Effects of Processing Parameters on Mechanical Properties and Structure of Banana Fiber-Reinforced Composites

Dan-Thuy Van-Pham[1]*, Minh Tri Nguyen[1], Chanh-Nghiem Nguyen[2], Thi Truc Duyen Le[1], Thi Yen Nhu Pham[1], Khai Thinh Nguyen[2], Yukihiro Nishikawa[3] and Qui Tran-Cong-Miyata[3]

[1]*Department of Chemical Engineering, Can Tho University, Can Tho City, Viet Nam*
[2]*Department of Automation Technology, Can Tho University, Can Tho City, Viet Nam*
[3]*Department of Macromolecular Science and Engineering, Graduate School of Science and Technology, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan*

Received November 27, 2017; Accepted January 14, 2018

ABSTRACT: The mechanical properties of unidirectional natural fiber-reinforced composites are generally affected by several processing parameters during compression molding. This study investigates the effects of processing temperature, time, and pressure on the tensile and flexural properties of acrylonitrile butadiene styrene reinforced by banana fibers. X-ray CT imaging was employed to find the relationship between the mechanical properties and structure of the processed composite. Besides, the water absorption of composites was observed and the way in which the mechanical properties evolved after water absorption was analyzed. The tensile and flexural properties of the unidirectional banana fiber-reinforced composite were found to be inversely proportional to the porosity. In addition, high-pressure compression molding might result in cracks and floating fibers that would significantly reduce its mechanical properties. The composite with the highest strength, smallest porosity and lowest water absorption was optimally prepared at T = 170 °C, t = 20 min, and P = 100 kg cm^{-2}.

KEYWORDS: Banana fiber, composite, compression molding, porosity, X-ray CT

1 INTRODUCTION

The interest in using natural fibers as reinforcement in polymer has increased dramatically over the past few years. Natural fiber is considered one of the environmentally friendly materials with several advantages such as low cost, high modulus, low density, high specific strength, non-abrasiveness and biodegradability [1]. Many studies have been conducted on natural fibers such as kenaf, bagasse, jute, ramie, hemp and oil palm [2–8]. In Viet Nam, especially in the Mekong Delta, banana is popularly cultivated. At present, banana pseudostems or banana fibers are waste products in Viet Nam. Published research on banana fibers is still limited. Research on banana-reinforced composites not only has scientific meaning but also leads to a positive environmental impact by taking advantage of locally sourced waste materials [9] to produce potential products, such as ceiling, furniture, etc., from the obtained composites.

In some studies, the effects of banana fiber fraction on mechanical properties were investigated for composite production from banana fiber and various matrices such as polyester and epoxy [10–12]. Several treatment methods were also carried out on banana fiber to improve the mechanical properties of banana fiber-reinforced composites [13, 14]. However, only the structure of the fractured surfaces was observed by scanning electron microscope (SEM). The effects of processing parameters on the structure of the composites, especially the porosity in composites, have not yet been studied. In 2002, Joseph *et al.* concluded that the interfacial shear strength was higher in banana fiber embedded in phenol formaldehyde (PF) than glass fiber in PF, which indicated a strong adhesion between the lignocellulosic banana fiber and PF resoles [15]. In 2013, Sakthivel and Ramesh showed that banana fiber-reinforced composite was the best natural composite polymer matrix composite among those fabricated by using coir, banana and sisal fibers [16].

**Corresponding author*: vpdthuy@ctu.edu.vn

DOI: 10.7569/JRM.2018.634107

Acrylonitrile butadiene styrene (ABS) is a common thermoplastic polymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. Due to its desirable properties, such as good mechanical properties, chemical resistance, toughness, dimensional stability, good surface appearance, and easy processing characteristics, ABS has been widely used in many fields [17–19]. However, ABS exhibits certain limitations, especially low mechanical properties, which can be overcome by addition of fibers [19, 20].

In this study, banana fibers were used to reinforce acrylonitrile butadiene styrene (ABS). As compression molding is still a common, fundamental technique for the production of thermoplastic-matrix composite in Viet Nam, various conditions of processing temperature, time and pressure on the tensile and flexural properties of the compression molding composites were successively investigated. In addition, X-ray computed tomography, which is known to be able to quantitatively determine the porosity with a reasonable degree [20], was applied for structure observation and porosity determination. The analyzed porosity allowed further understanding of the effects of processing parameters on the mechanical properties of the composite.

2 EXPERIMENTAL

2.1 Banana Fibers Preparation

Banana fibers were extracted from banana pseudostems that were collected in the city of Can Tho, Viet Nam. The leaf sheaths from the pseudostems were separated, cut and mechanically combed by using a self-developed fiber extracting machine. Then, the obtained fibers were cleaned and dried before fiber mat production.

