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# Mechanical and thermal properties of recycled polypropylene bamboo fibre-reinforced composites

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**ABSTRACT**

In this article, a kind of green composite was prepared from recycled polypropylene (r-PP) which was further reinforced with various loadings of chemically modified bamboo fibres. Effects of bamboo fibre loading on the mechanical and thermal properties of r-PP/bamboo composites were studied. Those properties were characterized by tensile testing, impact testing, thermogravimetric analysis (TGA), and differential scanning calorimeter (DSC). Standardized test specimens with 0%, 10%, 20%, and 30% mass fractions of bamboo fibre were obtained by an extrusion process which was then finalized on injection molding. The experiment revealed the tensile strength and strain of the composite become greater with the increase of bamboo fraction in the ultimate value of 20% mass fraction. The composite with 10% bamboo fibre loading recorded the highest value of impact strength. Meanwhile, it was evident that the presence of bamboo fibre decreased the thermal stability of recycled polypropylene materials. Therefore, this composite material may find good potential for semi-structural loading applications in relatively low-exposure working.



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## 1. INTRODUCTION

Plastic recycling is an alternative solution to the problem of the large accumulation of plastic waste in the world. Significant efforts are required to improve the quality of the material by increasing the use of recycled plastic as a substitute or complementary to virgin plastics. Several methods such as blending with the original plastic, stabilization process with certain additives, and the addition of filler material have been employed to improve the quality of recycled plastic materials. It has been found that fibre or rigid filler addition to recycled plastic can significantly change its mechanical properties [1].

Natural fibres are now widely used as a filler for thermoplastic composite due to their environmental advantage. Compared to synthetic reinforcing fibres, natural fibres are relatively low-cost [2]. The use of natural fibres as organic fillers in recycled plastic provides additional ecological benefits through the utilization of renewable materials. Several studies have shown changes in the microstructure and mechanical properties of recycled plastics with the addition of various types of natural fibres [3]–[5].

Bamboo is a type of natural fibre that has high mechanical strength, high stiffness, low density, and low selling price and is easy to obtain compared to other natural fibres such as flax, straw, and bananas [6]. The strength and stiffness of bamboo fibre are comparable to those of glass fibre [7] or wood fibre [8].

However, bamboo fibre has a much lower density and is cheaper than glass fibre and wood fibre [9]. In addition, bamboo fibre does not pose a health risk in the processing [10].

There are several types of research on the use of bamboo fibre as a composite reinforcement that has been previously carried out. Chattopadhyay *et al.* [11] stated that 50% by volume of bamboo fibre in polypropylene composites resulted in an increase in impact strength of 37%, flexural strength of 81%, and tensile strength of 105%. Cunhong *et al.* [12] showed that the surface treatment of fibre on bamboo was able to increase the mechanical strength of the resulting polypropylene-bamboo composite. In addition, another study also stated that the tensile strength and modulus of elasticity in bamboo composites increased after the addition of the volume fraction of bamboo fibre [13].

Previous research by the author has explored the use of recycled materials as the matrix of bamboo-based composite. The mechanical properties measured by impact strength on bamboo composites with recycled high-density polyethylene (HDPE) matrices were better than composites with virgin HDPE matrices [14]. However, it was found that virgin HDPE/bamboo composites had better thermal stability than r-HDPE/bamboo composites [15].

The use of recycled polypropylene as a composite matrix is also widely studied. Rosa *et al.*, [16] investigated the effect of almond tree fibre on the mechanical properties of recycled polypropylene (r-PP) composites with fibre volume fractions of 1%, 5%, 10%, and 15%. It was found that there was an increase in tensile strength with a fibre fraction of 1%. Another study has been conducted by Hoang *et al.* [17] on analyzing the microstructural and mechanical properties of r-PP reinforced with short spruce fibres with different fractions of 10%, 30%, and 40%. Microstructural properties were evaluated using differential scanning calorimetry (DSC) and wide-angle X-ray scattering (WAXS). The results of the analysis using DSC and WAXS showed that the addition of fibres led to an increase in the degree of crystallinity of the polymer and the development of new crystalline phases. Those studies indicate the potential use of natural fiber, including bamboo fiber, in reinforcing the r-PP matrix.

