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The Effect of Fiber Orientation and Composition on Mechanical Properties of Coconut Fiber-Reinforced HDPE Waste Polymer Composites

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ABSTRAK

Pemanfaatan limbah berbasis serat alam sebagai penguat komposit menjadi alternatif material ramah lingkungan untuk aplikasi teknik, khususnya pada komponen pesawat tanpa awak (Unmanned Aerial Vehicle). Penelitian ini bertujuan untuk mengetahui pengaruh variasi fraksi volume limbah tusuk sate berbahan dasar bambu sebagai filler terhadap sifat mekanik komposit bermatriks polistirena serta potensi penggunaannya sebagai material propeller UAV. Limbah tusuk sate diproses menjadi partikel berukuran 50 mesh dan diberi perlakuan alkali menggunakan larutan NaOH 5%. Komposit dibuat dengan metode hot press pada suhu 140 °C selama 5 menit dengan variasi fraksi volume filler:matriks sebesar 50:50, 60:40, dan 70:30. Pengujian sifat mekanik meliputi uji bending berdasarkan ASTM D790 dan uji impak Charpy berdasarkan ASTM D256-03, serta dilakukan pengamatan mikro menggunakan mikroskop optik. Penelitian menunjukkan bahwa variasi fraksi volume berpengaruh signifikan terhadap sifat mekanik komposit. Komposit dengan fraksi volume 60% filler dan 40% polistirena menunjukkan nilai kekuatan bending dan ketangguhan impak terbaik. Pengamatan mikro menunjukkan distribusi filler yang lebih homogen pada variasi tersebut sehingga mampu meningkatkan ikatan antara matriks dan filler. Hasil ini menunjukkan komposit limbah tusuk sate berpotensi digunakan sebagai material alternatif propeller UAV skala ringan

ABSTRACT

The use of natural fiber-based waste as composite reinforcement is an alternative environmentally friendly material for engineering applications, especially in Unmanned Aerial Vehicle components. This study aims to determine the effect of variations in the volume fraction of bamboo-based skewer waste as filler on the mechanical properties of polystyrene matrix composites and their potential use as UAV propeller materials. The skewer waste was processed into 50 mesh particles and given an alkali treatment using 5% NaOH solution. The composite was made by hot press method at 140 °C for 5 minutes with variations in the filler:matrix volume fraction of 50:50, 60:40, and 70:30. Mechanical property testing included bending tests based on ASTM D790 and Charpy impact tests based on ASTM D256-03, as well as micro observations using an optical microscope. The study showed that variations in the volume fraction had a significant effect on the mechanical properties of the composite. The composite with a volume fraction of 60% filler and 40% polystyrene showed the best bending strength and impact toughness. Microscopic observations showed a more homogeneous filler distribution in this variation, thereby improving the bond between the matrix and filler. These results indicate that the skewer waste composite has the potential to be used as an alternative material for light-scale UAV propellers

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are aircraft that operate without an onboard pilot and are controlled remotely or autonomously. Initially developed for military purposes such as reconnaissance and combat operations, UAVs have increasingly been adopted in civilian sectors including agriculture, mapping, environmental monitoring, and logistics as a result of advances in control systems, sensors, and software technologies (Gertler, 2012) . Despite their growing applications and efficiency improvements, the use of UAVs in civil airspace continues to face regulatory and safety challenges (Grubesic & Nelson, 2020) .

various flight conditions. Composite materials are therefore widely used due to their superior strength-to-weight ratio compared to conventional materials such as metals. Composites consist of a matrix and a reinforcement phase, which are combined to produce enhanced mechanical properties. Recent composite research has increasingly focused on the use of natural fibers as environmentally friendly reinforcements (Agarwal et al., 2017) .

Bamboo is a promising natural fiber due to its rapid growth rate, high mechanical strength, low density, and high cellulose content. Its abundant availability, particularly in Indonesia, makes bamboo a sustainable material for composite applications (Illya & Bali, 2021) . Bamboo fibers provide a renewable and cost-effective alternative to synthetic reinforcements such as glass or carbon fibers, while maintaining good tensile strength and reducing environmental impact (Gupta et al., 2015) .