2.2 Banana Fiber-Reinforced Composite Preparation

Unidirectional banana fiber mats were prepared by using a hydraulic press machine (PAN STONE P-100-PCD, Taiwan). The straight banana fibers were arranged in the frame, then pressed at the temperature of 120 °C, pressure 75 kg cm^{-2} for 2 minutes. Under the mentioned experimental conditions, lignin plays the role of the adhesive in the fiber mat. Acrylonitrile butadiene styrene (ABS) was used as the matrix for composite production. ABS sheets were prepared from its pellets by using a hydraulic press machine (PAN STONE P-100-PCD, Taiwan) as well. The optimum conditions were found at the temperature of 170 °C, at the pressure of 100 kg cm^{-2} for 20 minutes. To make banana fiber-reinforced ABS plates, the UD banana fiber mats and ABS films with dimensions of 140 × 90 × 3 mm were stacked in sequence. Once again, the applied heat, pressure and holding time were controlled by using the hydraulic press machine. In this study, the effects of processing temperature, time and pressure on the mechanical properties of the obtained composites were successively investigated. The list of these samples under investigation is shown Table 1. All samples were prepared at fiber volume fraction of 30%.

2.3 Mechanical Properties Determination

Tensile tests were performed on composite samples to determine Young's modulus and stress at failure. The stress-strain curves were also obtained. The results of tensile strength, modulus, and elongation at break of the samples will hereinafter be shown for further discussion. The ASTM D3039/D3039M standard was followed to prepare the specimens and perform the tensile tests. A Zwick/Roell DO-FB050TN universal testing machine with mechanical clamping and a load cell of 50 kN was used with the crosshead speed set at 5 mm min^{-1}. The specimen dimensions were 250 mm by 25 mm with the distance between grips of 150 mm.

Three-point bending tests were performed following ASTM D790-03 to evaluate the flexural strength, modulus, and elongation at break of the materials. The Zwick/Roell DO-FB050TN testing machine was used, with a crosshead speed of 5 mm min^{-1} and load cell of 50 kN. The diameter of the loading and supporting members were 10 mm and 5 mm respectively. The 50 mm span was used for specimens with dimensions of 60 × 25 × 3 mm.

2.4 Surface Observation

As the tensile tests were performed, the cross section of the sample was observed by using a tabletop microscope (TM-1000, Hitachi, Japan).

2.5 Water Absorption Determination

To study the water absorption behavior of banana fiber-reinforced composites, samples with the

Table 1 List of samples processed under various conditions.

Sample ID	Temperature (°C)	Time (min)	Pressure (kg cm^{-2})
Sample 1	150	10	100
Sample 2	160	10	100
Sample 3	170	10	100
Sample 4	170	15	100
Sample 5	170	20	100
Sample 6	170	20	75
Sample 7	170	20	125

above-mentioned dimensions for mechanical properties measurement were prepared and immersed in a water bath at room temperature. After a certain time period, samples were taken out and the weight measured. The experiments were repeated until the weight of the samples was constant.

The percentage of absorbed water at time t was obtained as follows:

$$M_t(\%) = \frac{m_t - m_0}{m_0} \times 100$$

where m_0 and m_t are the initial weight and the weight at time t of the sample.

In addition, after water absorption of the samples was determined, the mechanical properties of the optimum samples were analyzed to clarify the effects of water absorption on the mechanical properties of samples.

2.6 X-ray Microtomography and Image Processing

As X-ray computed tomography is known to be able to quantitatively determine the porosity with a reasonable degree [20], it was applied in this study for observing the structure of the processed composite and determining the volume fraction of voids inside the composite. Microtomography scans were obtained by using an X-ray CT scanner (FLEX-M863-CT, Beamsense Co. Ltd., Japan) that can resolve very small density difference, typically 0.1 g cm^{-3} [21]. For image processing, a "3DV file analyzer" graphical user interface (GUI) was developed in this study. The GUI was built in MATLAB with functionalities such as standard 3D image processing, 3D particle analysis, porosity measurement, 3D visualizer. After scanning the sample using the X-ray CT scanner, a 3D volume file (.3dv file) is created and can be processed by "3DV file analyzer" to determine the sample porosity. At first, a region of interest (ROI) of the sample can be selected. Then, binarization will be applied to detect the voids in the ROI of the analyzed composite after applying a median filter for noise removal. Finally, the position and shape of the voids will be labeled and the total void volume in the ROI will be calculated in number of 3D voxels. To provide further analysis of the sample, 3D visualization of the sample was also supported.

3 RESULTS AND DISCUSSION

3.1 Structure of Extracted Banana Fibers

By using SEM, Barreto *et al.* and Mukhopadhyay *et al.* showed that the structure of banana fiber is similar to that of regular fiber with discrete net fibrils [22, 23]. Banana fibers, as well as other lignocellulosic fibers, are constituted of cellulose, hemicellulose, lignin, pectin, wax and water-soluble components. In this study, the extracted banana fibers were observed by X-ray CT (Figure 1). The net fibrils were clearly observed. The diameter of banana fibers used in this study was found to be in the range of 0.025–0.19 mm with the mean value of 0.075 mm and standard deviation of 0.031 mm.

3.2 Effects of Processing Temperature on the Mechanical Properties of Composite

To determine the effects of processing temperature on the mechanical properties of composites, the holding time and pressure were fixed at 10 min and 100 kg cm^{-2} respectively while the samples were processed at 150, 160, 170 and 180 °C. However, the sample processed at 180 °C was burnt. Tensile strength of fiber-reinforced composites processed under various temperature conditions is higher than that of ABS matrix (Table 2). The tensile and flexural properties of the other samples are shown respectively in Figure 2a,b. The highest tensile properties were obtained under 170 °C.

