Effects of the Incorporation of Nano-Bamboo Charcoal on the Mechanical Properties and Thermal Behavior of Bamboo-Plastic Composites

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To illustrate the effects of nano-bamboo charcoal (NBC) on the properties of bamboo plastic composites (BPC), nano-bamboo charcoal-bamboo plastic composites (NBC-BPC) were prepared at 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% (w/v) NBC and characterized. The effects of NBC on the water absorption, fractured surfaces, mechanical properties, and thermal properties of the composites were investigated. NBC had strong interfacial interaction in the BPC, which greatly improved the interfacial adhesion of bamboo flour (BF) and high-density polyethylene (HDPE). The water resistance, flexural strengths, and tensile strengths of the composites were enhanced compared with traditional BPC when the volume of NBC reached a specific loading. These results demonstrated that the incorporation of NBC slightly improved the thermal properties of the synthesized composites.

Keywords: Nano-Bamboo charcoal; Bamboo-plastic composites; Mechanical properties; Thermal properties; Water resistance

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INTRODUCTION

As soaring prices of raw materials for engineering and standard plastics, the pressure concerning the sustainability of natural reservoirs, and threats to the environment have prompted the use of natural recyclable materials for the development of polymer composites (Puglia *et al.* 2005; Jawaid and Khalil 2011). Although synthetic fibers are already used in reinforcement materials, natural plant fiber-reinforced materials have made great progress and are replacing synthetic fibers in various applications (Chand and Fahim 2008). Bamboo fiber is good reinforcement filler for the production of wood plastic composites. Due to the many advantages of bamboo fibers, such as availability, renewability, and short growth period of the raw materials, high strength-to-weight ratio, and excellent mechanical properties, bamboo fiber-reinforced polymer composites are increasingly implemented in daily uses. There have been numerous studies in the engineering, biology, thermatology, and material science industries that have promoted the better application of bamboo fiber in composites (Khalil *et al.* 2012), as doing so will accelerate development in the bamboo plastic composite industry and enlarge its scope.

The inadequate mechanical properties of many wood plastic composites are caused by the weak interface between wood flour and the polymer matrix (Tungjitpornkull and Sombatsompop 2009; Ayrilmis *et al.* 2012; Hosseinaei *et al.* 2012; Deka and Maji 2012). Conventionally, the properties of the bamboo plastic composites are primarily related to the internal interfacial characteristics of the materials. Bamboo

fiber possesses polar properties; its surface contains hydroxyl groups, which cause poor interfacial compatibility with non-polar polymers and generates holes and gaps between the bamboo fiber and the polymer matrix-bonding interface. This phenomenon promotes water absorption and weakens the mechanical properties of the composite, thus limiting its popularization and application. A variety of physical and chemical routes have been explored to improve the water resistance and mechanical properties of bamboo plastic composites (BPC), including modification of bamboo flour, incorporation of a compatibilizer, addition of a coupling agent, and other additives that improve the interfacial adhesion between bamboo flour and the polymer matrix. A few examples are potassium permanganate treatment (Sheng *et al.* 2014), alkali treatment, and treatment with silane and its derivatives (Kushwaha and Kumar 2010; 2011), as well as a coupling agent treatment (Osorio *et al.* 2011). In one interesting study, bamboo was coupled with glass fiber to reinforce hybrid composites (Thwe and Liao 2002). Starch resin and short bamboo fibers have been used to study the effects of fiber length on the mechanical properties of polymer composites (Takagi and Ichihara 2004), and bamboo nanofibers have been used for bamboo plastic composites (Huang and Netravali 2009). However, these methods have disadvantages, such as complicated processing routes, and they cannot effectively improve the interface bonding required to increase the comprehensive performance of the composite.