Waste bamboo skewers represent a growing source of organic waste from the culinary sector and are often discarded without proper management. Due to their light weight and relatively high stiffness, these wastes have potential as filler materials in polymer composites. The utilization of bamboo skewer waste not only reduces environmental pollution but also produces economical and eco-friendly composite materials. However, the mechanical properties of polymer composites are strongly influenced by filler mass, distribution, and interfacial adhesion between the filler and matrix. Therefore, this study investigates the effect of bamboo skewer waste mass as a filler in polystyrene-based composites for UAV propeller applications, using impact and bending tests to evaluate the mechanical performance (Khalid et al., 2021) .

Composites

Composite is a new type of engineered material consisting of two or more materials where the properties of each material are different from each other, both chemically and physically, and remain separate in the final result of the material (composite material). Due to the differences in the constituent materials, the composite between materials must be strongly bonded, so it is necessary to add a wetting agent. The purpose of the composite is to improve mechanical properties, simplify difficult designs in manufacturing, flexibility in shape/design that saves costs and makes the material lighter.

satay skewer waste

Bamboo skewer waste is a material with potential for use as a composite filler due to its lightweight, easy processing, and relatively good mechanical strength. Bamboo is known to have higher tensile strength and flexibility than some other wood species (Mohammed et al., 2024) . Utilizing bamboo waste as a filler not only increases the waste's utility value but also supports the principles of sustainability and a circular economy by lowering production costs and reducing waste (Mustafa et al., 2024) .

Several studies have shown that the addition of bamboo filler can improve the mechanical properties of composites, such as tensile strength, toughness, and impact strength, although the results are greatly influenced by the size, distribution of the filler, and fabrication method. (Costa et al., 2017) reported significant improvements in the tensile and compressive strength of bamboo-based composites, but their resistance to moisture needs to be addressed. Pretreatments such as heating or resin coating have been shown to improve intermaterial adhesion and the composite's resistance to environmental degradation (Silva et al., 2023) .

polystyrene

Polystyrene (PS) is a synthetic thermoplastic polymer synthesized through free radical polymerization of styrene monomers (C_8H_8), forming long chains with benzene ring groups bonded to carbon chains. The chemical structure of polystyrene is expressed by the general formula $(C_8H_8)_n$, where the bond between monomers occurs through covalent bonds that form a linear polymer chain (Nurrachmania, 2023) . Polystyrene is transparent, lightweight, rigid but brittle, and relatively stable to water and some chemicals, although it is not resistant to certain organic solvents. As a thermoplastic material, polystyrene does not have a definite melting point, but softens at a glass transition temperature (Tg) of around 90–105 °C and melts gradually at a temperature of 240–270 °C. Due to its ease of processing and low production costs, polystyrene is widely used in the packaging industry, polystyrene foam (EPS), household appliances, and disposable medical products.

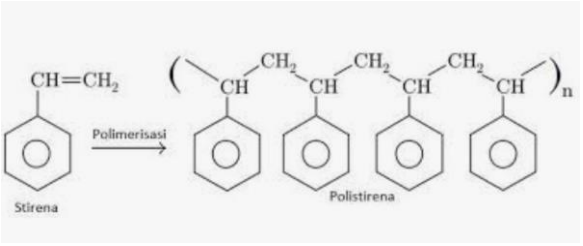

Figure 1. Polystyrene Chain Bonds

Impact Test

Impact testing aims to determine a material's resistance to sudden loads or impacts that can cause damage. This test is used to determine how much energy a material can absorb before experiencing permanent damage (fracture) and provides information on its toughness. The ASTM D 256-03 standard is as follows.

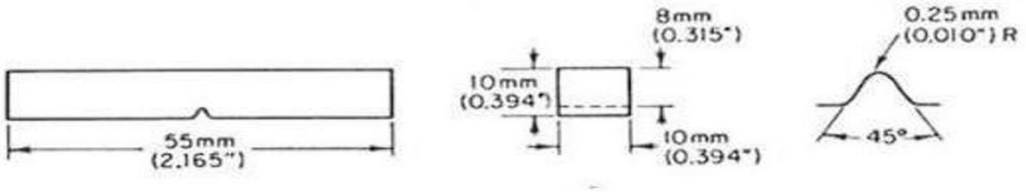

Figure 2. Impact Test Specimen

It can be calculated using the following equation:

Fracture strength (E) = m . g. □ (co□ □ − co□ □) (1)

Price impact (HI) = $\frac{E}{A}$ (2)

