Regular Article

Indah Widiastuti*, Holam Cahya Saputra, Sandy Sidik Wisnu Kusuma and Budi Harjanto

Mechanical and thermal properties of recycled high-density polyethylene/bamboo with different fiber loadings

https://doi.org/10.1515/eng-2022-0010
received March 22, 2021; accepted January 26, 2022

Abstract: The use of recycled polymers in natural fiber-based composites provides an additional competitive advantage with their environmentally friendly properties. This study utilizes recycled high-density polyethylene (r-HDPE) as a composite matrix with bamboo fiber reinforcement that has been treated with an alkaline process. This study aims to analyze the mechanical properties and thermal properties of r-HDPE composites manufactured by extrusion molding with different bamboo fiber loadings. The specimens were subjected to tensile and impact testing for evaluating the mechanical properties. Thermogravimetric analysis (TGA) was performed to identify thermal stability, while the differential scanning calorimeter (DSC) was used to analyze the melting point phase of each specimen. This study indicated that the tensile strength of the composites decreases with increase of fiber fraction. The composite with 0% bamboo fiber showed the highest tensile strength of 8.3 N/mm^2, while the lowest tensile strength is shown by the composite with 30% of bamboo fiber. Scanning electron microscopy showed porosity, pull-out, fiber cracking as the indicators for the material failure during tensile testing. From the impact test, it can be shown that the composite with 10% bamboo fiber records the highest impact strength at 37.7 J/m^2. The TGA indicated high thermal stability of r-HDPE composites with 10% of bamboo fiber at 362.4°C temperature. A similar result was also exhibited from the DSC test, where the material with 10% fiber loading shows a big change in melting phase temperature. This research evidences the effect of bamboo fiber in increasing the impact strength and thermal stability of recycled HDPE matrix. This material could be the alternative for light-bearing applications such as automotive indoor components.

Keywords: bamboo fiber, polymer composite, recycled HDPE, mechanical properties, physical properties

1 Introduction

Composite is an alloy of two or more materials, each of which has its own characters to form a new material that holds different properties with the constituent material [1]. Natural fiber reinforced polymer composites are materials that are in great demand in the manufacturing, automotive, and construction industries. Natural fiber reinforced polymer composites have advantages over synthetic polymer composites, especially in low manufacturing costs, low density, high strength and stiffness, good heat absorption, and good energy absorption [2]. Natural fiber reinforced polymer composite is an attractive potential alternative for synthesis fiber reinforced polymer composites [3].

The use of natural fibers as reinforcement in composite materials has attracted more attention considering their characteristics of biodegradability, lightweight, low manufacturing costs, high availability, not containing toxic substances, and high mechanical properties [3]. Bamboo fiber is a natural fiber that has a potential alternative as a reinforcing material due to its high cellulose content. Bamboo fibers are commonly called natural glass fibers because of their high strength in the culms. The high tensile strength of bamboo fibers at around 70 MPa makes it an alternative in composite reinforcement [4].

High-density polyethylene (HDPE) is a thermoplastic polymer possessing good chemical resistance and is the most widely used commercial polymer [5]. Recycled HDPE (r-HDPE) with bamboo fiber reinforcement is expected to be an alternative material which more environment-

* **Corresponding author: Indah Widiastuti,** Department of Mechanical Engineering Education, Universitas Sebelas Maret, Surakarta, Indonesia, e-mail: indahwidiastuti@staff.uns.ac.id
Holam Cahya Saputra, Sandy Sidik Wisnu Kusuma, Budi Harjanto: Department of Mechanical Engineering Education, Universitas Sebelas Maret, Surakarta, Indonesia

friendly. Several studies have shown changes in the microstructure and mechanical properties of recycled plastics with the addition of various types of natural fibers [6–8]. To our knowledge, there are few reports that have assessed the potential use of bamboo fiber in reinforcing the r-HDPE matrix.

Thus, this study aims to analyze the mechanical properties of r-HDPE/bamboo fiber composites with different fiber contents. The morphological structure analysis was also carried out to identify characteristics of failure. In addition, the study also analyzed the rate of thermal degradation of the composite material using thermogravimetric analysis (TGA) differential scanning colorimeter (DSC).

2 Materials and methods

In this study, the material for the composite material is r-HDPE derived from post-consumer waste. A plastic extrusion was used to manufacture the specimens.

