Bamboo and High Density Polyethylene Composite with Heat-Treated Bamboo Fiber: Thermal Decomposition Properties

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Heat treatment under controlled temperatures can help enhance bamboo's durability and dimensional stability. The treatment may simultaneously affect thermal and mechanical performance of bamboo fibers (BFs). The aim of this work was to study the effect of heat treating temperature on thermal decomposition kinetic properties of heat-treated BFs and resulting polymer composites using dynamic thermo-gravimetric analysis under nitrogen. Degradation models including the Kissinger and the Flynn-Wall-Ozawa methods were used to determine the apparent activation energy (E_a) of various materials. The results indicated that the thermal decomposition of the heat-treated BFs mainly occurred within a temperature range between 245°C and 354°C. The values of E_a varied from 161 to 177 kJ/mol and increased with increased heat treating temperatures for the fibers. The thermal decomposition of the heat-treated BF and high density polyethylene blends mainly occurred within a temperature range of 307°C and 483°C. The values of E_a were between 225 and 236 kJ/mol and decreased with the increase of fiber heat-treating temperatures. The established thermal decomposition kinetic parameters can help aid the development of polymer composites from heat-treated bamboo materials.

Keywords: Apparent activation energy; Heat-treated bamboo fibers; Thermal decomposition; TGA

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INTRODUCTION

In recent years, there has been increasing attention paid to polymer composites reinforced with natural fibers due to environmental concern and market demand for green materials (Lee *et al*. 2008). Common natural fibers used for composite processing include hemp, jute, kenaf, bagasse, bamboo, cotton stalk, rice husk, rice straw, and different types of wood. These materials are relatively low in cost, recyclable, and have high strength. Among these fibers, bamboo material has higher cellulose content and higher strength-to-weight ratio (Tan *et al*. 2011). However, untreated bamboo material is highly susceptible to attacks by moisture and biological agents such as decay and mold fungi, which can negatively affect its long-term durability and dimensional stability. Heat treatment under well-designed temperature and pressure conditions has been shown to be an effective technology to inhibit living organisms by modifying the material composition (*i.e.*, changing relative contents of cellulose, hemicellulose, lignin, and extractives in the material), leading to reduced nutrition for fungus growth (Bao 2009). Furthermore, hemicellulose within the material has a high hygroscopicity as a result of the free hydrophilic groups connecting the main and side molecular chains. It was shown that the content of hemicellulose after heat treatment decreases, and hydrophobic polymers are created at heat treating temperatures (Wålinder and Johansson 2001; Deng 2004). On the other hand, excessive heat treatment (in terms of temperature and/or treating time) can lead to increased material brittleness and reduced structural integrity (Phuong *et al.* 2007). Thus, well-controlled heat treatments can help reduce the hygroscopicity, expansion, and contraction of bamboo materials, leading to improved dimensional stability, while maintaining its mechanical performance.

The heat treatment process is normally done under oxygen-deficient conditions at temperatures above 120^{o}C for a certain time period. After heat treatment, thermal performance properties of the material may change as a result of the chemical composition changes. An understanding of the thermal decomposition process of heat-treated natural fibers can help aid the development of polymer composites from the heat-treated materials. Activation energy is one of the key parameters used to describe thermal decomposition behavior of the polymer materials under various heating rates. Thermal decomposition study of natural fibers has been primarily motivated by applications such as renewable biomass energy and biofuels, and forest fire propagation control. Published data of activation energy for natural fibers are in the range of 160 to 170 kJ/mol (Mohan *et al*. 2006; Brown *et al*. 2001; Chen *et al.* 2006; Yao *et al.* 2009). Previous research on thermal decomposition of bamboo fiber shows that the activation energy of bamboo fiber (BF) is in the range of 160 to 165 kJ/mol (Yao *et al*. 2008). However, there is a lack of research on activation energy and other thermal properties for heat-treated bamboo fibers in relation to composite processing.

For bamboo-reinforced polymer composites, previous studies primarily focus on the effects of processing, bamboo fiber loading, particle size, types of coupling agents or chemical modifiers and their loading rate on physical and mechanical properties, interfacial characteristics, and morphologies of the resulting composites (Liu *et al.* 2008, Li *et al*. 2010; Wong *et al.* 2010; Liu *et al*. 2009; Chen *et al*. 2009; Li *et al*. 2008). Few published papers have dealt with heat-treated bamboo fiber reinforced polymer composites so far. Since bamboo-fiber reinforced polymer composites are a combination of bamboo (in the form of fibers or particles) and a thermoplastic matrix, the bamboo material determines how the composite absorbs water. A study on heat-treated bamboo/high density polyethylene (HDPE) composites shows that the water absorption of the composites decreased with the increase of the fiber heat-treating temperature, and that the mechanical properties of 180^{o}C heat-treated BF/HDPE composites are similar to those from untreated BF/HDPE composites (Zhou 2009).