For a better understanding of the processing temperature effect, the porosity (volume fraction of voids

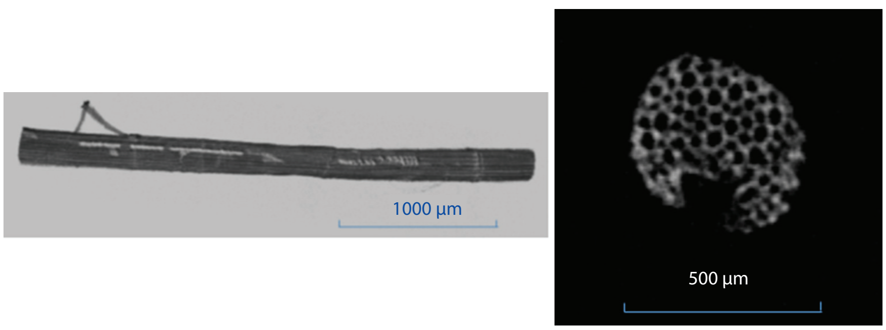


Figure 1 Structure of banana fibers observed by X-ray CT (**a**) along the length and (**b**) at cross section of the fibers.

Table 2 Tensile strength of ABS matrix and banana fiber-reinforced composites processed under different processing temperature conditions.

Sample	Processing temperature	
	150 °C	**170 °C**
ABS matrix	37.69 MPa	38.37 MPa
Composite	40.15 MPa	98.73 MPa

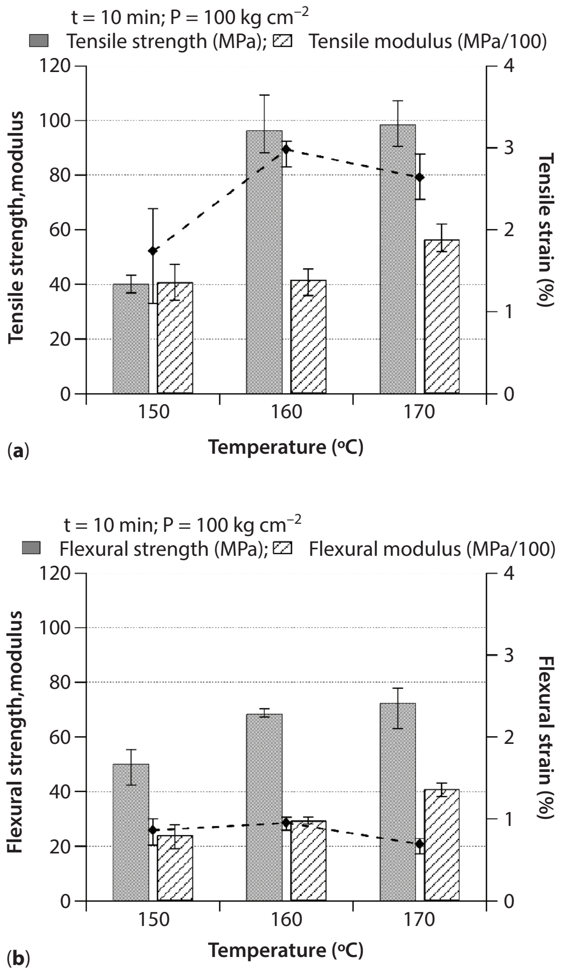


Figure 2 Effects of processing temperature on (**a**) tensile and (**b**) flexural properties of banana fiber-reinforced composites.

inside the sample) was calculated (Figure 3). It was observed that the tensile and flexural strength of the sample increased while the porosity dramatically decreased (from 4.237% to 0.05%) at higher processing temperature in the range of 150–170 °C. This indicated that lower viscosity at higher temperature had allowed ABS to flow easily to fill the voids in the sample, resulting in better reinforced composite material. In other words, the tensile and flexural properties of the UD banana fiber-reinforced composite were inversely proportional to the porosity.

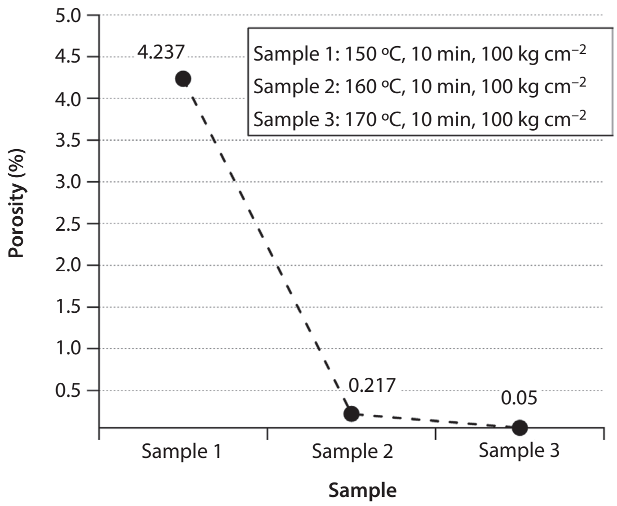


Figure 3 Porosity in banana fiber-reinforced composites processed at various temperatures.

