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Research Article

Date Palm Fiber-Reinforced Recycled Polymer Composites: Synthesis and Characterization

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In this research study, Recycled Polymer (RP) composites are synthesized by using compression molding process, initial mixtures of RP and Date Palm Fibers (DPF) with four different lengths (e.g., 2.5, 5, 7.5, and 10 mm) and weight ratios (e.g., 5, 10, 15, and 20 wt%). The RP composites utilized in this study are polyethylene and polypropylene. The mixtures of RP and DPF are heated at 80°C and then poured into a priori prepared mold. The mold is designed to have three cavities for three specimens in order to characterize them through impact, creep, and tensile tests. The results showed that the hardness and impact increased with this process. In addition, an increase in the DPF up to 15 wt% was observed with a small increase in the DPF length. High creep resistance was also observed to be 10 mm with 20 wt% in the DPF specimens. The maximum strain was obtained in a 2.5 mm fiber length with 5% of DPF due to ductility of the plastic matrix. Moreover, with a small ratio of tough DPF, short fibers are unable to block or resist rapid plastic deformation in specimens. In fact, the DPF specimens of 10 mm length with 20 wt% exhibit a high tensile strength of 78 N/mm^2 in comparison with other composite specimens. This is due to the length and content of fibers, which improve transferring action and microfailure modes.

1. Introduction

Thermoplastic material has replaced most of the metals used in many applications. Commercial consumption of plastic has become noticeable in the past centuries, despite of the increase in its price. Therefore, reinforced plastic material was developed to reduce prices and increase efficiency [1]. To replace metals with thermoplastics, their properties must be improved to be the perfect competitor to metals, as most metal-based applications require high hardness and high impact strength. Stronger plastic composites (e.g., natural fibers and polymer) can offer considerable advantages because they (1) are low cost materials, (2) are available, (3) can be easily manufactured, (4) have low density per unit volume, (5) have high strength, and (6) are not toxic and not harmful to the skin and eyes [2]. Moreover, mixing natural fibers with petrochemical polymers increase the degradability of composites. This type of polymer is a source of environmental pollution, and it is harmful to wildlife when spread in the environment. Globally, approximately 40 million tons of single-use plastic packaging are used annually [3]. Recently, the interest in recycling plastic has been increased in order to reduce environmental pollution and energy consumption in addition to using the resources appropriately. In fact, recycling contributes effectively in the reduction of production costs.

The shape of fibers is typically cylindrical with a diameter of 100-1000 μm. The main components of fibers are cellulose, hemicellulose, and lignin where hemicelluloses and lignin are considered to be the support material in cellulose microfibers. Composites reinforced with natural fibers are among the most promising advanced materials because of their similar properties with some metals, which are used in most modern engineering structures [4]. Fiber-reinforced composites include parts made for airframes, cars, spacecraft, ships, many sports equipment, and infrastructure [5]. The use of synthetic fibers, produced from petroleum, has been decreasing due to the continuing tendency to introduce natural fibers in modern engineering applications. Natural fibers are found in animals and plants

Table 1: Research studies on thermoplastic-based RP-DPF composites.