Bending Test

A bending test is a testing method used to measure the strength of a material under bending loads. This test provides information on how much a material can withstand bending stress before experiencing failure, such as fracture or permanent deformation. The purpose of a bending test is to assess how a material reacts to bending loads. In this case, we can determine the material's flexural strength, how much deformation it can tolerate before breaking, and how resistant the material is to damage due to the applied load. Bending tests are carried out by placing the sample on two or four supports . The load is slowly applied at the center point or two points on the sample to produce bending. The sample will experience deflection, and the data obtained will be used to calculate the flexural strength and flexural modulus of elasticity. ASTM D790 Standard are as follows :

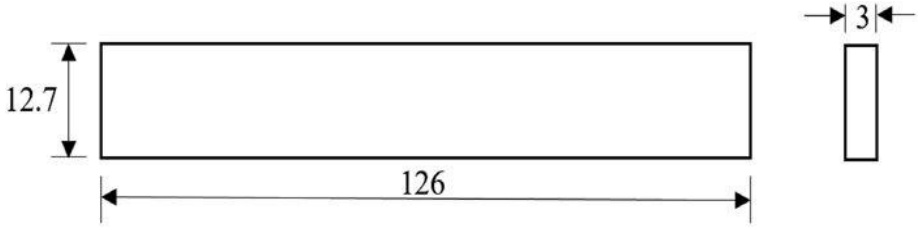

Figure 3. Bending Test Specimen

It can be calculated using the following equation:

Modulus of Elasticity (*Flexural Modulus*). Calculated using the formula:

$$E_f = \frac{L^3 m}{4bh^3} \quad (3)$$

Flexural *Strength* is calculated using the formula:

$$\sigma_f = \frac{3PL}{2bh^2} \quad (4)$$

Micro Observation

Microscopy is the process of viewing and analyzing a material's structure at a microscopic scale using tools such as an optical microscope, digital microscope, or electron microscope. In the context of composite material testing, microscopy aims to understand the material's internal characteristics that are invisible to the naked eye. This includes observing the distribution of fibers or reinforcement particles, the interface conditions between the reinforcement and the matrix, and detecting micro-defects such as voids, fine cracks, delamination, or porosity.

In this study, micro observations were made using *digital tools. microscope* , in this observation, the composite specimen of PS waste and skewer waste particles that had undergone bending and impact tests was selected . The following is an image of the results of micro observations on the best bending test specimen and impact test specimen.

2. METHOD

This research was conducted at the Materials Engineering, Chemical Engineering and Mechanical Engineering Laboratory of Malikussaleh University from September to November 2025.

Tools in Research

The equipment used in preparing the samples in this study included several main tools, namely a digital scale that functions to measure the mass of materials with high accuracy, as well as a measuring cup used to measure the volume of additional materials if needed. A Hot Press was used to assist the heating process of the materials so that they are easily processed and mixed well. A blender functions to chop and crush the skewer waste into particles. Two types of iron molds were used in this study, each measuring 13 x 7.5 x 0.4 cm and 6 x 3.5 x 1 cm, respectively, as containers for forming composite samples. A 50 mesh sieve was used to refine the particles so that the resulting particle size was constant. The mixing and shaping process of the material was carried out using a spatula to ensure material homogeneity. After that, the resulting samples were tested using a bending test machine and impact test to determine the mechanical strength of the material that had been made.

Material in Research

The materials used in this study consist of several main components, namely skewer waste which is made into particles that function as a composite reinforcing material, and polystyrene which is used as a matrix or base material. To increase the adhesive power between the fiber and the matrix, a 5% NaOH solution is used as a pretreatment (alkalization) for the skewer waste particles. In addition, there is gasoline (ethane) in the mixing process or chemical reaction that occurs during the manufacture of the composite which functions as a solvent that helps soften the polystyrene so that it is easily mixed with the particles. Meanwhile, aluminum foil is used to facilitate the printing process and prevent the material from sticking to the mold during the composite sample manufacturing process.

Composite Manufacturing

Initial processing of satay skewer waste involves collecting the skewers and cleaning them of dirt and dust. The skewers are then soaked in a 5% NaOH solution to reduce lignin, washed with hot water, dried for 24 hours, and then ground into particles using a blender.

The composite production process begins with sorting plastic waste containing polystyrene. Next, the gasoline solution is placed in a container to be mixed with polystyrene at a predetermined weight. Also included are ground satay skewer particles that have been sieved using a 50-mesh sieve. The mixed ingredients are then stirred with a spatula to ensure homogeneity.

The composite production process involves placing a homogenized mixture of materials into an ASTM-compliant mold and pressing it at 140°C for 5 minutes, followed by a compression of 10 kg/m^2. This process is repeated for each composition variation, and the resulting samples are cut to ASTM standards for testing purposes.