Work has been done to determine the apparent activation energy and the thermal decomposition of reinforced polymer composites. For example, Geum-Hyun Doh *et al.* (2005) studied the thermal behavior of liquefied wood polymer composites and proved that thermal stability of the fibers is necessary for a better consolidation process of composite materials. Chrissafis *et al*. (2009) found that thermal stability of HDPE was enhanced due to the incorporation of SiO_2 nanoparticles. The use of SiO_2 had no effect on decomposition mechanism, but had some influence on the activation energy values.

Degradation modeling as an important approach to calculate the apparent activation energy, E_a, has been done using various thermal kinetic equations. The equations provide a quantitative characterization of reaction process in order to evaluate the stability and compatibility of the materials, and to determine the effective working life and the optimal production process (Hu 2008). Thermal kinetic models mainly consist of integral and differential methods. The Phadnis, Coats-Redfern, Modified Coats-Redfern, and Flynn-Wall-Ozawa methods are the common integral methods (Yao *et al*. 2008). The Kissinger and Freeman-Carroll methods are the normal differential methods. These models can help determine the most probable mechanism function $f(\alpha)$ and kinetic parameters such as E_a and pre-exponential factor (A).

The objectives of this study were to investigate the thermal decomposition process of heat-treated BFs and resulting BF-HDPE composites through a dynamic thermo-gravimetric analysis (TGA), and to establish their E_a values as influenced by fiber heat-treating temperatures. The Kissinger and Flynn-Wall-Wzawa methods were used in the analysis. Our future papers will focus on the non-isothermal crystallization, physical, and mechanical properties of heat-treated bamboo fiber reinforced polymer composites.

MATERIALS AND METHODS

Raw Material and Preparation

Moso bamboo (*Phyllostachys edulis*) was used for this study. Green bamboo sections with diameter varying from 70 to 100 mm were collected and were cross-cut and sawn into strips. All strips were dried at 100±2^{o}C for 48 h to reduce their moisture content to about the 6% level. The strips were then randomly divided into three equal weight groups. One group was used as the control and the two other groups were subjected to heat treatment at 150^{o}C and 180^{o}C temperatures for 2 h. All three groups were then hammer-milled, and the crushed material was screened to pass a 40-mesh screen.

High density polyethylene (HDPE AD60-007 with MFR = 0.7 g/10 min at 190^{o}C/2.16 kg, density = 0.96 g/cm^3) was provided by ExxonMobile Chemical Co. (Houston, TX, USA). MAPE (Epolene^{TM} G2608 with MFR 6 to 10 g/10 min at 190°C/ 2.16 kg, M_F=65,000 g/mol, and acid number 8 mg KOH/g) from Eastman Chemical Co. (Kingsport, TN, USA) was utilized to increase the compatibility between fillers and plastic matrix.

Composite Sample Preparation

Melt compounding with 40% BF, 58% HDPE, and 2% MAPE was performed using an intermesh, counter-rotating Brabender twin-screw extruder (Brabender Instruments Inc., Hackensack, NJ, USA) with a screw speed of 40 rpm. The temperature profile of barrels was (feeding zone) 150 - 175 - 175 - 175 - 175°C (die). The extrudates were quenched in a cold water bath and then pelletized into granules, which were oven-dried at 70°C for 12 h and bagged for further testing.

TGA Procedure and Data Analysis

Before the tests, heat-treated BFs and BF HDPE blends were dried in an oven (LC-233 B1, Espec Co. Hudsonville, MI, USA) at 70°C for 24 h. Thermal decomposition was observed in terms of global mass loss by using a STA 409PC thermo-gravimetric analyzer (Netzsch Co. Selb, Germany). The temperature change was controlled from room temperature (30±3°C) to 700°C at five different heating rates of 5, 10, 20, 30, and 40°C/min. The sampling segment was set as 2.5 s per point. Thermal decomposition was carried out at low or moderate heating rates to keep possible heat/mass-transfer intrusions at a minimum. A high purity nitrogen stream (99.5% nitrogen, 0.5% oxygen content) was continuously passed into the furnace at a flow rate of 40mL/min at room temperature and atmospheric pressure.