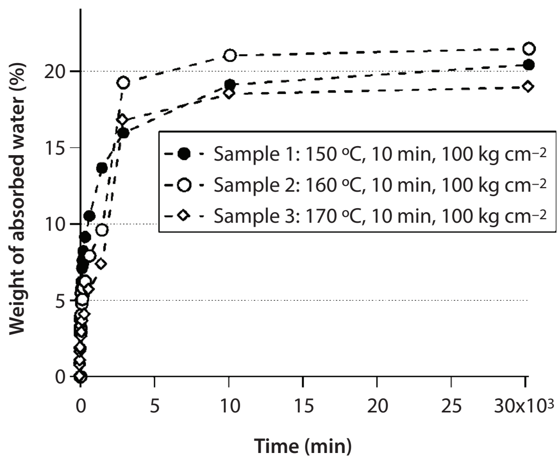


Figure 4 Water absorption of banana fiber-reinforced composites processed at various temperatures.

In addition, the amount of water absorption of these samples was calculated and is shown in Figure 4. The amount of absorbed water increased with time and became unchanged after seven days. The lowest amount of water was absorbed by the sample that had been processed at 170 °C, which should achieve the highest mechanical properties and lowest porosity (according to the results presented in Figure 2).

3.3 Effects of Processing Time on the Mechanical Properties of Composite

Holding time for this study was suggested at 10, 15, 20 and 25 min while processing temperature and pressure were fixed at 170 °C and 100 kg cm^{-2} respectively.

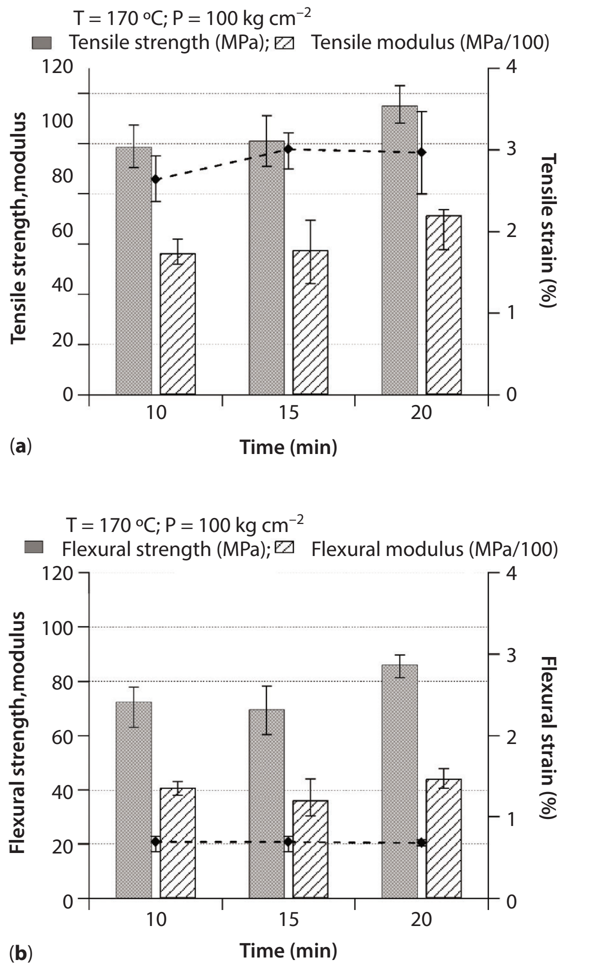


Figure 5 Effects of processing time on (**a**) tensile and (**b**) flexural properties of banana fiber-reinforced composites.

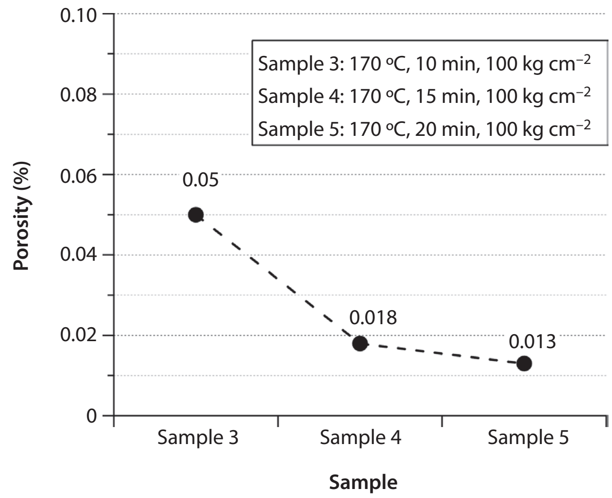


Figure 6 Porosity in banana fiber-reinforced composites processed in various times.

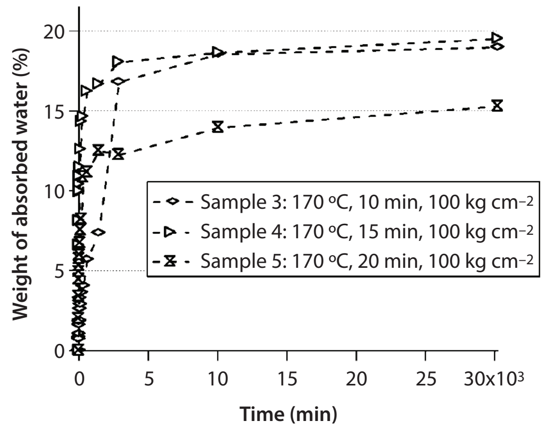


Figure 7 Water absorption of banana fiber-reinforced composites processed in various times.

Figure 5 presents the effects of processing time on the tensile and flexural properties of the composites. It should be noted that the composite sample being processed in 25 minutes had been burnt; thus, its mechanical properties could not be presented in Figure 5.