Table 1. Research design

No	Specimen	Mass fiber (kg)	Power broken (J)	Resilience (J/mm ^{2})
1	50% particle + 50% PS			
2	60% particle + 40% PS			
3	70% particle + 30% PS			

3. RESULTS AND DISCUSSION

Result

Mechanical properties are properties that indicate the ability to receive loads, forces, or energy. The mechanical properties of a material reflect the relationship between the loads and energy received by a material and the reactions or deformations that will occur. The mechanical properties of a material are

divided into several properties, including strength , *stiffness* , *elasticity* , *hardness* , fatigue, *toughness* , *plasticity , and* creep -*crack.* PS

, including impact testing . *and* bending testing *(bending test).* Composite that used is a composite made from *polystyrene waste* (PS) and satay skewer waste, comparison of volume fraction variations, namely (particle : PS, 5 0 : 5 0; 6 0 : 40; and 70 : 30) .

Bending Test

Bending testing was conducted after the process of making particle-reinforced composites from satay skewer waste using plastic waste and polystyrene to determine the effect of bending strength with a predetermined volume fraction. The test was conducted on Wednesday, September 2, 2025, at the Mechanical Engineering Laboratory of Malikussaleh University. The number of specimens tested was 15 specimens, where each variation had 5 specimens to be tested. The shape of the specimens to be tested is in Table 2.

Table 2. Bending Test Results on Composites

Faction Volume (%)	Specimen Number	Maximum Force (kgf)	Bending Stress (MPa)	Modulus Elasticity (GPa)
Particle : PS 50 : 50	1	2	20.59	2.44
	2	3	30.88	3.66
	3	3	30.88	2.44
	4	3	30.88	3.66
	5	3	30.88	1.22
Average			**28.82**	**2.68**
Particle : PS 60 : 40	1	3	30.88	2.44
	2	4	41.18	3.66
	3	4	41.18	3.66
	4	4	41.18	3.66
	5	3	30.88	2.44
Average			**37.06**	**3.17**
Particle : PS 70 : 30	1	4	41.18	3.66
	2	4	41.18	1.22
	3	5	51.48	4.88
	4	5	51.48	4.88
	5	4	41.18	3.66
Average			**45.30**	**3.66**

Table 3. Impact Test Results on Composites

Specimen Number	Faction Volume (%)	*Degree*		Fracture Energy (joules)	Price Tenacity (joules/mm ²)
		a	*ß*		
1	Particle : PS 50 : 50	160	136	20,519	0.256
2		160	136	20,519	0.256
3		160	134	22,809	0.285
4		160	135	21,655	0.270
5		160	135	21,655	0.270
Average				**21,431**	**0.267**
1	Particle : PS 60 : 40	160	140	16,171	0.202
2		160	142	14,123	0.176
3		160	140	16,171	0.202
4		160	141	15,138	0.189
5		160	141	15,138	0.189
Average				**15,348**	**0.191**
1		160	145	11,218	0.140
2		160	147	9,403	0.117

3	Particle : PS 70 : 30	160	144	12,168	0.152
4		160	145	11,218	0.140
5		160	146	10,306	0.128
Average				**10,862**	**0.135**

Discussion

Table 2 shows that the obtained bending stress values ranged from 20.59 MPa to 51.48 MPa. A bar chart for the bending stress comparison can be seen in Figure 4.