The fundamental rate equation used in all kinetic studies is generally described as,

$$d\alpha/dt = \kappa f(\alpha) \tag{1}$$

where k is the rate constant and $f\,(\alpha)$ is the reaction model, a function depending on the actual reaction mechanism. Eq. (1) expresses the rate of conversion, $d\alpha/dt$, at a constant temperature as a function of the reactant concentration loss and rate constant. In this study, the conversion rate α is defined as,

$$\alpha = (W_o - W_t)/(W_o - W_f) \tag{2}$$

where W_t, W_o, and W_f are time t, initial, and final weights of the sample, respectively. The rate constant k is generally given by the Arrhenius equation,

$$\kappa = A\,exp(-E_a/\mathrm{RT}) \tag{3}$$

where E_a is the apparent activation energy (kJ/mol), R is the gas constant (8.3145 J/K mol), A is the pre-exponential factor (min^{-1}), T is the absolute temperature (K). A combination of Eqs. (1) and (3) gives the following relationship:

$$\frac{\mathrm{d}\alpha}{\mathrm{dt}} = Aexp\left(-\frac{E_a}{RT}\right) f(\alpha) \tag{4}$$

For a dynamic TGA process, introducing the heating rate, $\beta = dT/dt$, into Eq. (4), Eq. (5) is obtained as:

$$\mathrm{d}\alpha/\mathrm{dt} = \left(\frac{A}{\beta}\right) \exp\left(-\frac{E_a}{RT}\right) f(\alpha) \tag{5}$$

Equations (4) and (5) are the fundamental expressions of analytical methods to calculate kinetic parameters on the basis of TGA data. Two of the most common “model-free” methods for determining the activity energy include the Kissinger and Flynn-Wall-Ozawa methods (Yao *et al.* 2008). In the Kissinger method, $\ln(\beta/T_P^2)$ is plotted against $1/T_P$ for a series of experiments at different heating rates with the peak temperature, T_P, obtained from the derivative TG (DTG) curve. The iso-conversional Flynn-Wall-Ozawa (F-W-O) method is an integral method, which leads to $-E_a/R$ from the slope of the line determined by plotting $\log\beta$ against $1/T$ at any certain conversion rate.

RESULTS AND DISCUSSION

Thermal Decomposition of Heat-treated Bamboo Fibers

The thermo-gravimetric curves of heat-treated bamboo fibers at a heating rate of 40°C/min are shown in Fig. 1. All TG and DTG curves had similar trends, consistent with the same thermal decomposition mechanism. As shown in the DTG curves, a low-temperature shoulder peak and a high-temperature main peak were observed at about 270^{o}C and 330^{o}C, respectively, which were caused by the thermal decomposition of hemicellulose and cellulose, respectively. Since the region of the hemicellulose was close to that of cellulose, and the content of hemicellulose was less than that of cellulose, the shoulder peak was overlapped in the main peak. Lignin had a good stability. The main degradation of lignin occurred at temperatures above about 350^{o}C.

Thermal decomposition characteristic parameters were calculated from TG, DTG (first derivative), and D^2TG (second derivative) curves. Figure 2 shows the calculation method of the parameters by using BFs treated at 150^{o}C at a heating rate of 5^{o}C/min as an example. The onset temperature of decomposition, T_O, and the shift temperature of decomposition, T_S , was obtained by drawing the tangent lines of the DTG with the point of the first and the last peak of the D^2TG curve and making the value of DTG zero. The peak temperature, T_P, was determined by the maximum of the DTG, which was the fastest speed of the decomposition. The decomposition characteristic parameters of BFs under various heat treatment temperatures are shown in Table 1. To exclude the influence of the heating rate, T_O, T_P, and T_S were obtained by a linear extrapolation to $\beta = 0$ (Fig. 3). The mass loss percentages corresponding to the T_O, T_P, and T_S were designated as WL_O, WL_P, and WL_S, respectively. Table 2 shows the calculated decomposition parameters and standard deviation data.

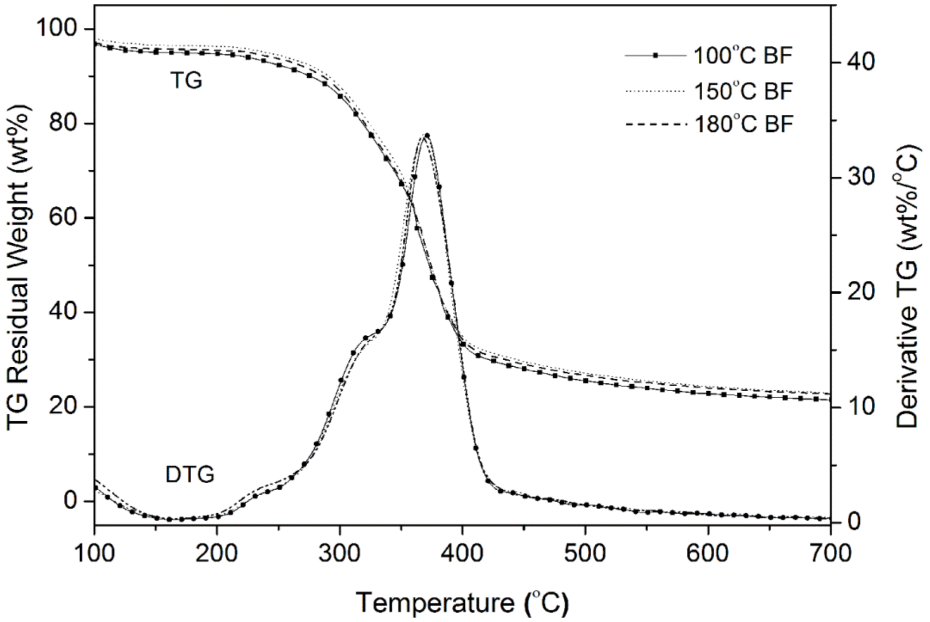

Fig. 1. Thermo-gravimetric decomposition process of heat-treated BFs at the heating rate of 40^{o}C/min