The use of bamboo and recycled polymer as composite material are attractive due to their sustainable characteristics and potential exceptional mechanical and physical properties. However, to the best known of the authors, the potential of recycled polypropylene and bamboo fibre as environmentally friendly composite materials has not been fully explored yet. In thermoplastic-based composite, it is beneficial to conduct not only mechanical testing but also thermal analysis in evaluating material performance. To take full advantage of bamboo-based composite as an engineering material, it is necessary to select a proper ratio of the fiber and matrix materials to achieve specific requirements for various applications. In this current study, the evaluation of mechanical and thermal properties of r-PP/bamboo composites was carried out on different material compositions. Evaluation of mechanical properties was performed using the tensile and impact tests, while thermal stability and melting phase change (Tm) were used to evaluate thermal properties. In response to the growing need for eco-friendly materials in several industries, the bamboo fibre-reinforced recycled polymeric composites investigated in this current work could be an attractive option.

## 2. RESEARCH METHOD

### 2.1. Materials

The composite matrix used in this study is recycled polypropylene, which was obtained from a collecting point in Central Java. Meanwhile, the composite filler is bamboo fibre in 5 mesh sizes derived from a *petung* bamboo tree (*Dendrocalamus asper*) The part of the bamboo used in this study was the lower part of bamboo without the outer skin. Table 1 shows the mass fraction of bamboo fibre in each specimen.

Table 1. Mass fraction of bamboo fibre and recycled polypropylene feed for the extrusion process

| Mass fraction of Bamboo Fibre | rPP | Bamboo |
|---|---|---|
| 0% | 200 gr | 0 gr |
| 10% | 180 gr | 20 gr |
| 20% | 160 gr | 40 gr |
| 30% | 140 gr | 60 gr |

### 2.2. Manufacturing process

The composite specimens were manufactured on different compositions as shown in Table 1 using a two-step process of extrusion and injection molding. Extrusion was utilized for manufacturing composite filaments in the form of extrudate, and injection was utilized for producing test specimens by standard requirements for mechanical testing. Before processing, both the fiber and matrix materials were first prepared to ensure the cleanliness and size requirements.

**2.2.1. Preparation of the fibre and matrix material**

The bamboo piece was cut and separated between the inner and outer sides. The parts from the inner side were then crushed to a size of 5 mesh. The crushing fibres (Figure 1) were soaked in 5% NaOH solution for 3 hours at room temperature 25 °C, which was then washed 2 times using distilled water and dried for 8 hours at room temperature 25 °C and for 6 hours using an oven at 50 °C as recommended by Manalo *et al*. [18]. On the other hand, the recycled polypropylene as the composite matrix was crushed into a size of 5 Mesh, cleaned using distilled water and then dried under the sun for 8 hours (Figure 2).


Figure 1. Bamboo fibre

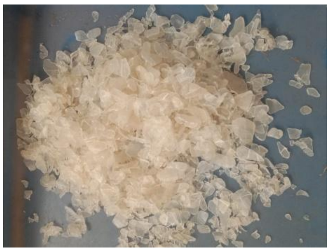


Figure 2. Recycled polypropylene

**2.2.2. Composite manufacturing**

The manufacture of composite specimens is carried out by mixing r-PP and bamboo of a predetermined mass fraction into filament composites using an extrusion machine which is then followed by the forming of specimens using an injection molding machine. The barrel temperatures of the extrusion machine are set sequentially at 170 °C, 180 °C, 180 °C, and 170 °C. The pelletized mix results were processed in an injection machine with molding temperatures of 180 °C and 90 °C with a holding time of 20 minutes. The temperature was set considering that Polypropylene has a melting temperature (Tm) of 186 °C and a crystallization temperature (Tc) of 135 °C [19].

**2.3. Mechanical tests**

The mechanical characteristics of composite materials, such as material strength, ductility, and ductility of a material, were assessed through tensile testing. Meanwhile, to ascertain a composite specimen's strength and investigate the impacts of notch presence, notch shape, temperature, and other variables, impact testing was conducted. A material's capacity to sustain impact loads was also assessed using the impact test. The average values from five replications were calculated in each measurement of tensile strength, elastic modulus, and impact strength.

**2.3.1. Tensile test**

The tensile test of bamboo fibre-reinforced r-PP composite specimens was carried out to measure the material strength and resilience of a material. It employed the standard of ASTM D638-14 type V commonly used for polymer-based composite. The standard specimen size is shown in Figure 3. The tensile test was performed using the Universal testing machine of Zwick Roell 20 kN with a vertical withdrawal of the specimen at a speed of 5 mm/min.