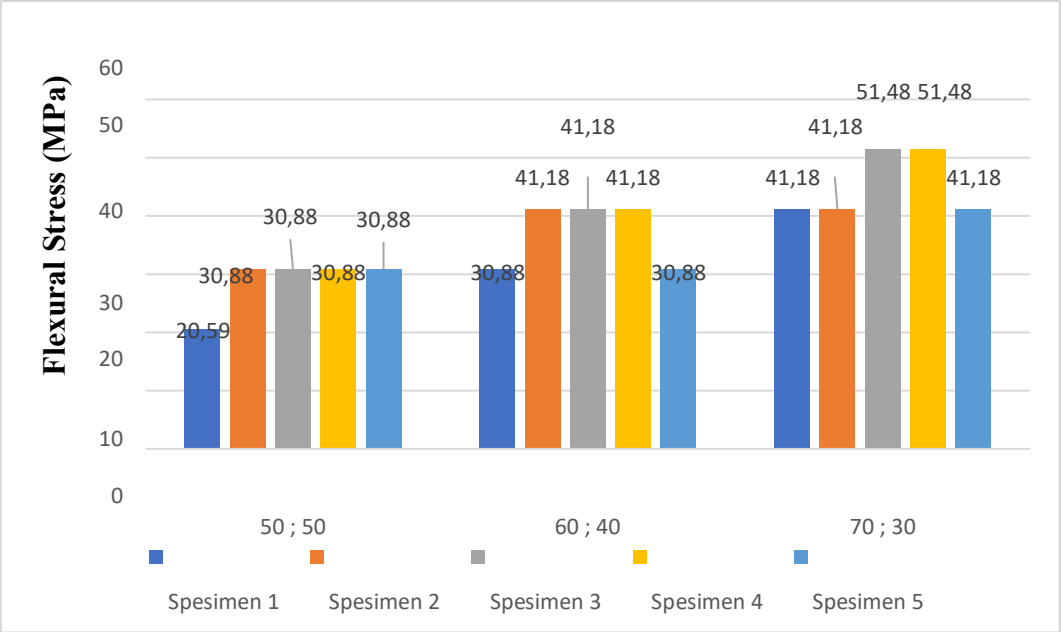

Figure 4. Bar Diagram of Comparison of Bending Stress from Test Results Bending

The 50:50 composition, the flexural stress value ranged from 20.59 MPa to 30.88 MPa. Specimen 1 showed the lowest value, while specimens 2, 3, 4 and 5 showed the highest value. When the composition was changed to 60:40, there was a significant increase in specimens 2, 3, 4, reaching a flexural stress value of 41.18 MPa. Meanwhile, specimens 1 and 5 tended to be stable at 30.88 MPa. A similar thing also happened in the 70:30 composition, where specimens 3 and 4 again showed the highest performance of 51.48 MPa. This shows that the material ratio containing more reinforcing material can increase the flexural strength of the polystyrene composite reinforced with skewer waste particles.

Table 2 shows that the obtained elastic moduli ranged from 1.22 GPa to 4.88 GPa. A bar graph for the comparison of elastic moduli can be seen in Figure 5.