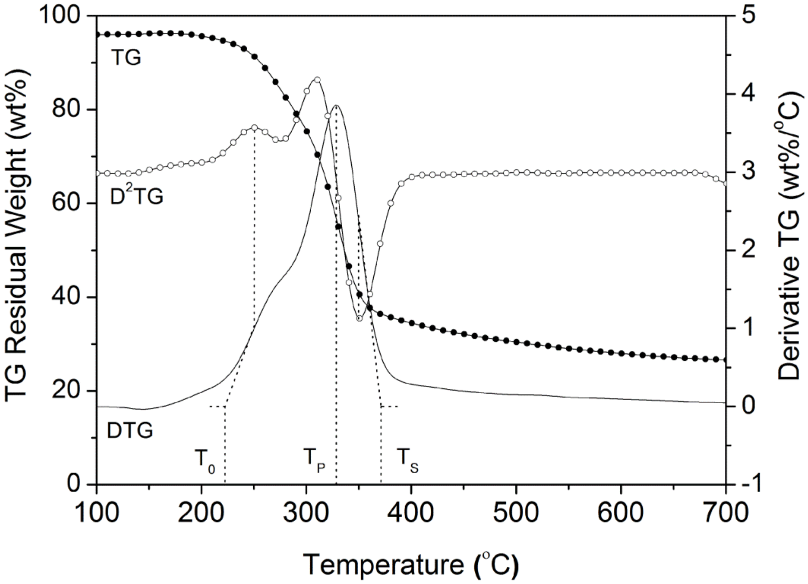

Fig. 2. Determination of decomposition characteristic parameters of heat-treated fibers using 150°C heat-treated BFs as an example at a heating rate of 5°C/min

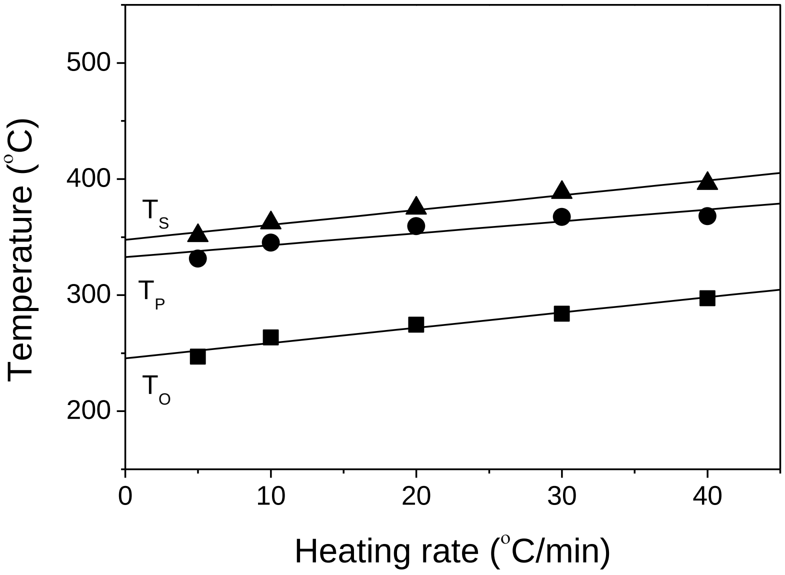

Fig. 3. Determination of decomposition characteristic parameters (*i.e.,* onset, peak, and shift temperatures) of heat-treated fibers using 100°C heat-treated BFs as an example

Table 1 shows that T_O, T_P, and T_S of all BFs increased with the increasing heating rates as a result of the true temperature of the samples lagging behind the surrounding environment temperature during testing. The temperatures and weight loss difference between the onset and shift points, (T_S -T_O) and (WL_S-WL_O), indicated the main thermal decomposition fraction happened over a temperature range of about 100°C. The weight loss fraction ranged from about 50% to 56% among the four heating rates used (*i.e.*, 5, 10, 20, 30, and 40°C/min), and the decomposition temperatures were in the range of 247°C to 297°C. However, there was no notable difference among values of WL_O, WL_P, and WL_S from different heating rates.