Bamboo charcoal (BC) is an environmentally friendly material with excellent performance properties. It is widely used in garments and textiles, decorations, and the development of new materials. It is internationally known as the new environmental protection guard of the 21st century and called the "black diamond." Bamboo charcoal can be produced from *Moso* bamboo plants that grow in southern China; after their lifespan of five years, they are treated in a dry coking process at a high temperature above 800 °C. The most notable characteristics of BC are its hexagonal molecular structure, solid quality, and fine porosity. The specific surface area of BC is 700 m^2/g, which is equivalent to the size of a basketball court and 2.5 to 3 times higher than that of wood charcoal. Bamboo charcoal contains approximately five times as many rich minerals as wood charcoal and greater than 10 times charcoal adsorption capacity (Lou *et al.* 2007). Bamboo charcoal has many functions, such as purifying water and air, supplying negative ions, adsorbing foul smells, releasing far-infrared rays, regulating air humidity, disinfection (Zhao *et al.* 2008; Nitayaphat *et al.* 2009; Yang *et al.* 2009), and the conducting and blocking of electromagnetic wave radiation, *etc*. When Li *et al.* (2014) studied the influence of bamboo charcoal on the properties of wood plastic composites (WPC); they found that BC in WPC has a strong interface interaction. The water resistance, flexural properties, tensile properties, and thermal behaviors of WPC with BC were improved relative to traditional wood plastic composites.

Conventionally, the enhancement of a granular filling system depends on the interface bonding strength between the particles and matrix. BC nanoparticles, which are of nanometer size, fill holes, resulting in denser composite materials. At the same time, nano bamboo charcoal (NBC) particle distribution between macromolecular chains can have the effect of physical cross-linking, which enhances the matrix. Therefore, the incorporation of NBC has the potential to fill holes at the interface of bamboo flour (BF) and high-density polyethylene (HDPE) in order to enhance its interface bonding and improve its performance. This study investigated the effects of NBC on the water absorption, mechanical properties, and thermal properties of BPC.

EXPERIMENTAL

Materials

Nano-bamboo charcoal (NBC) was purchased from Jiangshan Green Bamboo Charcoal Co., Ltd. (Jiangshan, China). Bamboo flour (BF), recycled high-density polyethylene (HDPE), lubricant, compatibilizer (maleic anhydride grafted polyethylene, MA-g-PE), and other additives were supplied by Anhui Guofeng Wood-plastic Composites Co., Ltd. (Hefei, China).

Methods

Preparation of samples

Formulations of the mixtures and abbreviations used for the respective composites are shown in Table 1. The BF was dried prior to synthesis to a moisture content of below 2% (by weight). The required amount of BF, recycled HDPE, NBC, and other additives was calculated according to the corresponding formulations, and the components were combined in a high-speed mixer for 10 min. Then, the mixture was added to a twin-screw pelletizer(model HT-35, Nanjing Rubber and Plastics Machinery Plant Co., Ltd., Nanjing, China) with a temperature profile of 165/176/185/185/185/180/180/165 °C for each temperature field (zone 1 to zone 8), respectively, and a rotating speed of 130 rpm. After that, the pellets of NBC-BPC with and without NBC were added to twin-screw extruder (model HTY-30, Nanjing Rubber and Plastics Machinery Plant Co., Ltd., Nanjing, China) with a temperature profile of 150/175/175/165/150 °C for each temperature field (zone 1 to zone 5), respectively, and a rotating speed of 66.7 rpm. Finally, sheet samples of the composites were fabricated.

Table 1. Mixture Formulations and Abbreviations for the Respective Composites

Sample	BF (%)	Recycled HDPE (%)	NBC (%)	Compatibilizer (%)	Additives (%)
NBC-BPC1	50	45.5	0	2	2.5
NBC-BPC2	50	43	2.5	2	2.5
NBC-BPC3	50	40.5	5	2	2.5
NBC-BPC4	50	38	7.5	2	2.5
]NBC-BPC5	50	35.5	10	2	2.5
NBC-BPC6	50	33	12.5	2	2.5

Scanning electronic microscopy (SEM)

SEM was performed on a Hitachi S-4800 microscope (Tokyo, Japan) with an accelerating voltage of 3.0 kV; the fracture surfaces of the samples were coated with a thin layer of gold before analysis.