2.1 Materials

r-HDPE obtained from local waste processing centers was crushed into a size of 5 mesh before being washed thoroughly. Gigantochloa apus bamboo was chosen as the reinforcing material since it possesses good flexibility and soft fibers. The dried bamboo fibers were cut into 5 mesh sizes and then alkalized by soaking them in a 10% NaOH solution for 6 h. Treatment of bamboo fibers was carried out to improve the adhesion and interfacial between the reinforcing and binder materials [9]. Following this, the fibers were washed using clean water and dried into an oven at 100°C for 2 h. The bamboo fibers were then soaked in a 6 mg solution of stearic acid for 2 h and oven-dried afterwards. Stearic acid is used to reduce the natural hydrophilicity of the fiber [10].

2.2 Specimens preparation

The composite specimens were manufactured using an extrusion molding machine on barrel temperatures of 170, 175, 180, and 185°C and a screw rotation of 25 rpm. Composite specimens with different fiber loading of 0, 10, 20, and 30% from total mass in each specimen were then cut according to standard sizes for tensile and impact testing (Figure 1).

2.3 Mechanical testing

In this study, the tensile strength test referred to the ASTM D638 standard [11]. The composite specimens were vertically pulled on a 5 N load at a crosshead speed of 10 mm/min until breaking. The testing data were derived from the winTest™ analysis, including Young modulus, stress, and strain.

The principle of impact testing is to calculate the energy received to break the specimen. Impact testing referred to the ASTM D 4812 standard (un-notched) with the Izod method [11].

Scanning electron microscopy (SEM) is used to analyze the morphological, microstructure, and crystallographic physical properties of a material [12]. It is performed on the fractured specimen after the tensile test.

2.4 Thermal analysis

The TGA was carried out according to the ASTM E 1131 test standard [13]. The weight of each specimen is 10 mg

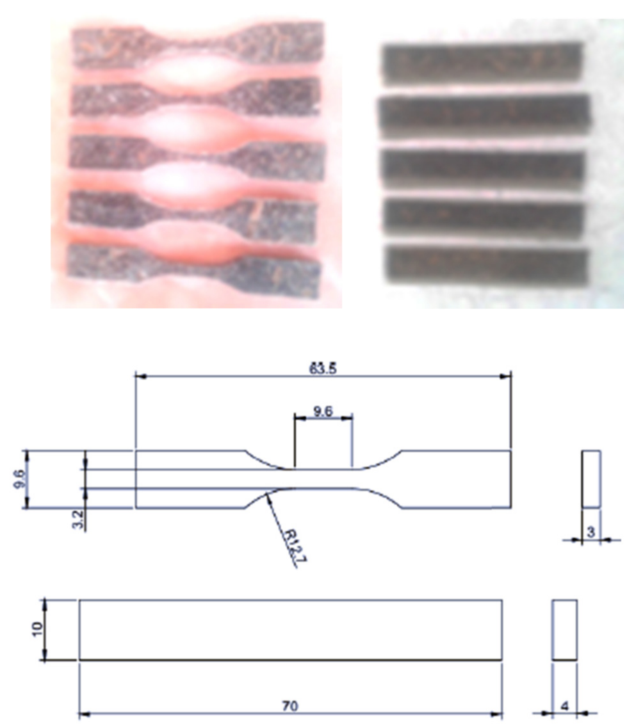

Figure 1: Tensile and impact specimens of r-HDPE/bamboo composite.

in a rectangle shape with a size of 3 mm × 3 mm. The test was scanned from room temperature to a temperature of 600°C under a nitrogel atmosphere with a flow rate of 50 mL/min at a heating rate of 10°C/min. Meanwhile, the dynamic scanning calorimeter (DSC) was used to identify changes in the melting point phase of the specimens. The DSC was performed following the ASTM E 473-85 test standard [13]. It used the same dimensions as the TGA specimens.

3 Result

3.1 Mechanical properties

Understanding the mechanical properties of the composite material would help to identify appropriate use and determine the resistance of the composites in certain applications. The mechanical strength of the material was obtained from an average of five measurements for each composition.

Figure 2 shows the effect of fiber loading on the tensile strength and modulus of elasticity of the composite. The value of tensile strength and modulus was derived from the average of five specimens in each treatment. The standard deviation of tensile strength and modulus ranged from 1.05 to 1.52 N/mm^2 and 26.7 to 53.1 N/mm^2, respectively. The tensile strength of the composites decreases with increasing fiber loading. The material with 0% bamboo fiber has the highest tensile strength of 8.298 N/mm^2, while the r-HDPE composite with a 30% bamboo fiber fraction indicates the lowest tensile strength of 4.880 N/mm^2. On the other hand, elasticity modulus shows an increasing trend with larger fractions of fiber in the r-HDPE matrix. It indicates that more bamboo fiber tends to lead the composite to be stiffer and more brittle.