Table 1. Decomposition Characteristic Parameters of Heat-treated Bamboo Fibers

Sample	β ($^{\circ}$C/min)	Temperature				Weight Loss			Residue
		T_{O} ($^{\circ}$C)	T_{P} ($^{\circ}$C)	T_{S} ($^{\circ}$C)	T_{S} - T_{O} ($^{\circ}$C)	$\mathrm{WL_O}$ (%)	$\mathrm{WL_S}$ (%)	$\mathrm{WL_S}$-$\mathrm{WL_O}$ (%)	(%)
100BF	5	247.0	331.5	351.1	104.1	8.1	64.5	56.4	17.8
	10	263.5	345.1	362.1	98.6	9.3	62.9	53.6	21.5
	20	274.4	359.4	374.9	100.4	9.9	62.2	52.3	24.0
	30	283.9	367.4	388.4	104.5	8.7	62.5	53.8	23.9
	40	297.2	368.0	396.1	98.9	9.6	63.5	53.9	22.4
150BF	5	249.8	329.2	351.3	101.5	8.2	58.1	49.9	27.6
	10	261.3	339.7	359.8	98.5	7.5	60.3	52.8	24.2
	20	271.9	353.4	374.6	102.7	7.1	61.7	54.6	23.3
	30	283.4	362.2	383.0	99.6	7.9	60.4	52.5	23.5
	40	291.9	365.9	385.9	94.0	7.6	57.4	49.9	23.6
180BF	5	247.5	334.0	353.9	106.4	7.1	62.9	55.8	23.7
	10	260.8	345.4	363.9	103.1	7.2	62.4	55.2	22.5
	20	277.4	360.3	377.7	100.3	7.8	62.4	54.6	23.6
	30	285.1	366.2	386.9	101.8	7.7	61.9	54.2	23.6
	40	292.8	367.6	386.8	94.0	7.8	58.1	50.2	23.6

Table 2. Decomposition Characteristic Parameters of Heat-treated Bamboo Fibers after a Linear Extrapolation to $\boldsymbol{\beta}$ = 0

Sample	Temperature			Weight Loss		Residue
	$T_{\mathrm{O}\,\beta\to0}$ ($^{\circ}$C)	$T_{\mathrm{P}\,\beta\to0}$ ($^{\circ}$C)	$T_{\mathrm{S}\,\beta\to0}$ ($^{\circ}$C)	$\mathrm{WL}_{\mathrm{O}\,\beta\to0}$ (%)	$\mathrm{WL}_{\mathrm{S}\,\beta\to0}$ (%)	(%)
100BF	245.7	332.8	347.8	9.1 (0.7)	63.1(0.9)	21.9(2.5)
150BF	247.2	328.2	349.8	7.6 (0.3)	59.6(1.8)	24.4(1.8)
180BF	246.5	334.8	353.7	7.5 (0.3)	61.5(2.0)	23.4(0.5)

Table 2 shows the extracted onset, peak, and shift temperatures, and the corresponding weight loss data. With increased heat-treating temperatures, all three characteristic temperatures increased, while the extracted weight losses at the onset and shift points decreased. Compared with the control sample (100BF), the residual weight percentage of treated fibers (150BF and 180BF) at the final temperature level increased. The increased decomposition temperatures, reduced weight losses, and increased residual sample weight percentage indicated the treated fibers were more thermally stable.

With the above data and degradation models including the Kissinger and Flynn-Wall-Ozawa (F-W-O) methods, the decomposition activation energies of various heat-treated bamboo fibers were evaluated. Figure 4 shows a typical iso-conversional plot from the F-W-O method using 150°C treated bamboo fibers as an example. The slopes of the lines at the conversion rates of 0.1 and 0.9 were somewhat different from the others as a result of the complex degradation during the starting and ending periods. Thus, the conversion rates ranging from 0.2 to 0.8 were used to calculate the E_a.

Table 3 shows the apparent activation energy values calculated from both the Kissinger and the Flynn-Wall-Ozawa method and the goodness of fit. As shown in Table 3, the activation energies were 161.7, 164.8, and 176.4 kJ/mol, respectively, for materials from three heat-treating temperatures (*i.e.*, 100, 150, and 180°C). The E_a values increased with the increase of the heat-treating temperatures, indicating enhanced thermal stability of the treated materials. It is well known that decomposition temperatures of both cellulose and hemicellulose are well above 200°C. The heat-treating temperature of 180°C did not have a significant influence on cellulose and hemicellulose materials. Several possible factors may contribute to the observed changes in the BF thermal stability properties. During the high temperature treating process, some small molecules under high temperatures may decompose (as indicated by the reduced weight loss percentage at the onset point - Table 2), which reduces the unstable substances in the BFs such as pigment and tannic. Also, the lignin at temperatures above about 150°C may soften, and reorganization and recrystallization may occur.