Reference	Fabrication method	Type and rations of fibers	Matrix materials	Mechanical tests
Alawar et al. [16]	Double screw extruder	Untreated date palm tree fibers with rations of 25 wt%.	Polypropylene	Tensile strength and modulus of elasticity
Sadik et al. [17]	Hand layup	Date palm frond fibers with rations of 30, 40, and 50 wt%.	Polyethylene	Tensile strength, bending strength, impact strength, and hardness
Mahdavi et al. [18]	Extruder, hand lumpy shapes, and hot press	Trunk, rachis, and petiole with rations of 20, 30, and 40 wt%.	Polyethylene	Tensile strength, and flexural strengths
Alewo et al. [19]	Casting poured into the prepared mold prepared samples were then cut according to ASTM	Date palm seed particle with rations of 5, 10, 15, 20, and 25 wt%.	Polyester	Tensile strength, elastic modulus, and hardness
Al-Otaibi et al. [20]	A twin-screw extruder and injection molding machine	Date palm fiber with rations of 5, 10, and 15 wt %	Recycled homopolymer polypropylene	Tensile strength and tensile modulus
Alsewailem et al. [21]	The blends were melt mixed for 10 min and then injected into a mold	Date pits with rations of 30 wt%	High density polyethylene (HDPE) and polystyrene (PS)	Tensile and impact
Lei et al. [22]	Composites with dimensions of $350 \times 350 \times 5\ mm^3$ were obtained using thermocompression. Thermocompression was performed in a hydraulic press	Wood and bagasse with rations of 30, 40, and 50 wt%	Recycled high density polyethylene (RHDPE)	The modulus and impact strength
Dehghani et al. [23]	Composites were prepared using twin-screw extruder followed by injection molding	Surface treated date palm leaf fiber with rations of 5, 10, and 15 wt%	Recycled poly (ethylene terephthalate)	Tensile strength, flexural strength, and impact strength
M.d. K. Hossain et al. [24]	Composites were prepared using 8 inch × 6.5 inch rectangular closed steel mold of 450KN Weber-press together with the HDPE pellets. The mold was then compressed with 100KN pressure at 145°C for 20 min and allowed to cool to room temperature	Jute-mat fiber with rations of 25 wt %	Density polyethylene (HDPE)	Tensile strength, young modulus, flexural strength, tangent modulus, and hardness
Masri et al. [25]	The reinforcement is mixed with the matrix and lignin. Then, the mixture (reinforcement/matrix/lignin) is poured into a metal mold to obtain plates of dimensions $240 \times 120 \times 10\ mm^3$; a holding pressure of 3.5 bar is applied for 10 min to ensure a good distribution of the mixture and to reduce the air in the LPC	Leaflet with rations of 70%	Recycled polystyrene	Three-point bending tests and elastic modulus

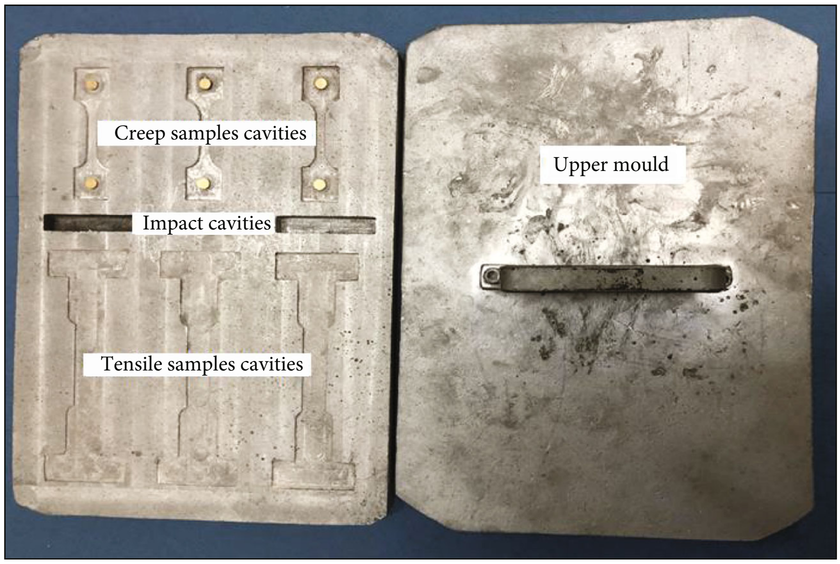


Figure 1: Iron compression mold after machining and polishing.

[6]. They provide the perfect alternative to expensive and environmentally harmful synthetic fibers [7]. In addition, they have high moisture absorption and low compatibility with the matrix. To remedy these shortcomings, the surface properties of fibers must be improved [8].

Many researchers have conducted their studies on the properties of thermosetting polymers with DPF composites [9–15]. However, in this research study, the mechanical properties of the thermoplastic-based RP-DPF composites have been enhanced by using natural fibers, recycled polyethylene and polypropylene, and steel mold in addition to using different fabrication method, matrix materials, fiber types, and weight ratios in comparison with the testing settings shown in Table 1 [16–25]. Note that the proposed fabrication method is performed with a lower cost in comparison with the methods introduced in the literature due to using recycled polyethylene and polypropylene polymers. In this study, the fabrication method involves softening, adding a reinforcement, mixing, and pouring the mixture into the mold. In fact, the results demonstrated in this study have been obtained by synthesizing recycled plastics with natural fiber composites using cheap and abundant material with good properties (e.g., low density per unit volume, high strength, and not toxic, and not harmful to the skin). It should also be noted that the results of the mechanical tests, demonstrated in Table 1, differ from each other due to the difference in fabrication method, matrix materials, and fiber types and weight ratios.

