designed with a bond strong enough to exploit the full potential of the fibers. Failure occurs not because of a breakdown in the bond between the fibers and the matrix, but because the fibers themselves have reached their strength limits[49,62]. Fiber failure without delamination indicates that the bond between the matrix and the fibers is excellent, allowing the fibers to function optimally in carrying the load until they eventually fail[46], indicating material failure at the fiber level rather than at the level of the bonds between the fiber and matrix, as shown in Figure 10(a).

The flexural modulus of elasticity in fiber composite materials is very important because this parameter provides an overview of the material's ability to undergo elastic deformation when given a bending load. The flexural modulus of elasticity measures the extent to which the material can return to its original shape after removing the bending load, which is directly related to the material's rigidity. In fiber composites, the flexural modulus of elasticity provides key information about how the fibers and matrix work together to withstand bending stress without experiencing permanent damage. The modulus of elasticity for each variation can be seen in Figure 11. By knowing the flexural modulus of elasticity, we can choose the right material according to application needs, ensure an optimal balance between strength and flexibility, and improve the quality and durability of composite products.

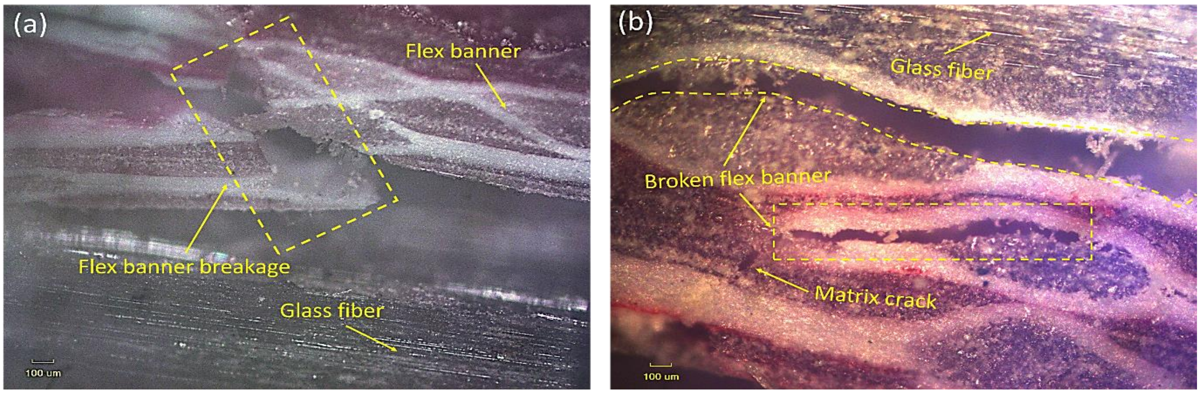

Figure 10. Macrograph of the failure mechanism in a composite material

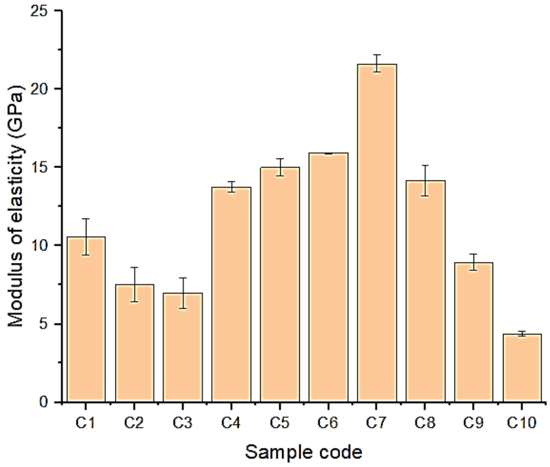

Figure 11. The flexural modulus of elasticity of each variation

C7 variation, which consists of 0^0 fiber orientation, has the best flexural modulus of elasticity (21.638 GPa) because the fibers in the composite are parallel to the direction of the applied bending load. In the composite, the fibers act as reinforcements that absorb stress, while the matrix binds the fibers and distributes the load. When the fibers are oriented at 0^0, the fibers directly absorb bending stress along the direction of the load, allowing the composite to resist elastic deformation more effectively[63]. Most of the tensile stress generated by bending loads is borne by the fibers, which have much higher strength and stiffness than the matrix. With 0^0orientation, the composite can exhibit a high flexural modulus of elasticity because the fibers work optimally in resisting bending strains, increasing the material's stiffness[54,64]. This allows composites with 0^0 fiber orientation to have high rigidity and the ability to return to their original shape after the load is applied without experiencing permanent deformation. In contrast to woven fiber, where the stress distribution is more even but not as efficient as 0^0 fibers in resisting one-way bending loads, composites with 0^0 fiber orientation will exhibit better strength and stiffness in applications that require dominant bending loads in one direction[21]. Overall, the 0^0 fiber orientation maximizes flexural strength and flexural modulus of elasticity, making it the best choice for applications where rigidity and resistance to bending loads acting in one direction are essential.