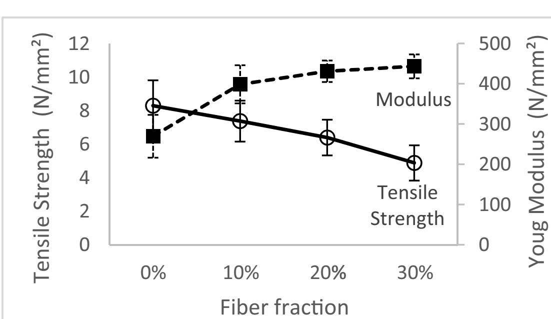

Figure 2: Tensile strength and Young modulus of r-HDPE/bamboo composite.

In comparison to other studies on the r-HDPE composite, the r-HDPE/bamboo composite in this study records a fairly low tensile strength. Charoenvai [14] studied r-HDPE reinforced by durian peels and found a difference in the tensile strength with different fiber loadings. It was known that the composite consisting of 10% durian peels fiber gained the highest tensile strength of 20.4 MPa and elasticity modulus of 560.394 MPa.

The potential causes for the low tensile strength of this r-HDPE/bamboo composite could be related to the absence of adhesive substances, incompatible barrel temperatures, and the use of random bamboo fiber directions.

As a result of the impact by the pendulum during the impact testing, the composite specimens were broken into two types of fractures. Figure 2(a) shows the complete fracture of the composite with a 30% fraction of bamboo fiber. It is indicated that the high fiber loading led the composite to become more brittle. Meanwhile, as shown in Figure 2(b), the incomplete fracture was observed in the composite with 10% fiber loading indicating a deformation of the material (Figure 3).

Figure 4 exhibits the effect of bamboo fiber loadings on the impact strength of the rHDPE-based composite. As clearly seen in the figure, the impact strength of the material with 10% fiber loading is higher than the r-HDPE without bamboo fiber on the value of 37.7155 kJ/mm^2. However, the impact strength tends to decrease with increasing fiber fractions of more than 10%. A study by Oza et al. [15] on r-HDPE/Rami composites found that the composite with 30% fiber fraction recorded the highest impact strength of 51.1 kJ/m^2. In that study, the r-HDPE matrix reinforced with 30% fiber fraction accounted for higher impact strength than the reinforcement of 30% bamboo fiber in this study.

3.2 Surface morphology

In this study, SEM was utilized in obtaining changes in the microstructure of the specimens during tensile testing. It is found that the image from SEM supports the finding of a decrease in tensile strength with increasing fiber loading.

The fracture surface of the r-HDPE/bamboo specimens after the tensile test for various fiber loading is shown in Figure 5. The cross-sectional observation of the specimens was focused on the interfacial of the bamboo fiber and the matrix. As shown in this figure, the SEM photograph of r-HDPE composites with 10% bamboo fiber indicates fairly high adhesion between the fiber and the matrix. No crack or break was evidenced

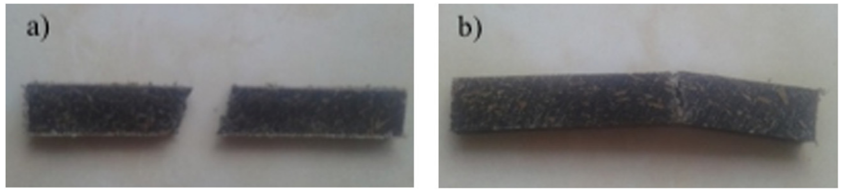

Figure 3: Fracture of specimens during impact test: (a) r-HDPE/30% bamboo fiber and (b) r-HDPE/10% bamboo fiber.

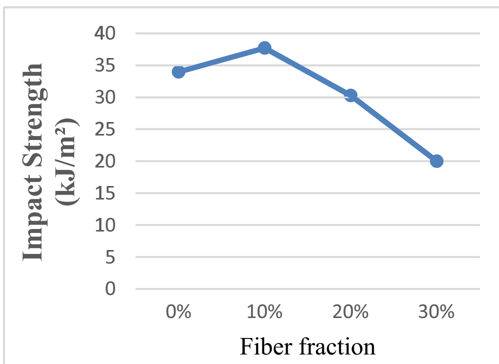

Figure 4: Impact strength of r-HDPE/bamboo composite.

in the interface between the r-HDPE matrix and the bamboo. It might be due to a high fraction of the r-HDPE (90%). Meanwhile, a pull-out was shown in the r-HDPE-20% bamboo composite after the tensile test.