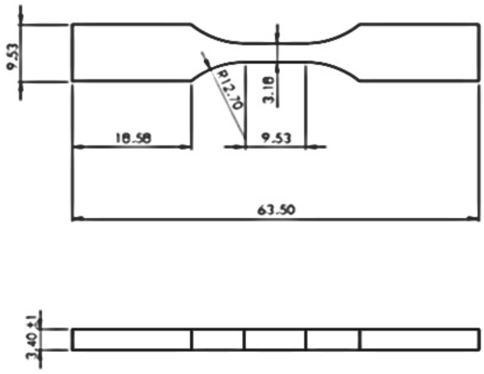


Figure 3. Tensile test specimen size

#### 2.3.2. Impact test

The impact test of the r-PP/bamboo composite was performed using the Izod method following the ASTM D4812 testing standard. It employed the standard specimen size of 65 mm x 12.9 mm x 3.2 mm. In measuring the impact strength, the composite specimen is clamped on the test equipment and the pendulum is swung from a certain height to hit the specimen. The potential energy of the pendulum decreases before and after hitting the specimen is the energy absorbed by the specimen. The impact test was carried out on the Zwick Roell 5.5 kN impact test with the Izod (unnotched) method. The pendulum for this impact test has swung from a height of an alpha angle (α) of 148. When the pendulum hits the clamped specimen at an angle of 0, the specimen will break and the pendulum creates an angle beta (β) which is the maximum point the pendulum swings. The test was carried out five times for each type of specimen and the average beta angle (β) for each type of composite specimen was obtained.

### 2.4. Thermal analysis

#### 2.4.1. Thermogravimetry analysis (TGA)

Thermogravimetry analysis (TGA) was used to evaluate thermal stability by measuring the mass reduction that occurs due to the decomposition of the composite material as a function of temperature and time. The parameters used were at a heating rate of 10 °C/min with temperatures ranging from 30 to 600 °C [20]. The furnace used was about 4 liters/hour with a maximum composite specimen size of 2 x 2 x 2 mm and a weight of 1 to 10 mg. The test standard used is ASTM E 1131. The brand of the machine used is Linseis STA PT 1600.

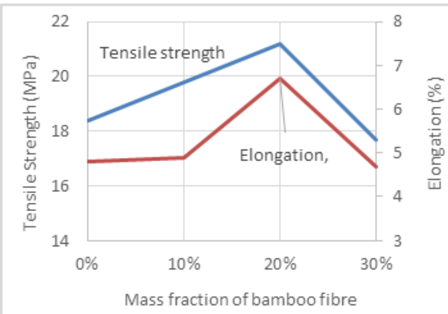
#### 2.4.2. Differential scanning calorimetry (DSC)

The DSC test was used to determine the melting phase change (Tm) of composite materials. The temperature used is 30 to 600 °C [20] with a heating rate of 10 °C/min and the condition of the furnace room is 4 liters/h. The weight of the composite specimen is about 1 to 10 mg with a size of 2 x 2 x 2 mm. The test standard used is ASTM E 473-85. The brand of machine used is Linseis STA PT 1600.

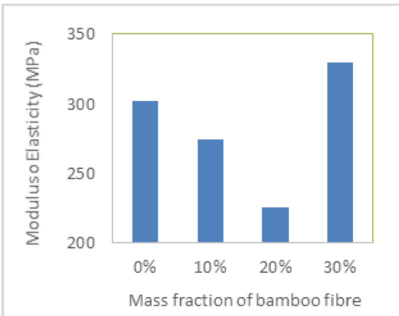
## 3. RESULTS AND DISCUSSION

### 3.1. Tensile properties

Figure 4 shows the tensile test of the r-PP/bamboo composite was carried out with a pulling speed of 5mm/minute. The average tensile strength and elongation are shown in Figure 4(a) and the modulus from five specimens of each treatment is shown in Figure 4(b).




(a)




(b)

Figure 4. Graph of tensile performance of r-PP/bamboo composite material: (a) tensile strength, elongation, and (b) Modulus of elasticity

In Figure 4 it can be seen that the tensile strength and strain increase with increasing bamboo fraction; as also indicated by Wang *et al*. [21]. Most of the specimens did not experience fracture while reaching the ultimate tensile point strength but experienced an elongation and reduction of the thickness. This generally occurs in elastic materials which are referred to as necking.