Water absorption properties

Water absorption was determined according to ASTM D570 (2005). For each test, three test specimens in the form of a bar with dimensions of 76.2 × 25.4 × 5 mm were cut from the composite sheet. The specimens were oven-dried oven at 50 ± 3 °C for 24 h, cooled in a desiccator, and immediately weighed (conditioned weight, W_1) to an accuracy

of 0.001 g. The specimens were then immersed in a container of distilled water at room temperature (23 ± 1 °C) for 24h. Afterwards, the test specimens were carefully dried using a dry cloth and immediately weighed (wet weight, W_2) to the nearest 0.001 g. The percentage increase in weight during water immersion was calculated as $(W_2 - W_1)/W_1 \times 100$.

Mechanical properties

The tensile and flexural tests were carried out *via* a universal testing machine (UTM; WDW-100, Jinan Shidai Shijin Testing Machine Group Co., Ltd., Jinan, China) according to the ASTM D638-10 (Type I; 2010) and ASTM D790-10 (2010) standards, respectively. For each test, five replicate test specimens from NBC-BPC composites with and without NBC were prepared, and their average values were recorded. The specimens for the tensile test had the following dimensions: 165 mm as the overall length, 13 mm as the width of the narrow section, 5 mm thickness, and 50 mm as the gage length. For the flexural test, the specimens possessed dimensions of 120 × 10 × 5 mm, with 80 mm as the support span. A crosshead speed of 5 mm/min and 2 mm/min was used for the tensile and flexural tests, respectively.

Thermal properties

The thermal behavior of the NBC-BPC composites with and without NBC was examined using a thermogravimetric analyzer (TG 209F3, Netzsch, Germany). Each composite was heated from 30 °C to 800 °C at a rate of 10 °C/min. Thermal decomposition temperatures of the composites were examined under a nitrogen atmosphere.

RESULTS AND DISCUSSION

Water Absorption Properties

Water absorption is one of the most important characteristics of BPC; it dictates the dimensional stability of the composites and determines their ultimate application in exposed outdoor environments. Water absorption in BPC is mainly ascribed to the presence of lumens and hydrogen bonding sites in the BF. Secondly, BF is a polar molecule that contains a large quantity of hydroxyl groups on its surface and that easily bonds with water molecules *via* hydrogen bonding. However, HDPE is a non-polar molecule, and HDPE does not completely cover the surface of excess BF. BF and HDPE combined in an inadequate manner leads to poor interfacial adhesion, with many tiny holes and gaps in the interface between BF and HDPE, which allows water molecules to easily enter and reduce the water resistance of BPC. Table 2 shows the water absorption for NBC-BPC with and without NBC. The 19.0 SPSS software was used for analysis; the chief statistical indexes were tested by Levene Statistic to confirm homogeneity of variance between groups. Variances analysis results are shown in Table 3. The data indicated that the volume of NBC properly influenced water absorption in NBC-BPC composites ($Sig<0.05$).

Theoretically, adding NBC to BPC would increase water absorption because NBC contains many pores and gaps on a porous structure (Li *et al.* 2014), which may contribute to water storage. However, based on the experimental data, the results of the test were contrary to the expectations based on theory. The water resistance of NBC-

BPC increased when a small amount of NBC was added, while the water resistance increased as the NBC content increased at identical volume contents of NBC below 7.5%. This result demonstrated that when the NBC filled the holes and gaps of the polymer matrix interface (see SEM images in Fig. 1), NBC increased the structural density of the composite, improved dimensional stability, and increased water resistance. Nevertheless, the composite was difficult to disperse when the volume of NBC powder was higher than 7.5%. At this point, self-aggregation occurred, and the scale effect of nanoparticles was abated. Cross-linking and twisting of the polymer molecular chain was affected, producing a poor interface that leads to water absorption. Higher NBC content yielded more drastic effects. The results revealed that appropriate volumes of NBC had a good dispersion and filling effect in NBC-BPC, producing a stronger interface that slightly improved the water resistance of the composite. However, the mechanism of the effects should be further studied.