As a longer processing time was applied to the sample, both tensile and flexural properties increased in the range from 10 to 20 minutes. However, it seemed that there should be a longer processing time for the sample to improve its mechanical strength, as the samples prepared in 10 min and in 15 min only differed slightly in mechanical strengths. The sample prepared in 20 min had the greatest tensile and flexural strengths, which were significantly differently from those of samples prepared in 10 or 15 min.

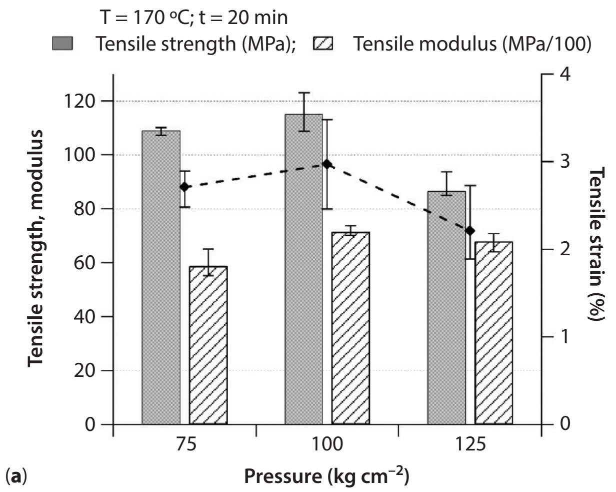
It is interesting to note that although low porosity was obtained when the sample was processed in 15 min compared to 10 min (Figure 6), there was an insignificant change in the sample's tensile and flexural strength (Figure 5). This suggested that there should be a significant drop in porosity for a banana UD mat-reinforced composite to improve its mechanical strengths. Significant difference in the mechanical strengths of two pairs of composite samples has been observed where the porosity difference was about 4 times between sample 5 and sample 3 (Figure 6) and between sample 3 and sample 2 (Figure 3).

Analyzing the amount of water absorption of these samples under different processing times, similar water absorption behavior was also observed as the amount of absorbed water increased with time and became unchanged after seven days of immersion time (Figure 7). It is noted that the amount of absorbed water was significantly reduced for the sample that had been processed in 20 min (Sample 5).

3.4 Effects of Processing Pressure on the Mechanical Properties of Composite

After the optimum processing temperature and time were determined, the effects of processing pressure were examined at 75, 100 and 125 kg cm^{-2}. It was apparent that the strength increased as the pressure increased from 75 to 100 kg cm^{-2} (Figure 8). However, the strengths and modulus decreased as the pressure increased from 100 to 125 kg cm^{-2}.

Therefore, the three-dimensional structure of the composite processed under pressure of 125 kg cm^{-2} was built and is shown in Figure 9, where fiber, polymer matrix, porosity, and crack are well illustrated in green, white, blue, and red respectively. The damage in structure was found in the sample (Figure 9a), which might be the effect of processing under high pressure (at 125 kg cm^{-2}). Besides porosity, cracks were also found in the sample under high processing pressure (Figure 9b). Under this pressure, the floating fibers were observed as well (Figure 9c). The induced cracks and floating fibers could have led to the significant decrease in the strength of composites.



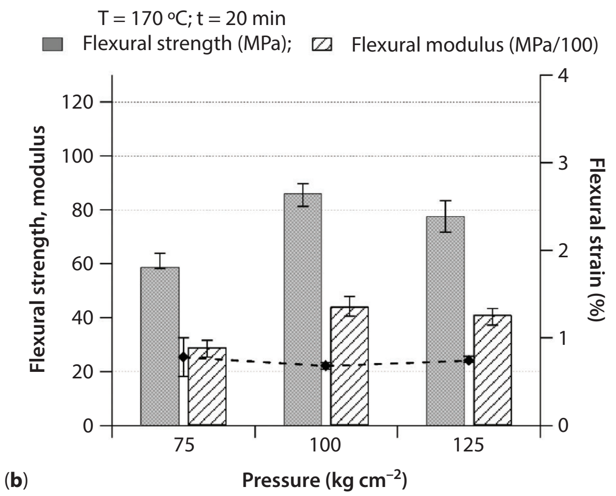


Figure 8 Effects of processing pressure on (**a**) tensile and (**b**) flexural properties of banana fiber-reinforced composites.

From the 3D structures of the samples that had been processed under various pressures, the samples' porosities were calculated. Under the pressure of 75, 100 and 125 kg cm^{-2}, the porosity was 0.638, 0.013 and 0.059% respectively. Based on the mechanical properties measurement (Figure 8) and porosity analysis (Figure 10), the sample prepared at T = 170 °C, t = 20 min, and P = 100 kg cm^{-2} performed at the highest mechanical strength and modulus, and had the lowest volume faction of porosity. Water absorption analysis showed that the sample prepared at the optimal conditions has the lowest water absorption amount (Figures 4, 7, and 11). The 3D model reconstruction of a banana fiber-reinforced composite at the optimal processing molding conditions is shown in Figure 12.

Additionally, a tabletop microscope was employed to confirm the uniform wetting of ABS matrix of the whole mat of fibers and to show the quality of the interfacial adhesion between fibers and the matrix. After tensile tests were performed, the surface of sample prepared at T = 170 °C, P = 100 kg cm^{-2} in 20 min was observed. The cross section of the sample showed good fiber-matrix interfacial adhesion (Figure 13).