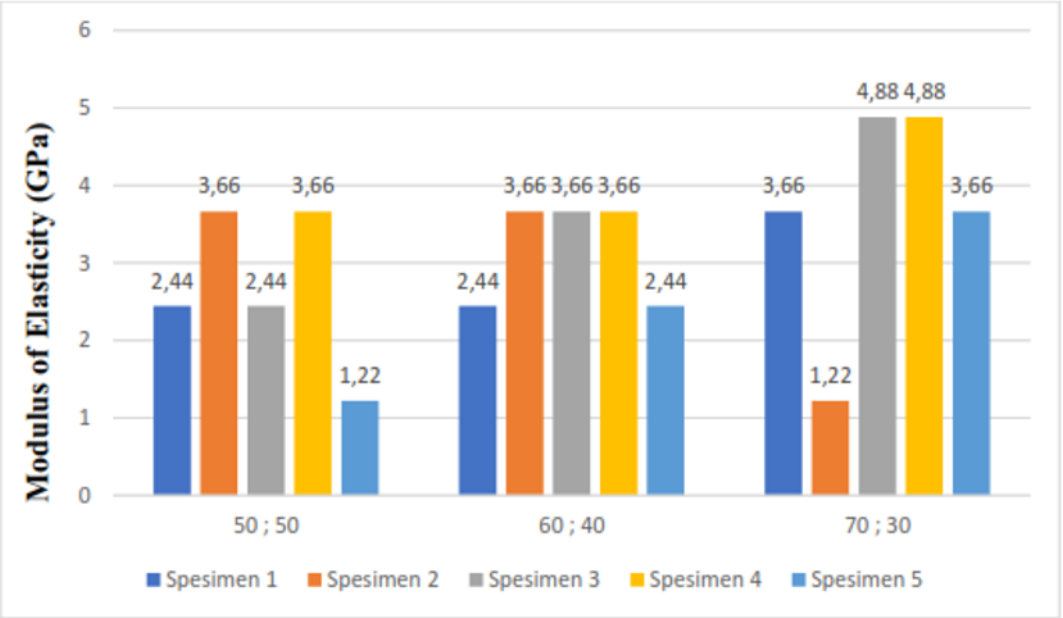

Figure 5. Bar Chart Comparing Elastic Modulus from Bending Test Results

Based on the bending test results on the 50:50 composition, the elastic modulus values are divided into three groups: specimen 5 with the lowest value of 1.22 GPa and composed with specimens 1 and 3 having a value of 2.44 GPa, while Specimens 2 and 4 show a higher value of 3.66 GPa. In the 60:40 composition, it occurs in specimens 1 and 5 with a value of 2.44 GPa, while specimens 2, 3 and 4 have a value of 3.66 GPa respectively. A similar condition also occurs in the 70:30 composition, where Specimen 2 remains at a low value of 1.22 GPa, while Specimens 3 and 4 show the highest value of 4.88 GPa, and Specimens 1 and 5 remain stable at 3.66 GPa.

Variations in the elastic modulus values indicate that the mechanical properties of the composite are strongly influenced by the distribution of the reinforcement–matrix, the volume fraction of the components, and the quality of the interphase bond. According to composite material theory, an increase in the elastic modulus can be achieved by adding rigid reinforcement, provided that the dispersion is even and the bond with the matrix is good (Callister, 2007). A decrease in the values in the 60:40 and 70:30 compositions indicates the presence of internal defects, uneven distribution of the reinforcement, or weak interphase bonding.

In contrast, Specimens 3 and 4 showed the highest elastic modulus value at 4.88 GPa at the 70:30 composition, indicating the best structural performance. This condition is thought to be influenced by a more optimal fabrication process, such as homogeneous mixing and even reinforcement dispersion. This is in line with Mallick's (2007) statement that the mechanical properties of composites are highly dependent on the quality of the manufacturing process, in addition to the material composition.

The similarity of flexural stress and elastic modulus values in several specimens indicates brittle material behavior, where the material fractures in the early stages of loading without significant plastic deformation. The flexural load is transmitted from the matrix to the filler until cracking and fracture occur simultaneously. This phenomenon is consistent with the findings of Soemardi et al. (2023) who stated that in composite bending tests, the yield point is often not clearly visible and failure generally occurs through matrix cracking and fiber breakage.

The toughness of a composite can be determined using an impact test, which measures the toughness or ability of a composite material to absorb energy before breaking (toughness). A comparison of the fracture strength values from the impact test results on 15 samples is presented in Figure , while the ductility values from the impact test results are presented in Figures 6 and 7.

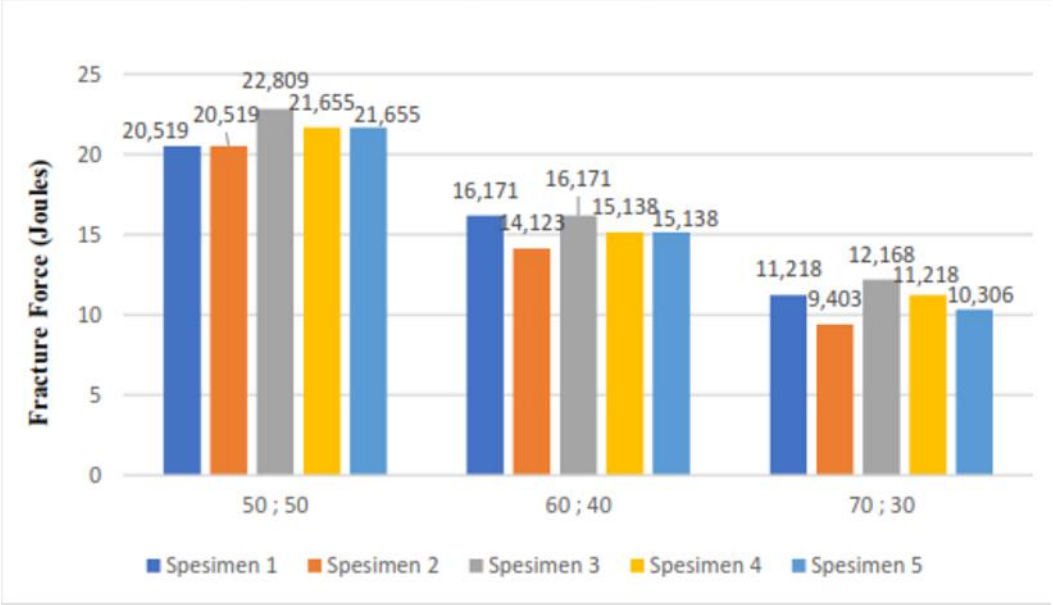

Figure 6. Bar Chart Comparison of Fracture Strength from Impact Test Results

Based on the Fracture Strength Bar Diagram, the specimen with a composition of 50:50 showed the highest fracture strength value, with absorbed energy ranging from 20.5–22.8 Joules. At compositions of 60:40 and 70:30, there was a decrease in impact energy to be in the range of 16.1–9.4 Joules, which indicates that variations in material composition significantly affect the toughness of the composite.

