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Mechanical Properties of Epoxy Composite Reinforced with Spent Coffee Ground and Coffee Husk

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Abstract. This study aims to investigate the effect of increasing the concentration of natural filler on the mechanical properties of Spent Coffee Ground (SCG) / Coffee Husk (CH) reinforced epoxy matrix composite. The materials used in this study are epoxy resin as a matrix and waste coffee grounds and coffee husks as natural fillers with sizes of 100-mesh and concentrations of 10, 20, and 30 wt.%. The results showed that SCG 10 wt.% produced the best mechanical properties compared to the other samples based on tensile strength (19.58 MPa), tensile modulus (1.70 GPa), flexural strength (44.55 MPa), and flexural modulus (2.32 GPa). On the other hand, CH 30 wt.% contributed the highest hardness value of 50.33 HRB compared to other samples. The findings in this study prove that the appropriate composition will affect the compatibility between the filler and the matrix, thus impacting the mechanical properties of the composite. This phenomenon can be seen based on microscope analysis, which shows a strong interaction between the matrix and filler and the formation of voids and agglomeration.

Keywords: Coffee ground, coffee husk, mechanical properties, natural filler, sustainable composites.

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1. Introduction

Natural filler is one of the reinforcements agent and alternative materials that are combined with polymer matrix as a composite because it presents a variety of advantages, including its abundance in nature, reducing production costs, and supporting physical, mechanical, thermal, and tribology properties [1], [2]. Several natural fillers based on agricultural waste that are compatible with polymer matrices include wood dust, nut shell, palm kernel, rice husk, and coffee ground [3], [4], [5], [6].

The coffee beverage industry continues to increase due to the public trend of enjoying coffee in various indoor and outdoor activities. This impacts the waste production of coffee grounds and coffee husk [7]. Using coffee waste as a natural filler in polymer matrix composites continues to show significant development because it involves sustainable development goals (SDG) practices such as low carbon footprint, economic growth, reducing environmental change, and creating a sustainable and innovative industry [8].

The characteristics and structure of coffee waste play a crucial role in interacting with the matrix [9]. Increasing the concentration of 0-60% coffee grounds into polypropylene increased the density from 0.91 g/cm3 to 1.04 g/cm^3, but decreased the tensile strength from 33.9 MPa to 11.3 MPa [10]. In addition, variations in filler loading of coffee husk waste of 20 - 40 wt.% also showed a downward trend in tensile strength from 5.65 MPa to 4.99 MPa [11]. The high amount of coffee particles in the matrix makes it difficult for the filler to migrate, thus creating a weak bond and accelerating failure [12].

Proper composition and fabrication methods will create homogeneous filler distribution and strong interlocking [13]. However, incompatible bonds between matrix and filler can lead to aggregation and voids [14]. The defect can occur due to the hydrophobic polymer and hydrophilic coffee waste forming poor adhesion [15]. This condition is a crucial aspect in the development of natural filler-reinforced composites due to the composite structure and defects that can affect the performance of the composite [16].

Combining coffee waste and different polymers will present diverse interaction behaviors in forming composites. Therefore, exploring and improving the understanding of coffee waste in the green composite industry is essential in research activities. This study investigates the filler content of spent coffee grounds and coffee husk types on the mechanical properties of epoxy matrix composites and the fracture surface. This study reveals the importance of understanding the composition and distribution of fillers in polymer matrix composites. Furthermore, using coffee grounds and coffee husks in composites reduces waste and supports the creation of industries that practice sustainable development goals (SDGs).

2. Methods

2.1. Material

The materials used in this research are epoxy resin (Epikote 828) as the matrix and epoxy hardener (651), which were purchased from IZE Solution Company, Selangor, Malaysia. Natural fillers consisting of spent coffee grounds and coffee husk as reinforcement were obtained from a local coffee shop in Jakarta, Indonesia. Spent coffee grounds (SCG) and coffee husks (CH) were converted into fine particle sizes of 100-mesh using a grinder and sieve shaker, dried at room temperature, and stored in plastic boxes under closed conditions to prevent direct contact with a humid environment.

2.2. Fabrication

SCG and CH were placed in a vacuum oven at 115 °C for 24 hours to remove the moisture content that could interfere with fabrication. Natural filler was put into a plastic box, and each type of CG and CH filler was combined with the epoxy based on the composition shown in Table 1.

The epoxy matrix and natural filler were placed in a plastic box and mixed using the principle of mechanical stirring until the filler was evenly distributed into the matrix. The composite was fabricated by the hand lay-up method, where the mixture was poured into a 30 x 30 x 0.3 cm plastic mold until it occupied all the space and was flattened using rolling. After that, the composite was allowed to harden at room temperature for 24 hours.