The highest strength and strain were recorded for composite with 20% of bamboo fraction with a tensile strength of 21.2 MPa and a tensile strain of 6.7%. However, the strength and strain of the 30% fibre mass fraction were lower than the one of 0% bamboo fibre. The voids between the fibre arrangements in the composite with a higher bamboo fraction could be the reason for the decrease in the tensile strength [22].

On the other hand, Young's modulus value of r-PP/bamboo fibre composite was inversely proportional to the tensile strength of the composite as shown in Figure 4(b). The highest value of Young's modulus value was shown in the 30% bamboo fibre mass fraction with a value of 330 MPa and the lowest modulus was shown in the composite with 20% bamboo fibre. It indicates that the composite with higher bamboo fibre content is more rigid and brittle compared to the ones with lower fibre loadings [22].

### 3.2 Impact strength

To ascertain a material's capacity to sustain impact loads, an impact test was conducted. Knowing this is necessary to ensure that the application complies with the requirements. The average impact strength for different bamboo fibre loadings is shown in Figure 5.

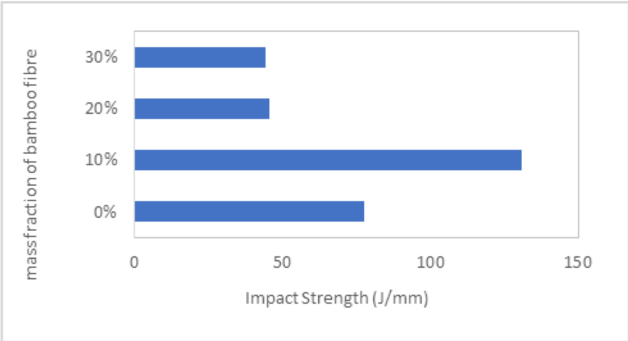
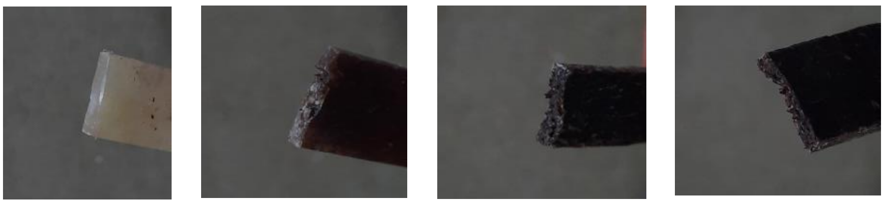



Figure 5. The impact strength of bamboo/r-PP composite in different fibre mass fraction

Figure 5 shows that 10% bamboo fibre content increased the impact strength of the r-PP specimen by 69% with a value of 130.98 J/mm2. However, the impact strength tends to decrease with increasing bamboo fibre loading after reaching the highest value on 10% fibre loading. The lowest value of impact strength was recorded on the 30% mass fraction of bamboo fibre with an impact strength of 44.24 J/mm2.

In the 10% mass fraction of bamboo fibre, the r-PP matrix can optimally bind the fibre which results in fewer voids or empty spaces within the composites. Figure 6 shows that the fractured specimen of the composite with 10% bamboo fibre contains fewer voids compared to the ones with higher fibre loadings. Oza *et al.* [23] indicated that the impact strength of a material will be increased with lower voids within the material. From Figure 6, two types of impact fracture were evident. Brittle fracture is shown for specimens with 0% (Figure 6(a)) and 10% (Figure 6(b)) bamboo fibre loading which looked shiny and contained fine grains. Meanwhile, the specimens with 20% (Figure 6(c)) and 30% (Figure 6(d)) fibre loading have ductile fractures which contain bamboo fibres that form like a brush.



(a) (b) (d) (d)

Figure 6. Impact fractured pattern in the specimens (a) 0% fibre, (b) 10% fibre, (c) 20% fibre, and (d) 30% fibre

### 3.3. Thermogravimetry analysis (TGA)

The TGA test was carried out on recycled polypropylene (r-PP) composites with different fractions of bamboo fibre reinforcement. The results obtained can be seen in Figure 7. Figure 7(a) is shown 0% fibre, Figure 7(b) is shown 10% fibre, Figure 7(c) is shown 20% fibre, and Figure 7(d) is shown 30% fibre.