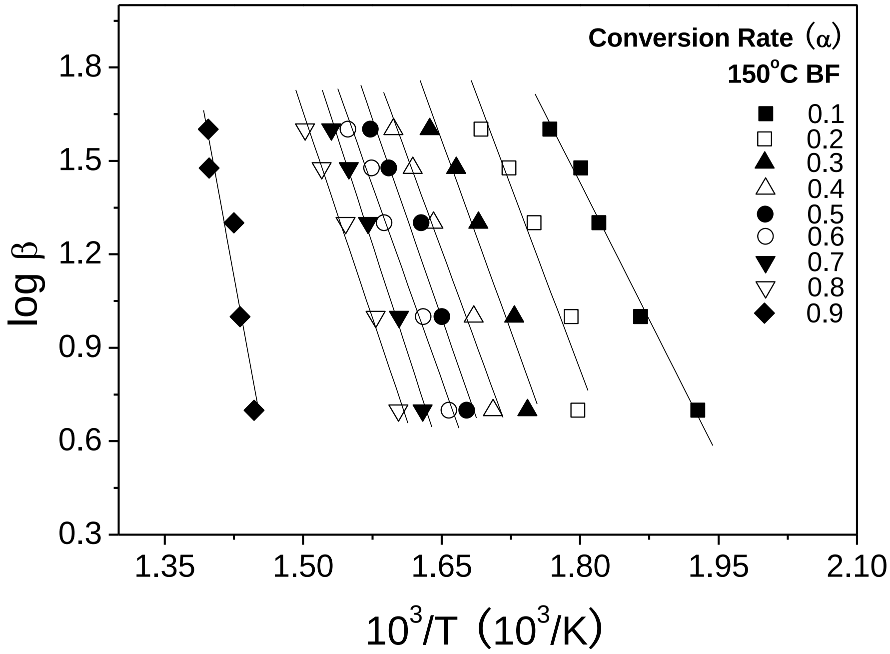

Fig. 4. Typical iso-conversional plot of the Flynn-Wall-Ozawa method

Table 3. Apparent Activation Energy of Heat-Treated Bamboo Fibers Calculated by the Kissinger and F-W-O Methods

Sample	Kissinger		Flynn-Wall-Ozawa	
	Ea	R^2	Ea	R^2
100BF	161.7	0.9820	163.8	0.9840
150BF	164.8	0.9962	166.5	0.9967
180BF	176.4	0.9820	177.6	0.9838

Treated BFs with increased thermal stability may help aid the development of polymer natural fiber composites, especially these using engineering plastics such as nylon as matrix material, where the thermal stability of the fiber at elevated temperatures is of major concern (Amintowlieh *et al.* 2010; Lei and Wu 2011). The establishment of the kinetic parameters for various fiber materials over an entire temperature range allows modeling of fiber degradation (*i.e.*, weight loss) during composite processing (Yao *et al.* 2009).

Thermal Decomposition of Heat-treated BF and HDPE Blends

Typical TG curves of heat-treated BF and HDPE blends at a heating rate of 40°C/min are shown in Fig. 5. Compared with the TG curve of HDPE, the curves of heat-treated bamboo fiber/HDPE blends had two steps of decomposition corresponding to the two peaks in the DTG curves caused by the thermal decomposition of BFs (~375°C) and HDPE (~520°C). The decomposition temperature of the lignocellulosic material like bamboo was obviously smaller than that of the HDPE.

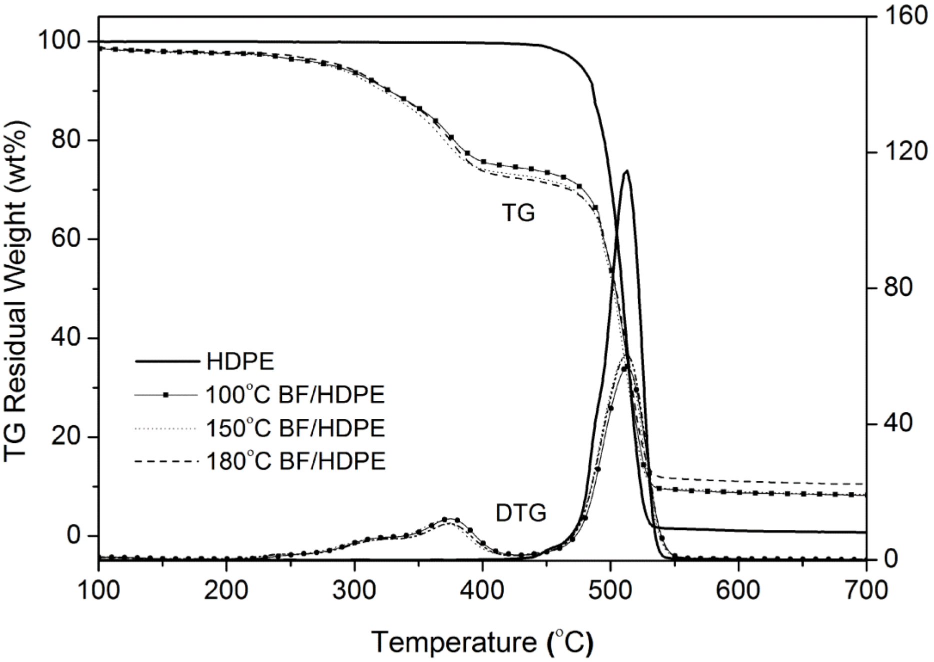

Fig. 5. Thermo-gravimetric decomposition process of heat-treated BFs and HDPE blends at the heating rate of 40°C/min