Toughness is the ability of a material to absorb energy before breaking, which is generally measured through impact tests such as Charpy or Izod (Callister & Rethwisch, 2014). The decrease in impact energy in the 60:40 and 70:30 compositions is caused by an imbalance between the matrix and the reinforcement, which results in uneven load distribution and increased stress concentration within the material (Gibson, 2007).

In contrast, a 50:50 composition allows for a more homogeneous distribution of matrix and reinforcement, allowing the microstructure to absorb shock loads more effectively. At higher reinforcement ratios, the material becomes stiffer but loses flexibility, reducing the amount of impact energy it can absorb (Hull & Clyne, 1996). Table 3 shows that the impact values obtained range from 0.117 J/mm 2 to 0.285 J/mm 2 . The bar graph for the impact value comparison can be seen in Figure 7.

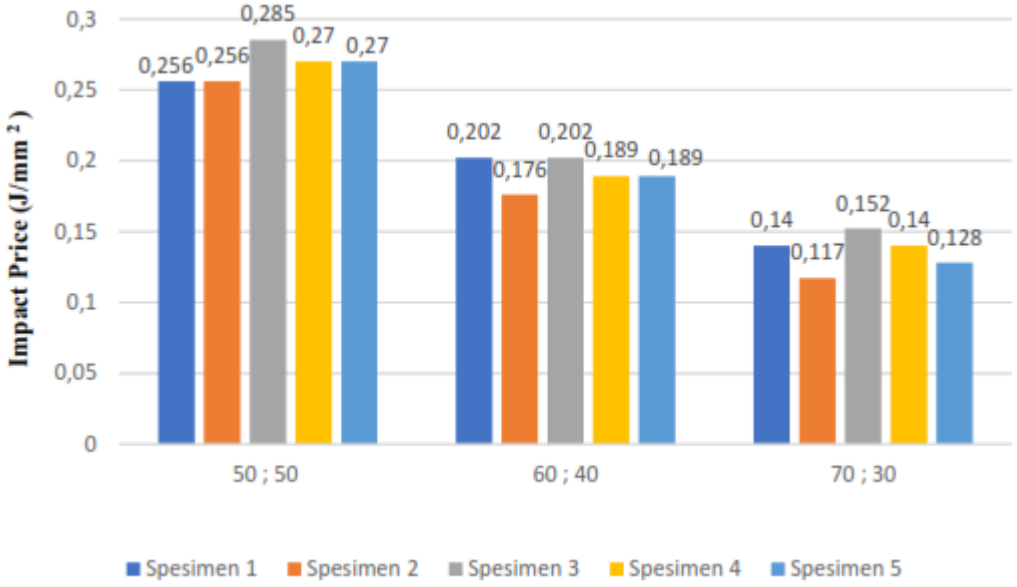

Figure 7. Bar Chart of Impact Price Comparison from Impact Test Results

The Impact Value Bar Chart shows that the 50:50 composition produces the highest impact value, which is 0.256–0.285 J/mm^2, which indicates the material's ability to absorb energy per cross-sectional area

optimally. This value reflects the composite's balanced microstructure between the matrix and reinforcement, resulting in a more even distribution of load and energy (Callister & Rethwisch, 2014).

At compositions of 60:40 and 70:30, the impact strength decreased significantly to within the range of 0.117–0.202 J/mm^2. This decrease was caused by excessive reinforcement content, which could potentially cause particle agglomeration, porosity, and microstructural defects, thus triggering initial cracking during impact loading (Hull & Clyne, 1996).

In addition, polystyrene as a matrix has a higher impact strength than filler. Excessive addition of filler disrupts the continuity of the matrix and reduces the energy absorption capacity, in line with the findings (Gurmu et al., 2024) which state that impact energy tends to decrease when the filler content exceeds a certain limit due to suboptimal filler distribution. Based on these results, the 50:50 composition can be concluded as the optimal ratio with the best impact performance, making it suitable for composite applications that require high toughness.