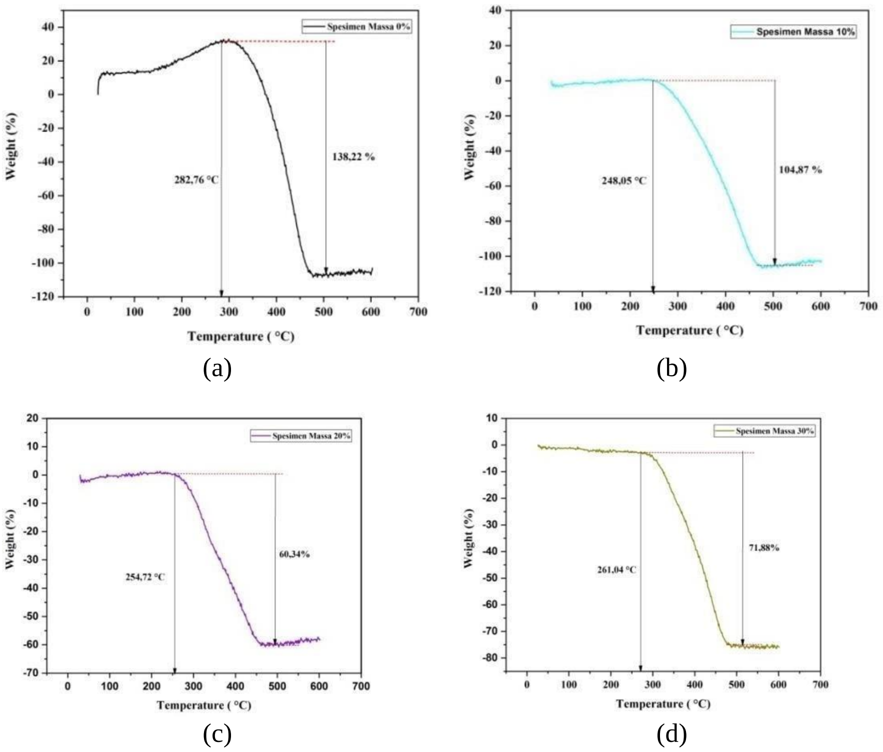



Figure 7. TGA of r-PP composite with different mass fractions of bamboo (a) 0% fibre, (b) 10% fibre, (c) 20% fibre, and (d) 30% fibre

The TGA graph exhibits three temperature regions of below 180 °C, from 180 to 470 °C, and above 470 °C. In the temperature region below 180 °C, the weight loss that occurs in the composite is relatively similar between each composite with different fibre loading. Different weight loss of the recycled polypropylene (r-PP) composite specimen with a variation of bamboo fibre reinforcement was observed in the temperature region of 180 to 470 °C and above 470 °C. The specimen containing no bamboo fibre showed a weight loss of 138.22% at the beginning of decomposition at a temperature of 282.76 °C. The detail for each type of composite is shown in Table 2.

Table 2. Thermal stability of composite recycled polypropylene with bamboo fibre reinforced

| Composite specimen | Thermal Stability | | |
|---|---|---|---|
| | Initial Temperature of Decomposition | Weight Loss Temperature 5% (°C) | Weight Loss Temperature 10% (°C) |
| 0% Bamboo Fibre | 282.76 | 322.6 | 340.15 |
| 10% Bamboo Fibre | 248.05 | 276.94 | 295.93 |
| 20% Bamboo Fibre | 254.72 | 288.57 | 307.38 |
| 30% Bamboo Fibre | 261.04 | 301.74 | 324.82 |

Thermal stability is determined at the temperature at which the weight decreases by a certain percentage. If the thermal stability is high, the weight loss will occur at higher temperatures. Zhang *et al*. [24] stated that the thermal stability of the polymer can be indicated from a weight loss of 5% or 10% of the initial weight loss of the composite material. The higher the temperature required to have 5% or 10% of the weight reduction, the more stable the polymer is. Table 2 shows that the bamboo fibre affects the thermal stability of the r-PP composite. The higher loading of bamboo fibre results in lower thermal stability of the composite. Gupta *et al*. [20] stated that the addition of large amounts of natural fibre can reduce the thermal stability of the composite. Collazo-Bigliardi *et al*. [25] confirmed that hemicellulose decomposes mainly from 150 to 350 °C, cellulose decomposes at 275 to 350 °C, and lignin decomposes gradually at 250 to 500 °C. The decomposition of lignin in bamboo fibre causes a reduction in mass to a temperature of more than 500 °C [26]. The TGA revealed that the specimen with no bamboo fibre shows better thermal stability compared to the bamboo fibre reinforced specimens.