2. Experimental Testing and Setup

2.1. Raw Material Preparation. In the present study, the raw materials were chosen from plastic scrap (i.e., thermoplastics RP such as polyethylene and polypropylene) as the matrix and DPF for reinforcement in order to synthesize polymer-DPF composites.

2.1.1. Matrix Material. The most important thermoplastics include low- and high-density polyethylene, polypropylene, polyvinyl chloride, and polystyrene [26]. Thermoplastics are used in many applications such as wires and many structures of mechanical parts and can be used effectively as a matrix for natural and synthetic fibers [27]. By reheating the plastics, it can be formed or reshaped according to the used molds. In this study, polyethylene and polypropylene polymers are recycled with a temperature below 230°C. Sorting, shredding, washing, softening, and shaping have been performed as the first steps to prepare the matrix material of composites.

2.1.2. Reinforced DPF. The reinforced material was chosen in this study to be DPF from leaf sheath. The DPF was obtained from a local Saudi date palm. The chemical composition was 43-46 wt% cellulose, 18-24 wt% hemicellulose, 20-28 wt% lignin, 5-10 wt% ash, and 2-11 wt% moisture content [13, 14, 28]. The mechanical properties of natural fibers depend on the central void, porosity, helical angle, and two degrees of crystallinity [29]. The DPF were collected in ethylene plastic containers. The samples were then washed with water and then alkali treatment (with 5 wt% NaOH solution for 30 min) has been done to improve the RP and DPF interfacial adhesion. At the room temperature, fibers were dried and then cut into average lengths of 2.5 to 10 mm using a sharp blade. After initial drying, they were dried again in a vacuum oven at 40°C for 12 hours. Then, fibers were kept in an insulated and emptied container for the time of use. Only fibers up to 0.3 mm in diameter were used for this study.

2.2. Mold Fabrication. Iron compression mold of dimensions 30 cm × 19 cm × 3 cm was fabricated by a CNC milling machine. The machining process has been conducted for specimen's cavities, prepared for tensile, impact, and creep tests, according to the standard dimensions of GUNT mechanical testing machine. In fact, three main shapes were

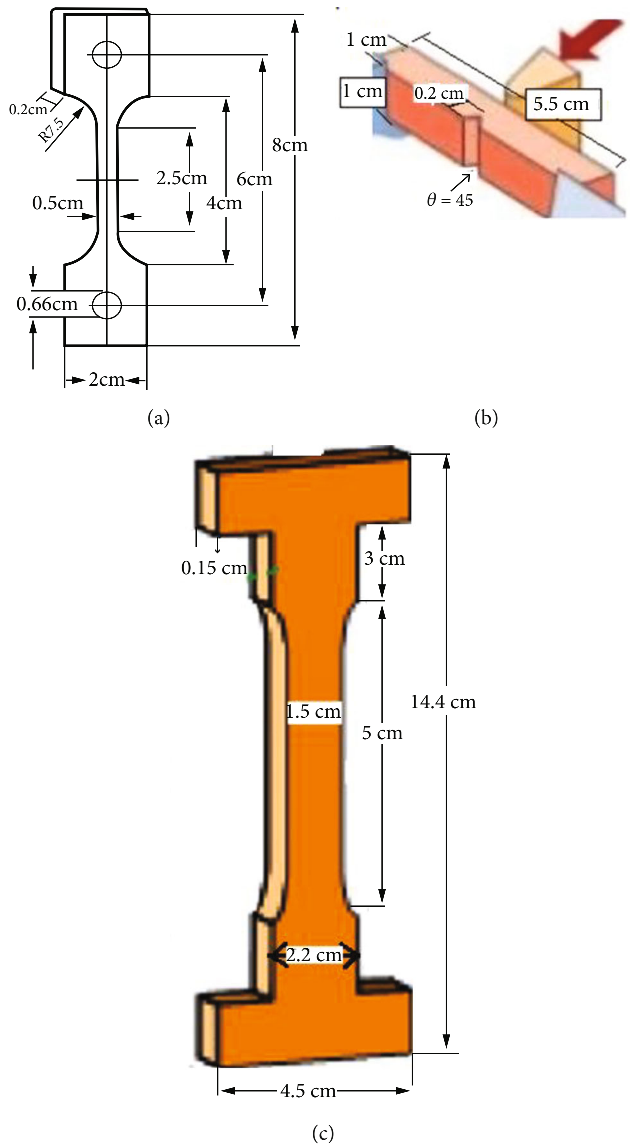


FIGURE 2: Specimens' dimensions for (a) creep, (b) impact, and (c) tensile tests.