Table 1. Composition epoxy matrix composite reinforced with SCG and CH.

Sample	Epoxy (wt.%)	Spent Coffee Ground (wt.%)	Coffee Husk (wt.%)
Epoxy	100	0	0
SCG10	90	10	0
SCG20	80	20	0
SCG30	70	30	0
CH10	90	0	10
CH20	80	0	20
CH30	70	0	30

2.3. Testing

Epoxy/SCG and epoxy/CH composites were fabricated for mechanical testing and microstructure analysis. The composites were cut using laser cutting to produce tensile, flexural, and hardness test samples by the dimensional standards and test specifications adopted in ASTM D638, D790, and D2240 [17], [18], [19]. Tensile and bending tests were conducted using a 30 kN universal testing machine (INSTRON 3369, United States) with a crosshead speed of 2 mm/min, and hardness testing was performed using a Zwick Roell Rockwell hardness tester. The fracture surface of the tensile test specimen was utilized as a sample for the composite microstructure test using MEIJI TECHNO, Japan, with 2.0 times magnification. Each composition was prepared with 7 test samples to obtain five reliable data points for further analysis.

3. Results and Discussion

3.1. Mechanical Properties

Epoxy/SCG and epoxy/CH composites with variations in weight fraction have been examined for mechanical properties, including tensile strength, tensile modulus, tensile displacement at the break, flexural strength, flexural modulus, and flexural displacement at the break as shown in Table 2.

Table 2. Mechanical properties of epoxy matrix composite reinforced with SCG and CH filler.

Sample	Tensile Strength (MPa)	Tensile Modulus (GPa)	Tensile Displacement at Break (mm)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Flexural Displacement at Break (mm)
Epoxy	19.16	1.49	1.33	33.74	2.17	2.29
SCG10	19.85	1.70	1.40	44.55	2.32	3.33
SCG20	18.54	1.41	1.21	29.84	1.74	2.25
SCG30	14.91	1.18	0.95	29.58	1.65	2.22
CH10	13.1	0.78	1.76	25.64	1.40	2.08
CH20	9.80	0.70	1.70	24.00	1.37	2.07
CH30	9.44	0.64	1.43	19.34	0.83	2.05

Table 2 shows that adding SCG and CH natural fillers with 10, 20, and 30 wt.% concentrations into the epoxy matrix significantly affects mechanical properties. The SCG 10 wt.% composite showed the most outstanding performance compared to the other samples based on tensile strength (19.85 MPa), tensile modulus (1.70 GPa), flexural strength (44.55 MPa), and flexural modulus (2.32 GPa). However, as the filler content increased, there was a decrease in all mechanical properties in both SCG and CH. In summary, the results of this study show that ECG composites have superior mechanical performance compared to ECH composites for the same amount of filler concentration.

The addition of 10 wt.% of SCG into epoxy contributes to the improvement of mechanical properties due to the formation of strong interlocking between the matrix and filler, resulting in stress being able to be transferred to the filler as a reinforcement of the composite [20]. In addition, the filler can inhibit the rate of crack propagation when the composite receives mechanical loads, thus supporting the increase in mechanical strength [21]. On the other hand, increasing the SCG and CH concentrations by 20 wt.% and 30 wt.% in the matrix contributed negatively to the decrease in mechanical properties, where the values were lower than those of pure epoxy. This phenomenon is caused by the presence of voids and the formation of agglomerations of fillers that accelerate the failure process of the composite [22]. CH composites show lower mechanical properties than SCG composites due to the large agglomeration formed and dispersed in the composite. This can occur because of poor wetting of the filler into the matrix caused by differences in material properties and interactions [23].

In the case of tensile displacement at break and flexural displacement at break, the SCG composites showed the highest values in the range of 1.18-1.70 mm and 2.22-3.33 mm, while the CH composites presented lower values of 0.64-0.78 mm and 0.83-2.68 mm. The SCG samples indicate a more flexible material characteristic due to the excellent interaction between matrix and filler, so that the composite can stretch longer before fracture. The ECH sample indicates brittle material characteristics due to the formation of agglomeration and voids, as presented in the microscope analysis results in Figure 1. The findings in this study show that coffee grounds with a concentration of 10 wt.% show strong potential as a natural reinforcement in epoxy composites. This opens opportunities for further research focusing on particle size optimization and chemical treatment. Moreover, natural filler can be applied for lightweight structures and the green material industry [24].