Pull-out is the release of the interface bond between r-HDPE and bamboo fiber due to the ineffective effect of the alkaline treatment on that section. The fractured bamboo fiber was clearly seen in the composite with 30% bamboo fiber. In addition, the SEM image also showed a debonding within the interface bond of r-HDPE and bamboo fiber. Debonding is the tearing of the bond between the binder and the reinforcement during testing and treatment. These are the reasons for low tensile strength in the material containing more fiber loading.

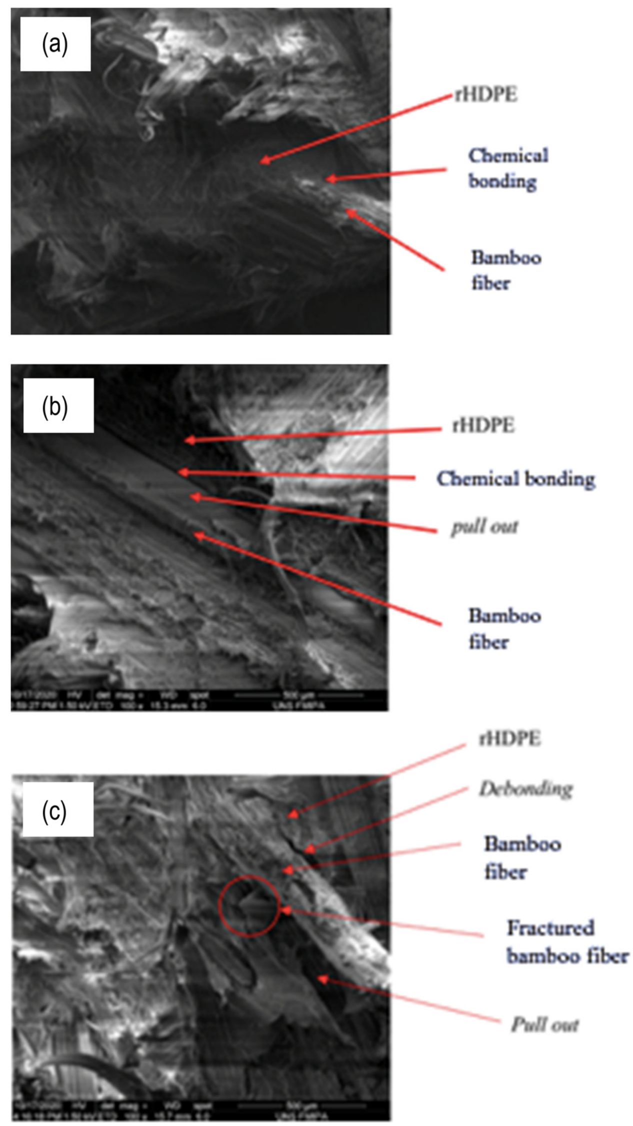

Figure 5: SEM image of the specimens: (a) r-HDPE-bamboo 10%; (b) r-HDPE-bamboo 20% dan; (c) r-HDPE-bamboo 30%.

3.3 Thermal analysis

TGA was used to evaluate the degradation of materials at high temperatures. Figure 6 shows the TGA graph of r-HDPE composite reinforced by various fractions of bamboo fiber. The graph shows three regions of temperature interval: below 200°C, between 200 and 490°C, and above 490°C. In the temperature region of below 200°C, the percentage of composite weight loss is relatively stable. However, in the temperature range of 200–490°C, the curve shows different trends of weight loss between various fiber loadings within the composite. It was observed that at the temperature of 490°C, the materials without any bamboo fiber recorded the most mass loss