TABLE 2: Raw materials used to prepare the specimens.

Specimen no.	RP content (wt%)	DPF content (wt%) with different lengths (2.5-10 mm)
1	95%	5%
2	90%	10%
3	85%	15%
4	80%	20%

needed for testing and were fabricated using iron compression mold. The iron compression mold, as shown in Figure 1, can be reused several times in molding the specimen. The dimensions of specimens, prepared for creep, impact, and tensile tests, were chosen according to the American Society for Testing and Materials (ASTM): standards D638 and D6110 [30] (refer to Figure 2).

The completed mold needs a high attention to ensure a smooth release of the composite when it cures in the mold. For the first time, five layers of wax were required to ensure that the surface is fully covered. After that, only two layers of wax were sufficient to remove the composite from the mold easily.

2.3. Composite Preparation and Characterization. RP-DPF composites were prepared according to different weight ratio and lengths as shown in Table 2. Five steps have been performed to prepare the specimen for testing: (i) softening, (ii) adding the reinforcement, (iii) mixing using a stir technique, (iv) pouring the mixture into the mold, and (v) cutting of specimens.

The electrical furnace used for testing contained a cylinder with a 100 mm inner diameter, 150 mm height, and 10 mm thickness. This cylinder is made of graphite crucible and covered by iron lid. The purpose of using the stirrer rod

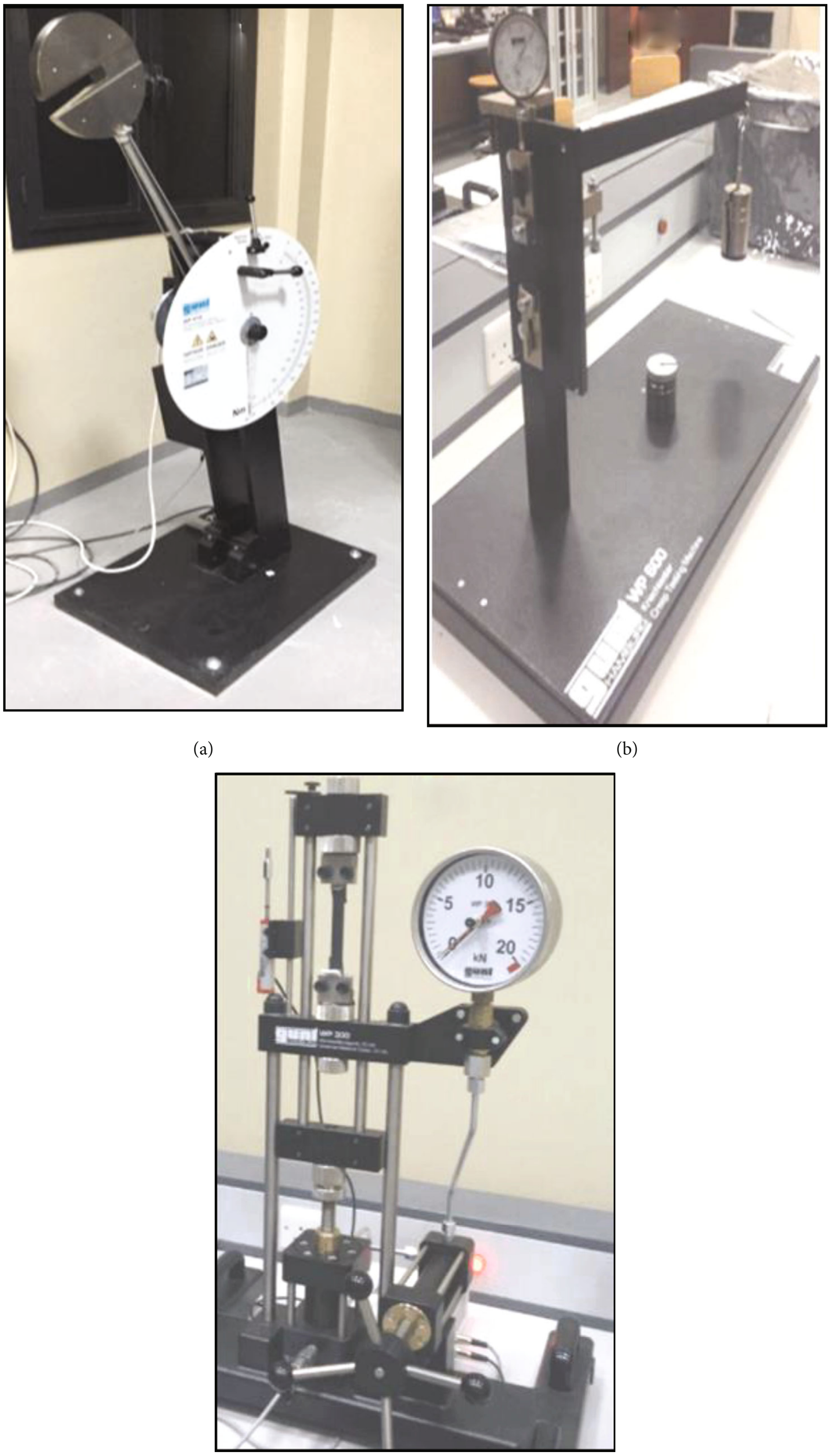
Figure 3: Different types of specimens with different lengths and weight ratios of DPF.