Figure 1 shows the effect of increasing the concentration of natural filler types of coffee grounds and coffee husks on the hardness of epoxy resin composite. Increasing the concentration of 10% SCG and CH shows a decrease in hardness from 40.18 HRB (pure epoxy) to 34.2 and 36.23 HRB. However, increasing the natural filler concentration to 20 and 30% shows an increasing trend to 42.23 and 48.53 HRB for SCG and 44.00 and 50.33 HRB for CH. The result of this study is that the appropriate filler concentration contributes significantly positively to the composites' hardness. According to Tellers et al. (2021), oil-extracted SCG makes the epoxy harder than the pure epoxy resin. Increasing filler content or using treated SCG tends to make the cured composite stiffer (higher modulus) and thus harder on micro- or macro-hardness scales [25].

The highest increase in hardness is shown at 30% natural filler concentration, where CH is higher than SCG because CH filler has a rigid structure [26]. Increasing the amount of filler supports the creation of a complex composite structure, and the filler inhibits the movement of epoxy molecules, resulting in a stiffer composite that is resistant to surface deformation [27]. However, the rigid characteristics of CH and the large filler create a strong structure that increases its hardness [28]. On the other hand, 10 wt.% of CH and SCG concentration shows the lowest hardness value compared to other specimens. This is due to natural fillers that cannot support the stability and robustness of the epoxy structure, so the composite easily experiences the phenomenon of surface deformation [29]. The composition, filler characteristics, and bond forming between the matrix and natural filler are crucial in creating a natural filler-reinforced polymer composite with superior performance.

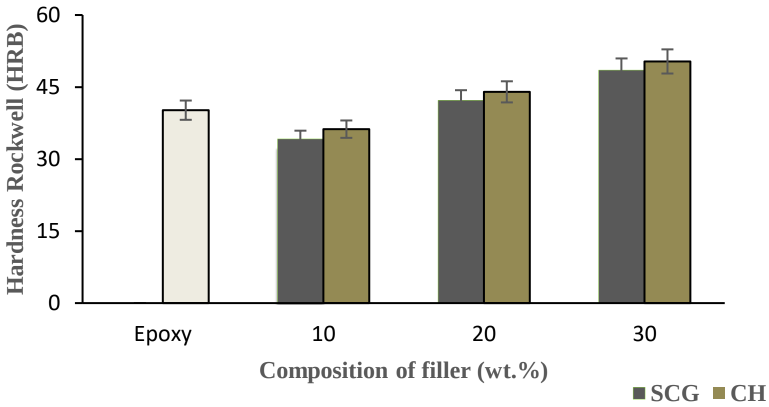

Figure 1. The hardness properties of epoxy matrix composite reinforced with SCG and CH filler.

3.2. *Fracture Morphology*

Macrostructure analysis aims to observe the fracture surface phenomenon of SCG and CH composites, where the fracture surface specimens used in this study are the results of tensile fractured tests of SCG (Fig. 2a-2c) and CH (Fig. 2d-2f) composites with varying natural filler concentrations of 10, 20, and 30 wt.%.

The macroscope analysis exhibits the appearance of crack bridging, indicating a strong interlocking between the filler and the matrix. This phenomenon occurs due to the decisive role of the filler in inhibiting crack propagation, thus contributing to superior tensile and bending strength (Fig. 2a). The increasing of SCG and CH concentrations to 20 and 30 wt.%, respectively, caused a complex behavior of the filler to move within the matrix during the fabrication and hardening procedure, resulting in void-type defects [30]. In addition, defects may be formed due to trapped air during the mixing process, insufficient bonding between the filler and the matrix, and the behavior of the filler to stick together and form groups [31]. The larger the number of voids and the larger the size (Fig. 2b-2c), the faster the failure mechanism will be, thus reducing the tensile and flexural strength, as shown in Table 2.

On the other hand, CH has different characteristics from SCG when combined with epoxy. Adding CH at concentrations of 10, 20, and 30 wt.% (Fig. 2d-2e) creates a combination of defects, including voids and agglomeration. The number of these filler aggregates appears to increase with increasing CH concentration, contributing to stress concentration and leading to failure of the matrix to transfer stress into the filler [32]. This phenomenon caused faster fractures and reduced tensile and flexural strength.

Through microscopic examination, Tezara et al. (2022) observed that composites with high filler loadings (around 40 wt.%) typically exhibit particle agglomeration and void formation. In contrast, those with moderate filler content (approximately 20–30 wt.%) show a more uniform filler distribution within the matrix [4]. These findings highlight that filler loading is a critical and adjustable parameter that must be optimized. While low to moderate levels of agricultural waste fillers can improve the stiffness and strength of epoxy composites, excessive loading often results in agglomeration, voids, and a consequent decline in mechanical performance [33].