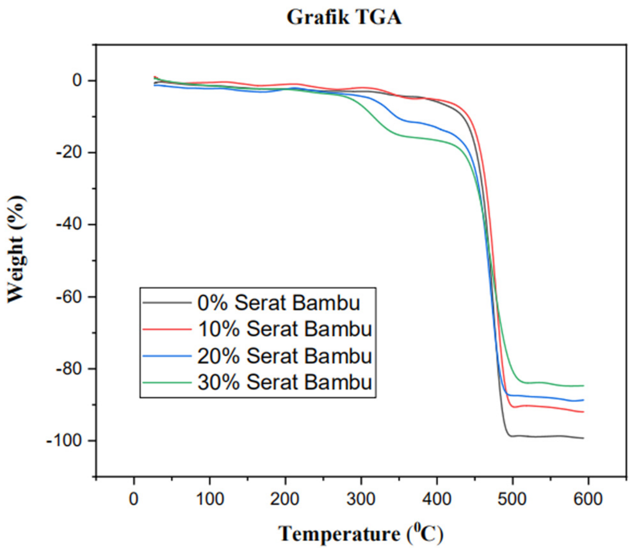

Figure 6: Graph of TGA.

at 94.88%. At the same time the composite with the highest fiber loading displayed the lowest loss at 80.34% of the mass. The residual mass of the composites was observed at a temperature above 490°C.

The initial temperature at which the degradation of the polymeric materials begins indicates the thermal stability of the material. Table 1 displays the thermal stability of r-HDPE composite in various bamboo fiber loadings.

It can be clearly observed from Table 1 that 5% weight loss in the material with different fiber contents occurs at the temperature varied between 287 and 393°C. At the same time the 10% weight loss was observed at the temperature range of 317–442°C and the decomposition temperature at 268–363°C. The initial temperature of the decomposition (loss of mass) shows the thermal stability of the material. The highest temperature of weight loss and decomposition was shown in the r-HDPE specimens reinforced with 10% bamboo fiber content. It can be concluded that this material composition exhibited the highest thermal stability.

In other works of natural fiber reinforced polymer, Medupin et al. [16] presented that the thermal stability of r-HDPE composites reinforced with 10% content of palm fiber was at a temperature of 215°C. It means that at the same amount of natural fiber, the r-HDPE/bamboo fiber shows higher thermal stability.

Following the TGA, the DSC was performed to evaluate changes in the melting point phase of the material due to the increase in temperature. Figure 7 displays the DSC curve exhibiting a slightly different melting temperature of different fiber loadings within r-HDPE composites. The endothermic peas in the DSC curves indicating changes of melting phase were observed in the temperature range of 120–135°C. Ginting [17] reported that the melting point of a husk fiber-reinforced polymer composite was at 128.43°C.

Table 1: Thermal stability of r-HDPE/bamboo composite

Fiber loading (%)	Temperature		
	5% weight loss (°C)	10% weight loss (°C)	Decomposition (°C)
0	392.66	440.16	357.52
10	391.28	441.65	362.40
20	319.14	352.73	289.14
30	287.01	317.14	268.71

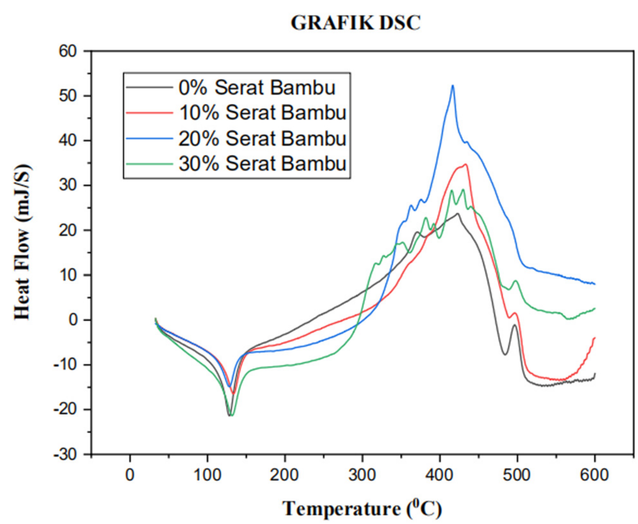

Figure 7: Curve of DSC.

Table 2 precisely displays the changes of melting phase within the composites for different bamboo fiber loading.

From Table 2, the highest temperature in which the melting phase changes was observed in the composite with 10% fiber loading. It confirms the finding of Vasdazara et al. [18], which revealed that fiber content in the

Table 2: Changes of melting phase of r-HDPE/bamboo composite

Fiber loading (%)	Changes of melting phase (°C)
0	128.59
10	133.21
20	127.79
30	131.94

polymer composites affects the point of change in the melting phase.