was to mix and distribute the added DPF in the thermoplastic matrix with slow motion and steady stirring to ensure that the mixing is done without formation of air bubbles (i.e., porosity). Plastic softening temperature ranged from 80 to 90°C and melting point ranged from 110 to 130°C. The reaction between plastic and oxygen started at 140°C in order to break the bonds in the main chain. The heating rate was 10°C/min, and the temperature was held at 80°C to make the plastic have high ductility. At 90°C, the DPF were added gradually for 10 minutes and held for 30 minutes with regular stirring to ensure a good homogeneity and wettability between the DPF and thermoplastic matrix. After getting the DPF homogenous, the DPF composite was compressed in an iron mold as shown in Figure 1. Before compressing the composite into the mold, it was necessary to reheat it, in order to improve the ductile condition, and restir it. These processes were repeated many times to fabricate different types of specimens with different lengths and weight ratios of reinforcements as shown in Figure 3.

Vickers hardness machine with a load of 60 kg was used for 5 seconds to investigate the influence of lengths and weight ratios of reinforcements on the DPF-polymer composite hardness. Four different testing points were taken for each specimens, and the average value was taken to eliminate any errors due to local nonhomogeneity. The four specimens were used to determine the average value of each property. The impact, creep, and tensile tests were carried out by using GUNT WP 410, GUNT WP 600, and GUNT WP 300 machines, respectively, as shown in Figure 4, in order to investigate the influence of lengths and weight ratios of reinforcements on DPF-polymer composites.

3. Results and Discussions

3.1. Hardness Test. Hardness measurement is one of the most rapid methods to determine the mechanical properties (i.e., tensile and impact strengths, creep, and wear) of the composites. Improvement of hardness depends on the amount, length, and uniform distribution of DPF. The results for average hardness values for different types of RP-DPF composites are shown in Figure 5.



(a) (b) (c)

Figure 4: Machines used for testing: (a) impact GUNT WP 410 machine, (b) creep GUNT WP 600 machine, and (c) tensile GUNT WP 300 machine.

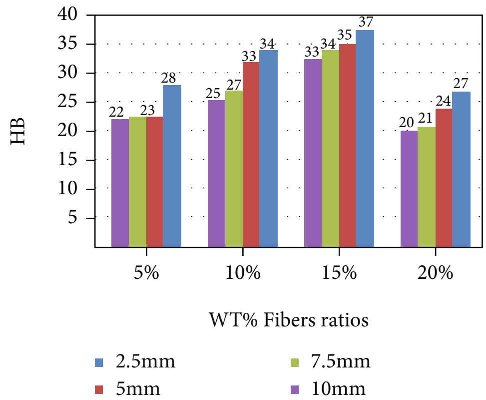


Figure 5: Average hardness values for RP-DPF composites for different lengths and weight ratios of DPF.