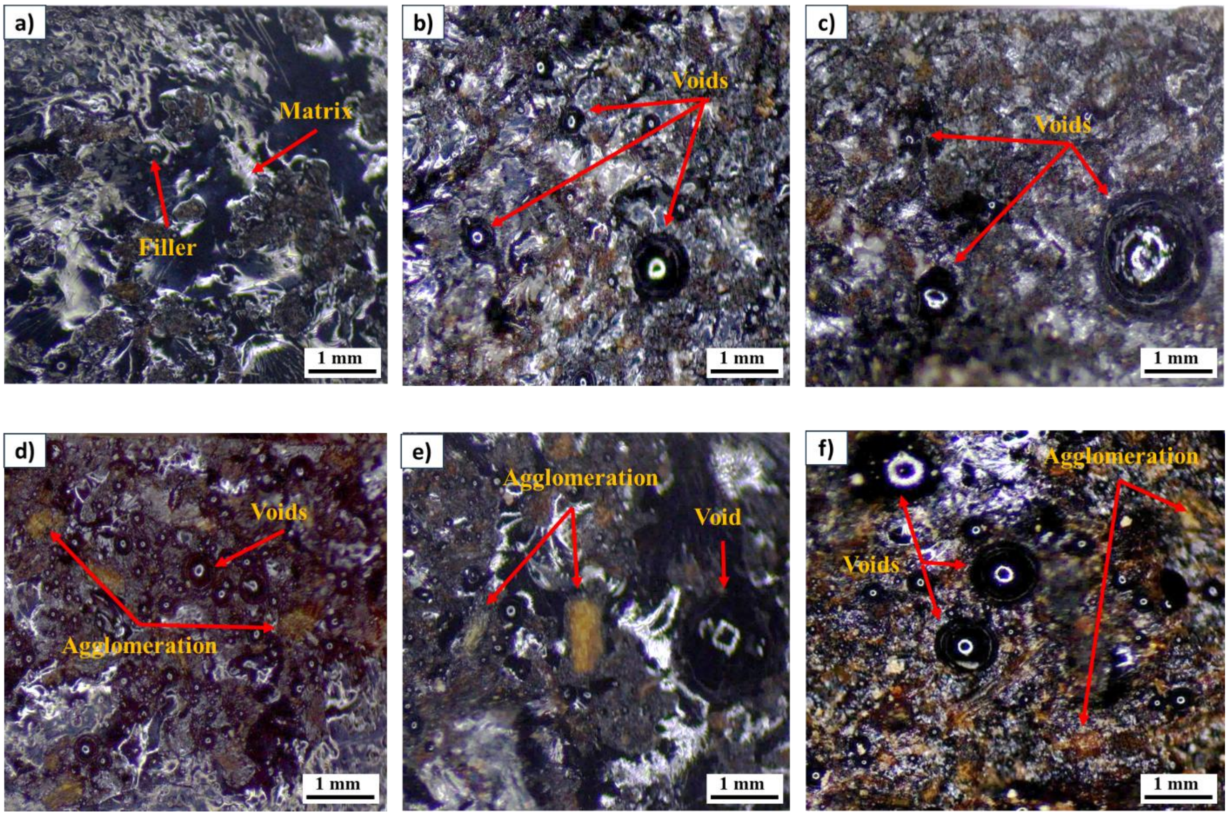

Figure 2. Tensile surface fractured of epoxy composite with SCG 10-30 wt.% (a-c) and CH 10-30 wt.% (d-e).

Conclusions:

This study successfully utilized spent coffee grounds (SCG) and coffee husks (CH) as natural fillers in epoxy composites, promoting sustainability by valorizing agricultural waste. The mechanical performance of composites reinforced with 10, 20, and 30 wt.% of SCG and CH was evaluated. Among all samples, the SCG composite with 10 wt.% loading exhibited the highest tensile strength (19.58 MPa), tensile modulus (1.70 GPa), flexural strength (44.55 MPa), and flexural modulus (2.32 GPa). In contrast, increasing filler content led to a decline in these mechanical properties for SCG and CH composites. Overall, SCG fillers outperformed CH in terms of mechanical strength at equivalent loadings. However, CH showed superior hardness at 30 wt.%, likely due to its contribution to a denser, more rigid matrix. Voids and agglomeration in CH-reinforced composites, especially at higher loadings, introduced stress concentration points and reduced structural integrity. The findings align well with the goals of sustainable development, especially SDG 12 on responsible consumption and production, by utilizing agricultural waste to make functional composite materials. This research shows a practical way to reduce environmental impact while supporting innovation in materials science. Besides, it offers practical knowledge for academics and researchers interested in eco-friendly materials. It provides a solid starting point for future work in waste-based composites, material improvements, and sustainable engineering solutions.

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