### 3.4. Differential scanning calorimetry (DSC)

The result of the DSC test for all specimens with different fibre loadings can be seen in Figure 8 and summarized in Table 3. Figure 8 shows the change in melting point temperature (Tm) on recycled polypropylene (rPP) composite materials with different fractions of bamboo fibre reinforcement. The melting phase change (Tm) was observed in the temperature range of 125 to 165 °C. The peak melting point occurs in the endothermic phase and a large decrease in heat flow occurs in the composite material. The results showed that the melting phase change (Tm) was influenced by the mass of each specimen. The specimens containing no bamboo fibre recorded the lowest melting temperature, while the other specimens with bamboo fibre had almost the same melting phase change around 1590-1600 °C. Therefore, it can be concluded that the addition of bamboo fibre may affect the melting phase change (Tm), al also confirmed by Zakikhani *et al*. [26].

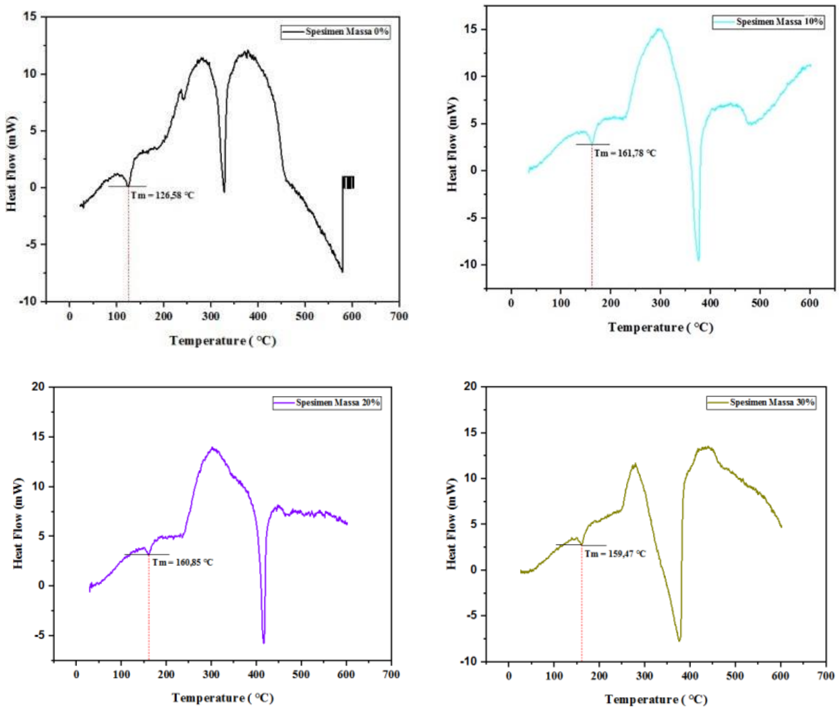



Figure 8. DSC graph of specimens with different values of bamboo fibre mass fraction

Table 3. Melt phase change (Tm) bamboo fibre reinforced recycled polypropylene composite

| Composite Specimen | Melting Point (Tm) °C |
|---|---|
| 0% Bamboo Fibre | 126.58 |
| 10% Bamboo Fibre | 161.78 |
| 20% Bamboo Fibre | 160.85 |
| 30% Bamboo Fibre | 159.47 |
| 40% Bamboo Fibre | 160.80 |

## 4. CONCLUSION

An investigation has been made into the effects of variations in the mass fraction of bamboo fibre on the strength of the r-PP/bamboo composite. The bamboo-based composites with recycled polypropylene demonstrated promising mechanical properties about tensile and impact performances. The r-PP reinforced bamboo fibre composite yielded a very promising result of tensile strength of 21.2 MPa with 20% bamboo fibre mass fraction and impact strength of 130.98 J/mm2 with 10% bamboo fibre loading. However, the thermal stability of the composites was greatly influenced by the reinforcing bamboo fibre. It is indicated the more the bamboo fibre loading within the composite the lower the thermal stability of the composite. On the other hand, the melting temperature of the bamboo fibre-reinforced composites was higher compared to one of the recycled polypropylene specimens. Therefore, the resultant materials have good potential for semi-structural loading applications in relatively low exposure working temperatures.

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