Thermal decomposition characteristic parameters for various composite blends were calculated from TG, DTG, and D^2TG curves, and the results are listed in Table 4. The calculation method of the parameters was the same as that used for BFs. Table 4 shows that T_O, T_P, and T_S of pure HDPE and all BF/HDPE blends increased with the increased heating rates. The values of T_O and T_S of the pure HDPE were higher than these for the composite blends. The T_O values of the BF/HDPE blends were 337±19°C, which are smaller than the corresponding temperatures for the pure HDPE, but higher than the temperatures for BFs (Table 1). This was because of the HDPE coating on the BFs, which prevented them from the fast thermal degradation. The mean values of T_S for the pure HDPE and BF/HDPE blends were 508±18°C and 507±16°C, respectively. The weight loss fraction of pure HDPE ranged from 65.8% to 87.3% among the four heating rates. The temperature and weight loss differences of the BF/HDPE blends between the onset and shift points averaged at 170±6°C and 74±2%, respectively.

During thermal decomposition, the residue of the pure HDPE was almost reduced to zero. The residues of the blends increased with the increased heat-treating temperature for the BFs. The residue of the 180°C-treated BF and HDPE blend was higher than that from the low temperature treated BF and HDPE blends. The value of (WL_S-WL_O) of the blends was reduced with increased heat-treating temperature of the fibers.

Table 4. Decomposition Characteristic Parameters of Heat-treated BF and HDPE Blends

Sample	β (°C/min)	Temperature				Weight Loss			Residue
		T_O (°C)	T_P (°C)	T_S (°C)	T_S - T_O (°C)	WL_O (%)	WL_S (%)	WL_S-WL_O (%)	(%)
HDPE	5	458.6	472.0	483.8	25.2	32.3	98.1	65.8	0
	10	471.4	482.7	496.3	24.9	32.0	96.8	64.7	0
	20	491.2	500.2	510.2	19.0	39.4	96.1	56.7	0
	30	498.8	509.8	523.1	24.2	34.9	97.0	62.1	0.4
	40	485.3	512.8	525.7	40.4	8.5	95.7	87.3	0.7
100BF/ HDPE	5	309.8	474.5	485.1	175.4	12.0	87.9	75.8	6.5
	10	325.2	483.6	497.7	172.5	12.8	89.5	76.7	6.6
	20	337.1	497.3	504.2	167.0	12.4	80.1	67.8	9.1
	30	352.9	509.9	522.4	169.5	14.0	87.8	73.8	7.3
	40	359.7	512.7	528.6	169.0	14.0	88.8	74.8	8.4
150BF/ HDPE	5	306.6	473.5	484.7	178.1	9.6	85.1	75.5	9.9
	10	320.8	483.4	495.7	174.9	13.0	87.0	74.0	8.1
	20	355.6	497.2	507.8	152.2	13.4	86.3	72.9	8.9
	30	346.5	509.0	521.0	174.5	13.1	86.9	73.8	7.5
	40	353.6	514.0	525.1	171.5	14.2	87.3	73.2	8.5
180BF/ HDPE	5	311.3	472.7	484.5	173.2	12.6	86.6	74.0	7.9
	10	323.7	484.9	496.0	172.3	12.9	86.4	73.5	8.8
	20	342.8	498.4	510.3	167.5	13.9	86.1	72.2	10.6
	30	349.9	509.5	512.8	162.9	13.0	86.7	73.7	9.5
	40	359.2	514.4	528.1	169.0	14.5	86.0	71.5	10.6

Based on the above data and degradation models, the values of decomposition activation energy, E_a, of various heat-treated BF and HDPE blends were evaluated. Figures 6 and 7 show typical iso-conversional plots from the Flynn-Wall-Ozawa method for pure HDPE and BF/HDPE composite blends, respectively. The slopes of the lines were used to calculate the E_a. Table 5 shows the apparent activation energy values calculated by both Kissinger and Flynn-Wall-Ozawa methods and the goodness of fit for pure HDPE and various composites.