It was found that the amount of absorbed water was almost unchanged after seven days in a water bath. Therefore, the optimum sample processed at T = 170 °C, P = 100 kg cm^{-2} in 20 min before and after seven days of immersion in a water bath was used to understand the effect of water absorption on the mechanical properties of composites. Figure 14 demonstrates the reduction in strength and modulus of composites after water absorption.

4 CONCLUSIONS

In the experimental study, fibers were extracted from banana pseudostems, and used to reinforce ABS for composite production. The common compression molding for composite was successfully applied to make UD banana fiber-reinforced composites. Composites prepared by compression molding at T = 170 °C, t = 20 min and P = 100 kg cm^{-2} had the highest mechanical properties with the smallest porosity and the lowest water absorption. It was found that the tensile and flexural properties of the composites were inversely proportional to the volume fraction of porosity. In addition, processing under high pressure might lead to a significant decrease in the mechanical

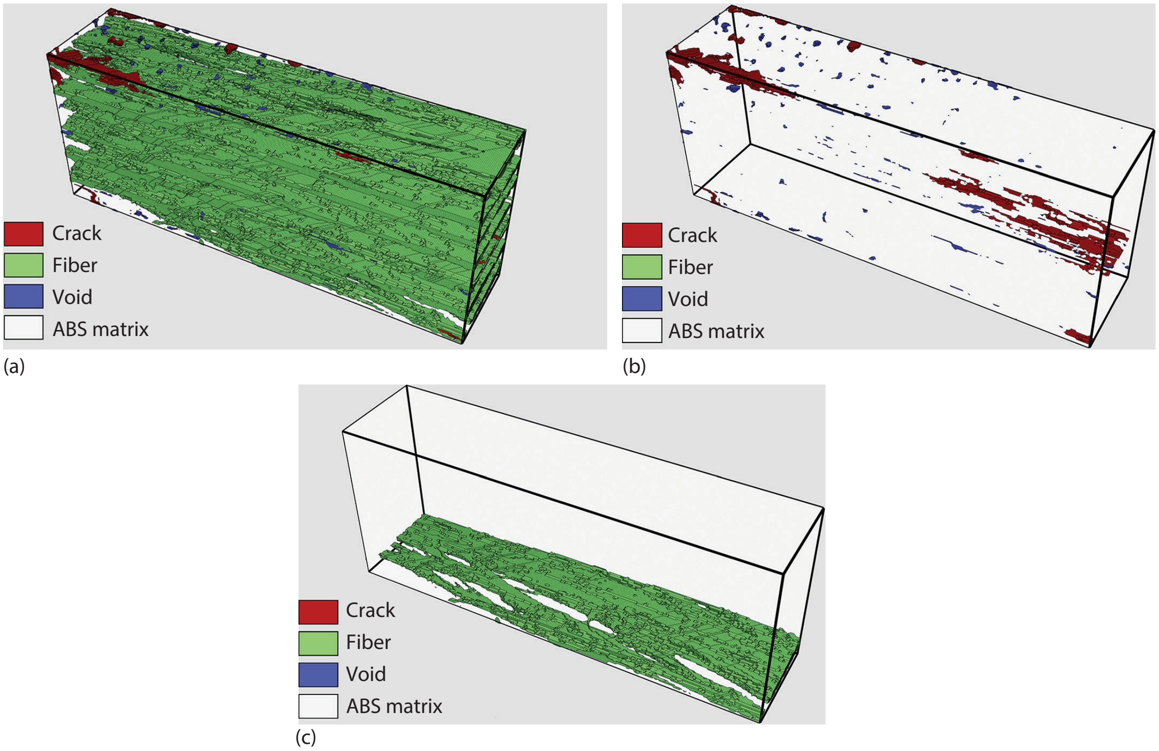


Figure 9 A banana fiber-reinforced composite processed at 170 °C in 20 min and under 125 kg cm^{-2}: (**a**) Three-dimensional whole structures, (**b**) void and crack distribution, and (**c**) 3D structure of one layer.

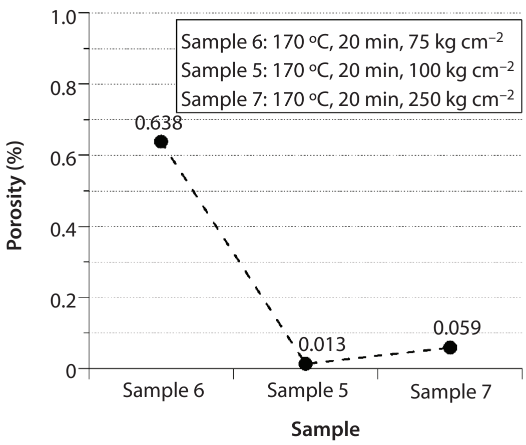


Figure 10 Porosity in banana fiber-reinforced composites processed under various pressures.