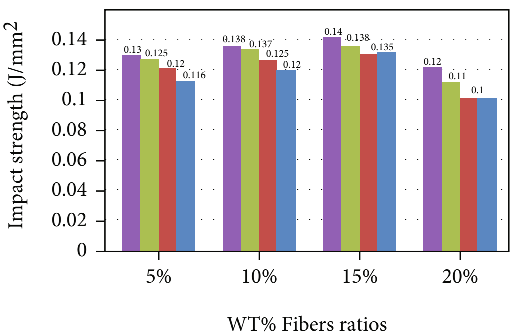


Figure 6: Impact strength for different lengths (2.5, 5, 7.5, and 10 mm) and different weight ratios (5 wt%, 10 wt%, 15 wt%, and 20 wt%) of DPF in the tested RP-DPF composites.

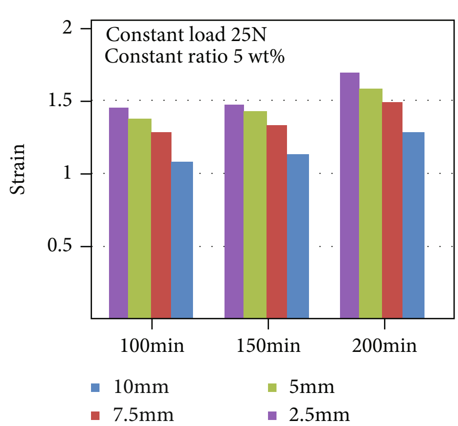


Figure 7: Strain values of RP-DPF composites for different lengths with constant weight ratio of 5 wt% and constant applied load of 25 N for different strain times.

In general, the hardness of RP-DPF composites with a 10 mm fiber length is less than the hardness of RP-DPF composites with other lengths of fibers (i.e., 2.5, 5, and 7.5 mm) at the same weight ratios (i.e., 5, 10, 15, and 20 wt %). In fact, the hardness of the RP-DPF composites with 10 mm fiber length and weight ratios of 5 wt%, 10 wt%,

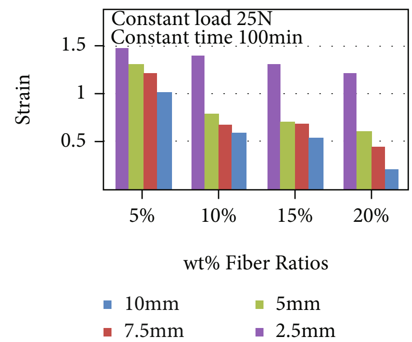


Figure 8: Strain values of RP-DPF composites for different lengths with different weight ratios and strain times and constant applied load of 25 N for 100 min strain time.

and 15 wt%, was 22, 25, and 33 HB, respectively. In other words, as the weight ratio increases, the hardness increases. With weight ratios of 20 wt% and fiber lengths of 2.5, 5, 7.5, and 10 mm, the lowest values of the hardness can be achieved. The highest hardness was observed to be 37 HB for the RP-DPF composites with 2.5 mm fiber length and weight ratio of 15 wt%. In general, the hardness results showed that shorter fibers have higher hardness in comparison with long fibers due to the good distribution of shorter fibers in comparison with the long fibers. Hardness also increases with increasing the content of DPF due to the high content of lignin, which refers to an irregular polymer chain (i.e., organic substance) that increases the strength and stiffness of RP-DPF composites. In the results proposed in this study, the contents of DPF and lignin were 15 wt% and 45 wt%, respectively. In addition, good interfacial bonding between the DPF and RP leads to higher strength of the composites [31–33]. The hardness of the RP-DPF composites with 20 wt% DPF decreases due to the less distribution of the agglomeration in the DPF, formation of porosity with a high amount of impurities during the mixing process, weak interfacial bonding between the RP and DPF in some parts, and disappearing of the RP matrix among fibers (i.e., weak mechanical properties). There is also a noticeable effect on the hardness due to the increase in gas bubbles within the matrix caused by the stirrer speed.

3.2. Impact Test. The improvement of the mechanical properties of the composite depends on the properties of the matrix and fibers. The impact test provides information about the bearing capacity of the composite to absorb shock before fracture. Therefore, brittle materials have less shock energy absorption in comparison with ductile materials. The toughness of materials is directly affected by the weight ratio and properties of toughness for both fibers and matrix, as well as the interfacial region and the withdrawal of fibers from the matrix [34–36]. In general, the impact increases with increasing the weight ratios and lengths of DPF as shown in Figure 6.