Table 5. Apparent Activation Energy, E_a, of Heat-treated BF and HDPE Blends Calculated by Kissinger and F-W-O Methods

Samples	Kissinger		Flynn-Wall-Ozawa	
	E_a	R^2	Ea	R^2
HDPE	219.8	0.9893	221.1	0.9905
100BF/HDPE Composite	235.6	0.9814	236.2	0.9833
150BF/HDPE Composite	228.7	0.9879	229.6	0.9892
180BF/HDPE Composite	225.9	0.9960	226.9	0.9964

Compared with the pure HDPE, heat-treated BF and HDPE blends had higher values of E_a. Thus, the reinforced polymer blends were more thermally stable. The E_a values of the composite blends slightly decreased with increased heat-treating temperature of BFs, probably due to the interfacial characteristic change of the blends. Avella *et al.* (2010) studied the effect of compatibilization on thermal degradation kinetics of HDPE-based composites containing cellulose reinforcements. They showed an increased activation energy for compatibilized blends with a coupling agent due to enhanced interfacial adhesion between the components in the composites.

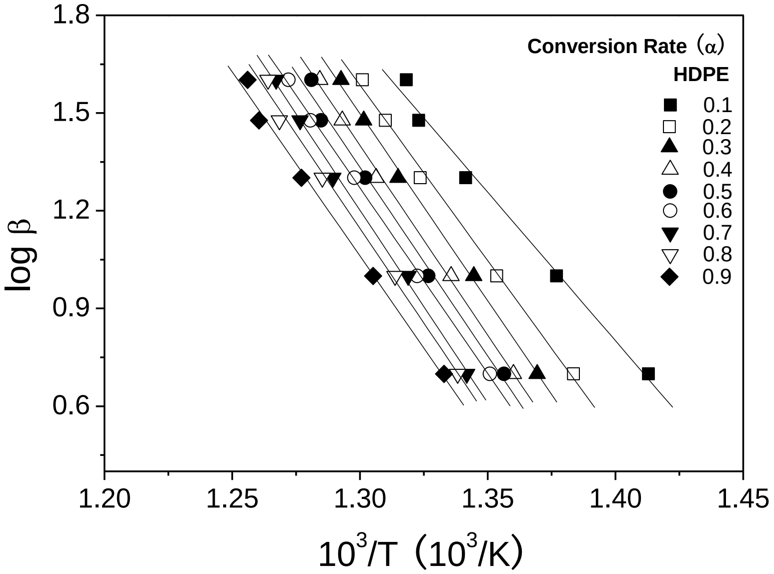

Fig. 6. Typical iso-conversional plot of Flynn-Wall-Ozawa method for pure HDPE

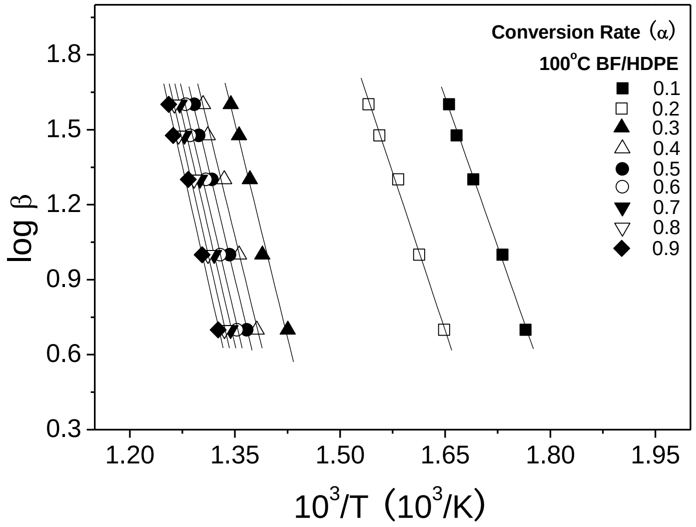

Fig. 7. Typical iso-conversional plot of Flynn-Wall-Ozawa method for bamboo fiber/HDPE blends

The results from the last section on BFs showed that treated BFs were more thermally stable compared with the control fibers. It could be possible that the prior heat treatment rendered the BFs more susceptible to damage during compounding due to increased brittleness and reduced flexibility, which could lead to less compatibilized blends from treated materials, and thus somewhat reduced thermal stability.

CONCLUSIONS

1. Dynamic TG analysis under nitrogen was used to investigate the thermal decomposition processes of heat-treated BFs and the resulting BF-HDPE composite

blends. Degradation models including the Kissinger and Flynn-Wall-Ozawa methods were used to determine the E_a values of the materials.

2. The TG and DTG curves of heat-treated BFs had similar trends as a result of similar thermal decomposition mechanism. Thermal decomposition of the fibers mainly occurred within a temperature range between 245°C and 354°C. Their E_a values varied from 161 to 177 kJ/mol and increased as fiber heat-treating temperatures increased.
3. The TG and DTG curves of heat-treated BFs and HDPE blends had similar trends, and thermal decomposition of the blends mainly occurred within a temperature range of 307°C and 483°C. The values of E_a for various composites blends were in a range of 226 to 236 kJ/mol and decreased as fiber heat-treating temperatures increased.
4. The established thermal decomposition kinetic parameters of various materials can help aid the development of polymer composites from heat-treated bamboo materials.

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