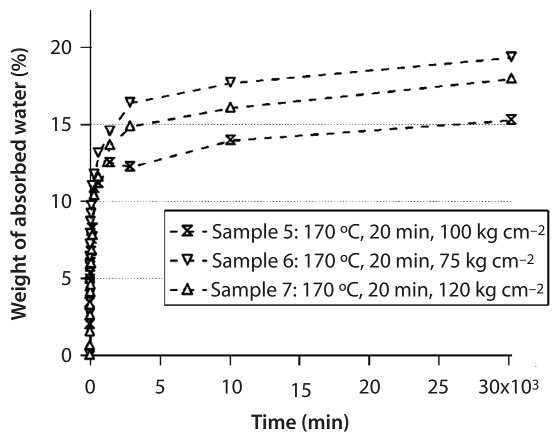


Figure 11 Water absorption of banana fiber-reinforced composites processed under various pressures.

properties of composites due to the induced cracks and floating fibers, as observed in the case of processing banana fiber-reinforced composite at 125 kg cm^{-2}. Furthermore, composite structure analysis is currently in progress and the results will be reported in the near future.

ACKNOWLEDGMENTS

The authors sincerely express gratitude to Dr. Truong Chi Thanh for lending his self-developed fiber extracting machine for cutting and combing the banana fibers. This study was funded in part by the Can Tho University Improvement Project VN14-P6, supported by a Japanese ODA loan.

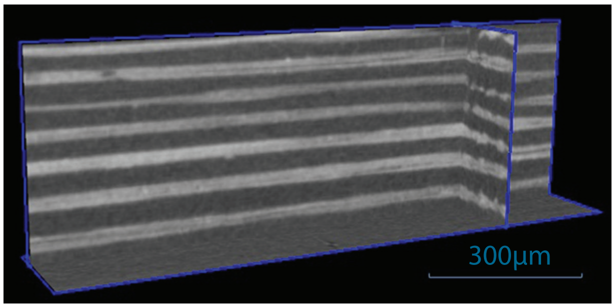


Figure 12 3D model reconstruction of a banana fiber-reinforced composite prepared at T = 170 °C, P = 100 kg cm^{-2} in 20 min.

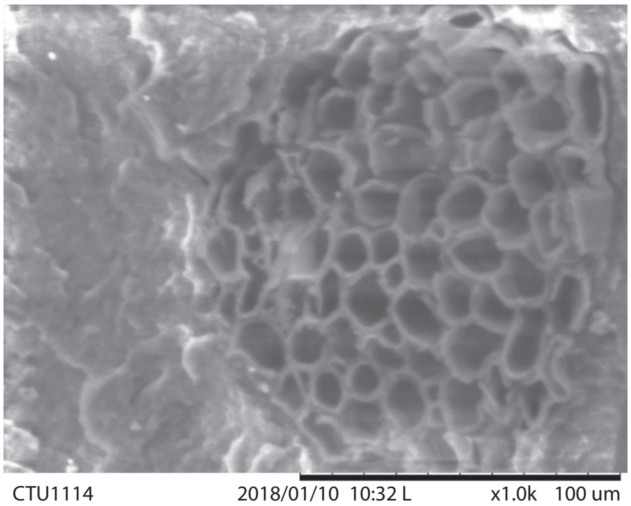


Figure 13 Cross section of banana fiber-reinforced composite prepared at T = 170 °C, P = 100 kg cm^{-2} in 20 min after tensile test.

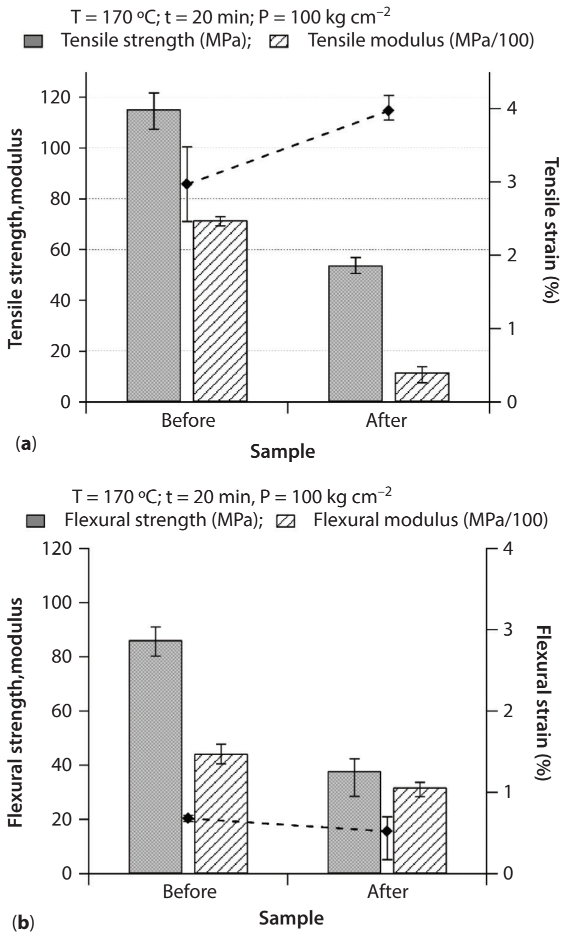


Figure 14 (**a**) Tensile and (**b**) flexural properties of banana fiber-reinforced composites prepared at T = 170 °C, P = 100 kg cm^{-2} in 20 min before and after water absorption.