In order to obtain a good impact measure, appropriate bonding and adhesion levels are required. Effective stress transfer between fibers and the matrix depends on the length of fibers. It should be noted that the length of fibers is critical

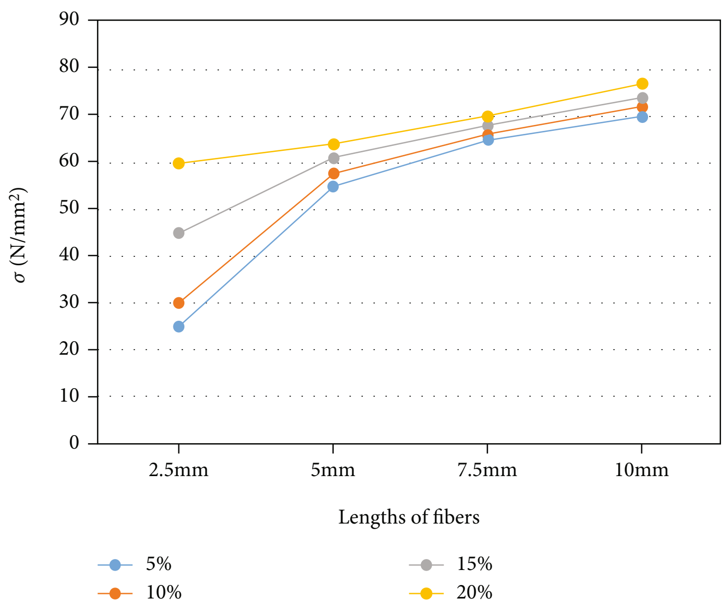


Figure 9: Tensile strength for different lengths and different weight ratios of DPF in the RP-DPF composites.

so that they should not be less than a certain value in order not to lead to a sample failure due to debonding at low loads. On the other hand, for fiber lengths larger than the critical length, the applied load leads to effective stress transfer between fibers and the matrix. Thus, higher impact strength can occur [37]. Random distribution of fibers with strong interfacial adhesion between RP and DPF leads to significant crack propagation resistance [38].

From the results in Figure 6, the impact strength, tested for 2.5, 5, 7.5, and 10 mm lengths, increases with increasing the DPF up to ratios of 15 wt%. Increasing the weight ratios and length of DPF increases the impact strength. Note that tough DPF with strong interfacial adhesion between RP and DPF in addition to the existence of fiber lengths that are greater than the critical length with good random distribution of DPF will achieve good stress transfer from the matrix to fibers. The impact strength of composites for different DPF lengths with 20 wt% DPF decreased due to the less distribution of agglomeration in DPF, porosity with high amount of impurities, and weak adhesion between RP and DPF due to the disappearing of RP matrix among fibers that certainly leads to lower stress transfer.

3.3. Creep Test. The strain variation with respect to time under a continuous loading can be used to measure creep. The most important factors that may affect the creep rate of composites are the fiber length, weight ratio, interaction with the matrix inside the composites, temperature, humidity, and the level of stress applied to the composite. Increasing the fiber content and the interfacial interaction between fibers and the matrix reduces the creep rate [39]. One of the challenges of replacing metals with thermoplastics is that many structural parts need to be rigid and provide high impact strength and low creep rate.

Figure 7 shows the strain values of RP-DPF composites for different lengths with a constant weight ratio of 5 wt% and constant applied load of 25 N. Initially, the creep rate is relatively high, while it decreases rapidly with time, which could be due to slipping and orientation of the polymer chains under constant stress. In addition, after the primary creep (i.e., high creep rate), the creep reaches a constant rate in the secondary creep stage. With a low stress level, the polymer may stay longer in this stage. In the final stage, creep rate increases again, leading to fracture of the material.