4 Conclusion

A systematic investigation of the mechanical and thermal properties of a bamboo-based recycled polymer composite has been reported. The mechanical strength of the composites tends to decrease with an increasing fraction of the fibers used. This finding has been confirmed by scanning electron microscopy, which displayed pull-out, debonding, and fiber cracking within the material, especially in the one with more bamboo fiber fraction. However, the r-HDPE composite with 10% bamboo fiber loading showed the highest values of impact strength at 37.7 J/m^2. Analysis of thermal stability also revealed that the 10% fiber loading in the composite improved the stability of r-HDPE material, as shown by the high decomposition temperature as well as the high melting point. This research evidences the effect of bamboo fiber in increasing the impact strength and thermal stability of recycled HDPE matrix

Acknowledgments: The authors acknowledge the Fundamental Research Grant of the Institute of Research and Community Service Universitas Sebelas Maret, Surakarta, Indonesia, for supporting the research work.

Conflict of interest: Authors state no conflict of interest.

References

[1] Jones RM. Mechanics of composite material. New York: Brunner-Routledge; 1999.
[2] Mathai VA, Mittal V. Polymer composites with functionalized natural fibers. In: Shimpi NG, editor. Biodegradable and biocompatible polymer composites. Cambridge: Woodhead Publishing; 2018. p. 157–86.
[3] Sathishkumar T, Navaneethakrishnan P, Shankar S, Rajasekar R, Rajini N. Characterization of natural fiber and composites – a review. J Reinforced Plast Compos. 2013;32(19):1457–76.
[4] Rassiah K, Ahmad MMHM. A review on mechanical properties of bamboo fiber reinforced polymer composite. Australian J Basic Appl Sci. 2013;7(8):247–53.
[5] Lailun Y, Atmaja L, Juwono H. Synthesis and characterization of HDPE plastic film for herbicide container using fly ash class f as filler Indonesian. J Chem. 2009;9(3):348–54.
[6] Thomason JL, Rudeiros-Fernández JL. A review of the impact performance of natural fibre thermoplastic composites. Front Mater. 2018;5:60.
[7] Chauhan V, Kärki T, Varis J. Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques. J Thermoplast Composite Mater. 2019. https://journals.sagepub.com/doi/abs/10.1177/0892705719889095.
[8] Bujjibabu G, Das VC, Ramakrishna M, Nagarjuna K. Mechanical and water absorption behavior of natural fibers reinforced polypropylene hybrid composites. Mater Today: Proc. 2018;5(5):12249–56.
[9] Chen H, Yu Y, Zhong T, Wu Y, Li Y, Wu Z, et al. Effect of alkali treatment on microstructure and mechanical properties of individual bamboo fibers. Cellulose. 2016;24:333–47.
[10] Grande C, Torres FG. Investigation of fiber organization and damage during single screw extrusion of natural fiber reinforced thermoplastics. Adv Polym Technol. 2005;24:145–56.
[11] Shah V. Mechanical properties. Handbook of plastics testing and failure analysis. New Jersey: John Wiley & Sons, Inc; 2007. p. 17–93.
[12] Zhou W, Apkarian R, Wang ZL, Joy D. Fundamentals of scanning electron microscopy (SEM). In: Zhou W, Wang ZL, editors. Scanning microscopy for nanotechnology: techniques and applications. New York, NY: Springer New York; 2007. p. 1–40.
[13] Shah V. Thermal properties. Handbook of plastics testing and failure analysis. New Jersey: John Wiley & Sons, Inc; 2007. p. 17–93.
[14] Charoenvai S. Durian peels fiber and recycled HDPE composites obtained by extrusion. Energy Procedia. 2014;56:539–46.
[15] Oza S, Wang R, Lu N. Thermal and mechanical properties of recycled high density polyethylene/hemp fiber composites. Int J Appl Sci Technol. 2011;1(5):31–36.
[16] Medupin RO, Abubakre OK, Abdulkareem AS, Muriana RA, Kariim I, Bada SO. Thermal and physico-mechanical stability of recycled high density polyethylene reinforced with oil palm fibres. Eng Sci Technol, Int J. 2017;20(6):1623–31.
[17] Ginting ME. Analisis termal dan struktur nano komposit dengan bahan pengisi nano partikel abu sekam padi. J Spektra. 2015;16(2):65–70.
[18] Vasdazara OL, Ardhyananta H, Wicaksono ST. Pengaruh penambahan serat cangkang kelapa sawit (palm kernel fiber) terhadap sifat mekanik dan stabilitas termal komposit epoksi/serat cangkang kelapa sawit. J Teknik ITS. 2018;7(1):119–23.