REFERENCES

1. K.P. Ashik and R.S. Sharma, A review on mechanical properties of natural fiber reinforced hybrid polymer composites. *JMMCE* **3**(5), 420–426 (2015).
2. R. Karnani, M. Krishnan, and R. Narayan, Biofiber-reinforced polypropylene composites. *Polym. Eng. Sci.* **37**(2), 476–483 (1997).
3. A.M.M. Edeerozey, H.M. Akil, A.B. Azhar, and M.I.Z. Ariffin, Chemical modification of kenaf fibers. *Mater. Lett.* **61**(10), 2023–2025 (2007).
4. H.A. Sharifah and P.A. Martin, The effect of alkalization and fibre alignment on the mechanical and thermal properties of kenaf and hemp bast fibre composites: Part 1—Polyester resin matrix. *Compos. Sci. Technol.* **64**(9), 1219–1230 (2004).
5. M.Y. Yuhazri, P.T. Phongsakorn, and H. Sihombing, A comparison process between vacuum infusion and hand lay-up method toward kenaf/polyester composites. *Int. J. Basic Appl. Sci.* **10**(3), 63–66 (2010).
6. T. Nishino, K. Hirao, M. Kotero, K. Nakamae, and H. Inagaki, Kenaf reinforced biodegradable composite. *Compos. Sci. Technol.* **63**(9), 1281–1286 (2003).
7. M.P. Ansell, S.J. Clarke, and S.R. Panteny, Modified polyester resins for natural fiber composites. *Compos. Sci. Technol.* **65**(3–4), 525–535 (2005).
8. P. Wambua, J. Ivens, and I. Verpoest, Natural fibers: Can they replace glass in fiber reinforced plastics? *Compos. Sci. Technol.* **63**(9), 1259–1264 (2003).
9. M. Lawrence, Reducing the environmental impact of construction by using renewable materials. *J. Renew. Mater.* **3**(3), 163–174 (2015).
10. L.A. Pothan, S. Thomas, and R. Neelakantan, Short banana fiber reinforced polyester composites: Mechanical properties, failure and aging characteristics. *J. Reinf. Plast. Compos.* **16**(8), 744–765 (1997).
11. L.A. Pothan, Z. Oommen, and S. Thomas, Dynamic mechanical analysis of banana a fiber reinforced with polyester composites. *Compos. Sci. Technol.* **63**(2), 283–293 (2003).

12. M. Ramesh, T. Sri Ananda Atreya, U.S. Aswin, H. Eashwar, and C. Deepa, Processing and mechanical property evaluation of banana fibre reinforced polymer composites. *Procedia Engineering* **97**, 563–572 (2014).
13. N. Venkateshwaran, A.E. Perumal, and D. Arunsundaranayagam, Fiber surface treatment and its effect on mechanical and visco-elastic behaviour of banana/epoxy composite. *Mater. Des.* **47**, 151–159 (2013).
14. S. Mishra, J.B. Naik, and Y.P. Patil, The compatibilising effect of maleic anhydride on swelling and mechanical properties of plant-fiber-reinforced novolac composites. *Compos. Sci. Technol.* **60**(9), 1729–1735 (2000).
15. S. Joseph, M.S. Sreekala, Z. Oommen, P. Koshy, and S. Thomas, A comparison of the mechanical properties of phenol formaldehyde composites reinforced with banana fibers and glass fibers. *Compos. Sci. Technol.* **62**(14), 1857–1868 (2002).
16. M. Sakthivel and S. Ramesh, Mechanical properties of natural fiber (banana, coir, sisal) polymer composites. *Science Park* **1**(1), 1–6 (2013).
17. M. Modesti, S. Besco, A. Lorenzetti, V. Causin, C. Marega, J.W. Gilman, D.M. Fox, P.C. Trulove, H.C. De Long, and M. Zammarano, ABS/clay nanocomposites obtained by a solution technique: Influence of clay organic modifiers. *Polym. Degrad. Stab.* **92**(12), 2206–2213 (2007).
18. G. Ozkoca, G. Bayramb, and E. Bayramlic, Effects of polyamide 6 incorporation to the short glass fiber reinforced ABS composites: An interfacial approach. *Polymer* **45**(26), 8957–8966 (2004).
19. G.L. Mantovani, L. Bresciani Canto, E. Hage Junior, and L.A Pessan, Toughening of PBT by ABS, SBS and HIPS systems and the effects of reactive functionalised copolymers. *Macromol. Symp.* **176**(1), 167–180 (2001).
20. A. Madra, N.E. Hajj, and M. Benzeggagh, X-ray microtomography applications for quantitative and qualitative analysis of porosity in woven glass fiber reinforced thermoplastic. *Compos. Sci. Technol.* **95**, 50–58 (2014).
21. Y. Nishikawa, S. Baba, and M. Takahashi, Optimization of X-ray computerized tomography for polymer materials. *Int. J. Polym. Mater.* **62**(5), 295–300 (2013).
22. A.C.H. Barreto, M.M. Costa, A.S.B. Sombra, D.S. Rosa, R.F. Nascimento, S.E. Mazzetto, and P.B.A. Fechine, Chemically modified banana fiber: Structure, dielectrical properties and biodegradability. *J. Polym. Environ.* **18**(4), 523–531 (2000).
23. S. Mukhopadhyay, R. Fangueiro, Y. Arpaç, and Ü Şentürk, Banana fibers – variability and fracture behaviour. *J. Eng. Fibers Fabrics* **3**(2), 39–45 (2008).