Figure 12(a) shows the damage area of the flex banner after the testing process.This failure occurs because the flex banner is weaker than glass fiber, so it cannot withstand the same tension or load as the glass fiber, and the flex banner will experience damage or fracture first. However, although the flex banner can fail first, this failure does not always mean total failure of the composite. Hybrid composites can be designed to exploit the cooperation between different reinforcing fibers[31]. When the weaker fibers begin to fail, the stronger fibers will take over most of the load, helping to slow the overall failure of the composite. Stronger fibers can increase the resistance of the composite to further structural failure[36].

The reinforcement in the hybrid composite has a different modulus of elasticity, so when the composite receives a load, the glass fiber may work harder than the other fibers. This can cause the glass fiber to experience higher stress, which eventually triggers damage or even failure of the glass fiber[34]. This mismatch in the modulus of elasticity can cause unbalanced loads in the composite, causing the glass fiber to break or crack as shown in Figure 12(b).Composites without fibers or reinforcements (C10 variation) have the lowest modulus of elasticity (4.382 GPa) because the resin matrix or other base material that form the material do not have structural reinforcement that can add stiffness and resistance to load. The modulus of elasticity is a measure of the stiffness of a material, indicating how much the material can resist elastic deformation when subjected to stress or load.

3.3. Analysis of variance (ANOVA)

The Minitab software statistical analysis shown in Table 5 confirmed that the composite configuration significantly affects both impact and flexural strengths. For impact strength, 97.15% of the variation is explained by sample code differences ($F = 75.58$, $p < 0.001$), while only 2.85% is attributed to error. Similarly, for flexural strength, 98.17% of the variation is due to sample configuration ($F = 119.86$, $p < 0.001$), with error contributing only 1.83%. These findings confirm that the differences in mechanical performance are systematic and highly reliable. The statistical validation demonstrates that the observed improvements are not random but strongly correlated with the hybrid composite design, reinforcing the originality and robustness of the study.

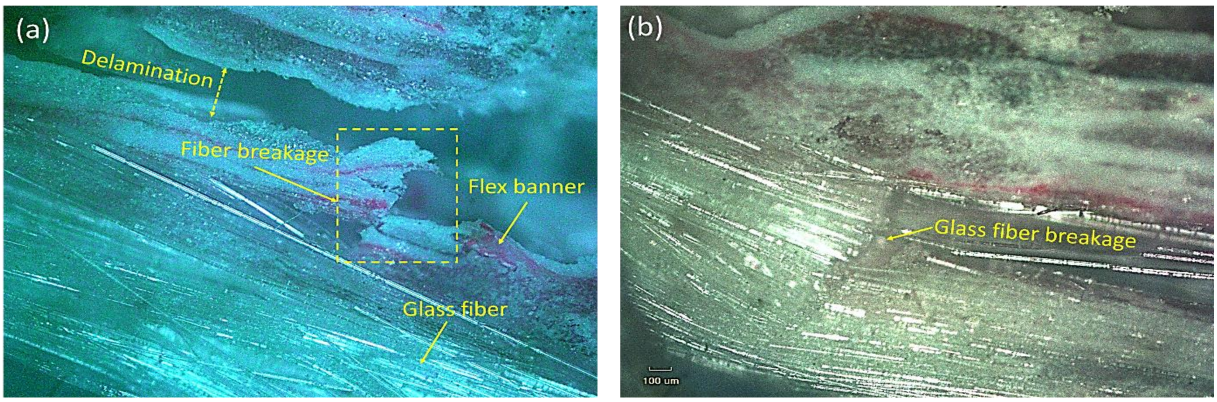

Figure 12. Fracture modes of (a) flex banner, (b) glass fiber

Table 5. Analysis of variance

Data	Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Impact strength (J/mm²)	Sample code	10	0.248651	97.15%	0.248651	0.02763	75.58	0.000 (sign.)
	Error	20	0.007311	2.85%	0.007311	0.00037		
	Total	30	0.255962	100%				
Flexural strength (MPa)	Sample code	10	324899	98.17%	324899	36099.9	119.86	0.000 (sign.)
	Error	20	6024	1.83%	6024	301.2		
	Total	30	330923	100%				

4. Conclusion

Utilizing flex banner waste as a composite reinforcement improves mechanical performance and solves environmental issues. By diverting difficult-to-decompose PVC-based plastic waste into engineered materials, this research supports the principles of a circular economy.Furthermore, the development of waste-based hybrid composites can reduce dependence on pure synthetic fibers, making them more environmentally friendly and sustainable.The test results show that glass fiber contributes significantly to increasing the strength of the composite. The highest strength increase is obtained by hybrid composites with glass fiber reinforcement having a fiber orientation of 0^0, while flex banner waste functions as a relatively effective additional reinforcement. Hybrid composites based on waste flex banners and glass fiber have potential applications in the automotive industry (interior panels), construction (lightweight building boards), and household appliances (tables, chairs, and shelves). Design recommendations that need to be considered include optimal fiber orientation and volume fraction variations to improve mechanical performance while maintaining sustainability. Further research is needed to optimize the production process and improve the bond between components so that this composite can achieve better performance in practical applications.

Acknowledgments

We thank LPPM UNNES for the research funding. The contract number is118.26.2/UN37/PPK.10/2024.

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