The creep strengthening is associated with the load transfer from the matrix to reinforcements. Fiber length and content both have significant effects on stress state. Short fibers reduce the maximum stress where long fibers have better stress transferring action than the short ones. Creep resistance increased by increasing the length and content of fiber as shown in Figure 7. Random orientation, good distribution, and long fibers with strong interfacial adhesion between RP and DPF raise significantly crack propagation resistance, which improves creep resistance [38, 40]. Many microfailure modes occurred during creeping such as fiber pulled out, fiber breakage, interfacial debonding, and matrix cracking, which lead to increasing the creep rate. By improving microfailure modes, the creep rate can be decreased.

From Figure 8, the strain decreased with increasing the DPF length and content. The strain for shorter fibers (i.e., 2.5 mm) of 2.5 mm with 5 wt%, 10 wt%, 15 wt%, and 20 wt % DPF content were 1.4, 1.3, 1.2, and 1.1, respectively. The maximum strain was obtained using the length of 2.5 mm and 5 wt% DPF content due to the ductility of the plastic matrix. With a small ratio of tough DPF, short fibers were also unable to block or resist rapid plastic deformation in specimens. The strain of long fibers (i.e., 10 mm) with 5 wt %, 10 wt%, 15 wt%, and 20 wt% DPF content were 0.97, 0.56, 0.5, and 0.2, respectively. The minimum strain was obtained using the length of 10 mm and 20 wt% DPF content. It was obvious that the content and length of fibers improve transferring action.

3.4. Tensile Test. Many researchers reported that adding natural fibers in a polymer has a significant effect on the tensile strength properties. In general, the tensile strength of the RP-DPF composites increase with increasing the fiber length and content as shown in Figure 9. When the matrix is reinforced with materials such as fibers or even metal powder, a decrease in ductility is observed and hardness is affected. From Figure 9, the tensile strength increases with increasing the DPF length and content in RP matrix. The tensile strength of shorter fibers (i.e., 2.5 mm) with content of 5 wt %, 10 wt%, 15 wt%, and 20 wt% DPF content were 26, 30, 45, and 60 N/mm^2, respectively. The minimum strength was obtained using a 2.5 mm length and 5 wt% DPF content due to ductility of the plastic matrix. A small weight ratio of stiffer short DPF reduces the maximum stress level. In addition, it was not able to hinder or resist crack propagation [39–41]. The tensile strength for long fibers (i.e., 10 mm) with 5 wt%, 10 wt%, 15 wt%, and 20 wt% DPF content was 70, 72, 75, and 78 N/mm^2, respectively. The maximum strength was obtained using a length of 10 mm and 20 wt% DPF content due to the fiber length and content that improve transferring action and microfailure modes. Reinforcement changes the paths and propagation of microcracks and fracture behavior. The changes in fracture behavior mainly occur because stress is transmitted along the material through the matrix and fiber interface. Thus, the interaction and adhesion of materials (i.e., the reinforcement and the matrix) and their general properties, including the surfaces of the reinforcement, have an important role in cracks and their occurrence. When a tensile load is applied directly to the samples, too much stress will be exerted on the fibers causing the weak fiber to fail. As the load continues, the intact fibers fail and stress shifts to the matrix leading to a failure.

4. Conclusions

A RP reinforced with various weight ratios of DPF was synthesized and characterized successfully. The mechanical properties such as hardness, impact, creep, and tensile strength are observed to be affected by DPF length and content. The results show that composites prepared with shorter fibers have higher hardness than those composites prepared with long fibers. The results also show that the hardness of the produced composites increases with increasing the fiber content up to 15 wt%. In addition, the impact strength increases with increasing the DPF length and content up to 15 wt%. The hardness and impact strength of composites with different DPF lengths and 20 wt% DPF content decrease due to the less distribution of agglomeration in DPF, porosity with high amount of impurities, and poor interfacial adhesion between the RP and DPF due to the disappearing of the RP matrix among fibers. The strain decreases with increasing the DPF length and content. The strain of the composites prepared with short fibers (i.e., 2.5 mm) and different fiber content (i.e., 5 wt%, 10 wt%, 15 wt%, and 20 wt%) were 1.4, 1.3, 1.2, and 1.1, respectively. The highest strain was obtained from a fiber length of 2.5 mm and 5 wt% DPF content due to ductility of the plastic matrix and the presence of a small ratio of tough DPF. Short fibers are also unable to block or resist rapid plastic deformation in specimens. The minimum creep and maximum strength were obtained using a fiber length of 10 mm and 20 wt% DPF content. It was clear that fiber length and content improve transferring action and microfailure modes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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