In this study, micro observations were conducted using a digital microscope with a magnification of 300 µm . In this study, micro observations were conducted using a digital microscope. The best composite specimens of skewer waste particles and polystyrene, which have undergone bending and impact tests. The following are images of micro observations of tensile and impact test specimens with the best values.

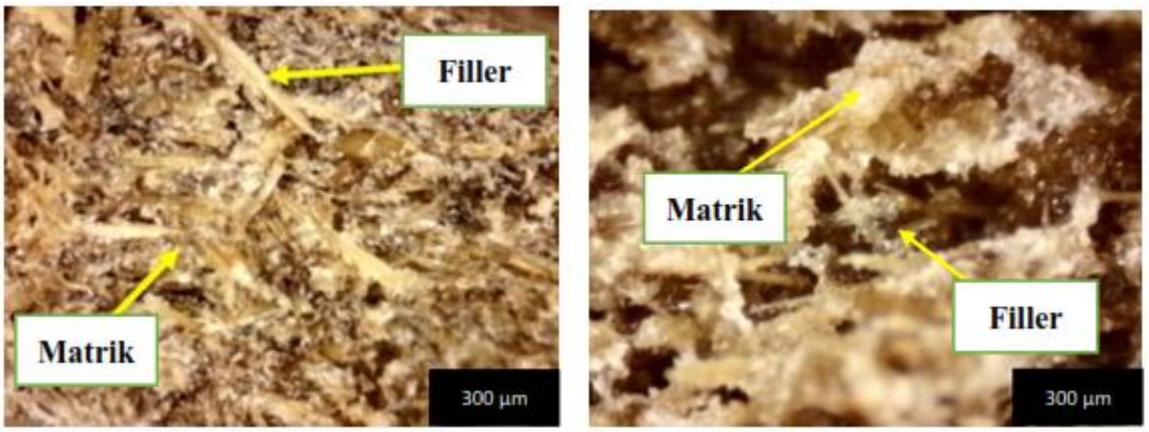

Figure 8. Micro Observation of Bending Test Comparison (70:30) and Impact Test Comparison (50:50)

Microscopic observations at 300 µm magnification showed that polystyrene composites reinforced with satay skewer waste particles, both at a ratio of 70:30 (bending test) and 50:50 (impact test), exhibited rough, inhomogeneous, and brittle fracture surface morphology. At a ratio of 70:30, weak interfacial bonding between the polystyrene matrix and the reinforcement particles was observed, characterized by the detachment of particles from the matrix and the presence of pores and voids. This condition causes local stress concentrations that accelerate crack initiation and propagation during flexural loading.

In a 50:50 composition, particle distribution is also uneven and tends to form agglomerations, thus strengthening stress concentrations. Interphase interactions appear less than optimal due to differences in polarity between the hydrophobic polystyrene matrix and the hydrophilic lignocellulose particles. This is characterized by clear phase boundaries, debonding, and the formation of micro-voids that weaken stress transfer within the material. Although there are indications of energy absorption through particle shearing mechanisms, the dominant fracture mechanism remains debonding, so that more impact energy is released through rapid cracks than absorbed by plastic deformation of the matrix.

Theoretically, composite toughness is strongly influenced by the quality of the matrix-reinforcement bond, the homogeneity of particle distribution, and the material's ability to resist and propagate cracks (Callister & Rethwisch, 2018). Differences in polarity in polymer-based composites with lignocellulose reinforcement often cause adhesion problems that trigger void formation and reduce mechanical properties (Sapuan, 2017). The failure mechanism in the form of debonding is a common characteristic of composites with weak interphase bonds and has a direct impact on low impact absorption energy (Hull & Clyne, 1996).

4. CONCLUSION

Bending tests showed that the polystyrene composite reinforced with skewer waste particles with a ratio of 70:30 had the best mechanical properties, characterized by a maximum bending stress value of 51.48 MPa and an elastic modulus of 4.88 GPa. This indicates that increasing the content of reinforcing materials can increase the flexural strength of the composite. Impact tests showed that the composite with a ratio of 50:50 had the best toughness compared to other variations, with a fracture strength value of 22.809 Joules and an impact value of 0.285 J/mm^2, which indicates the material's ability to absorb shock energy more effectively. Microstructural observations of the 50:50 composite showed weak interphase

bonds and inhomogeneous particle distribution, resulting in the formation of agglomerations and voids. This condition caused the failure mechanism to be dominated by debonding and rapid crack propagation, which contributed to a decrease in the impact toughness of the material.

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