Table 2. Water Absorption of NBC-BPC

Sample		NBC Volume (%)	Water Absorption (%)	Mean	Std. Deviation
NBC-BPC1	NBC-BPC1-1	0	0.5731	0.5727	0.0026
	NBC-BPC1-2		0.5699		
	NBC-BPC1-3		0.5751		
NBC-BPC2	NBC-BPC2-1	2.5	0.5417	0.5410	0.0008
	NBC-BPC2-2		0.5411		
	NBC-BPC2-3		0.5402		
NBC-BPC3	NBC-BPC3-1	5	0.5427	0.5401	0.0023
	NBC-BPC3-2		0.5391		
	NBC-BPC3-3		0.5385		
NBC-BPC4	NBC-BPC4-1	7.5	0.4446	0.4602	0.0159
	NBC-BPC4-2		0.4596		
	NBC-BPC4-3		0.4764		
NBC-BPC5	NBC-BPC5-1	10	0.4932	0.5138	0.0222
	NBC-BPC5-2		0.5109		
	NBC-BPC5-3		0.5373		
NBC-BPC6	NBC-BPC6-1	12.5	0.5763	0.5802	0.0310
	NBC-BPC6-2		0.5513		
	NBC-BPC6-3		0.6130		

Table 3. Analysis of Variance (ANOVA)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.029	5	.006	20.015	.000
Within Groups	.003	12	.000		
Total	.032	17			

Interfacial Morphology

Many properties of composite materials are affected by their morphological characteristics. Figure 1 shows SEM images of the tensile test fractured surfaces of NBC-BPC with different quantities of NBC. As shown in Fig. 1(a), the fracture surface of the composites without NBC (0% NBC volume) demonstrated two behaviors: (1) the two phases of BF and HDPE can be clearly seen, and BF was not well coated by HDPE; and (2) there were holes and gaps at the bonding interface between BF and HDPE, indicating a weak interaction between the polymer matrix and BF. This phenomenon leads to poor interfacial adhesion. In micrographs of the fracture surface of the composites with NBC (Figs. 1(b), (c), and (d)), NBC appeared to be well-dispersed in the gaps and holes on the bonding interface between the polymer matrix and BF, which resulted in a more compact interface structure with stronger interaction and interfacial adhesion. As the volume of NBC increased, the NBC particle distribution in the matrix grew larger and more distinct, while producing agglomerates (Figs. 1(e) and (f)). The NBC particles were not dispersed in the gaps and holes on the bonding interface, which blocked the movement of the polymer molecular chain on the substrate surface, affecting cross-linking and twisting. The BF was not well coated, leading to a weak boundary layer, reduced interface bonding, worse interfacial adhesion, and decreased comprehensive performance of the composite. The fracture surface morphology verified that NBC content affects water absorption and mechanical properties of bamboo plastic composites, which are discussed below.

Mechanical Properties

The mechanical properties of NBC-BPC with different NBC contents were determined and the 19.0 SPSS software was used for variances analysis (Table 4). After the incorporation of NBC, the flexural modulus and flexural strength of the composite slightly increased, achieving maximum values of 4650.07 MPa and 46.01 MPa, respectively, at 7.5% NBC (NBC-BPC4). Compared with the composite without NBC (NBC-BPC1), NBC-BPC4 demonstrated increases in flexural modulus and strength of 17.54% and 15.80%, respectively. However, further increases in NBC content decreased the flexural modulus and strength.

Table 4. Mechanical Properties of NBC-BPC with Different NBC Contents

Sample	NBC Volume (%)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Tensile Strengths (MPa)	Tensile Modulus (MPa)
NBC-BPC1	0	39.73 ± 0.27^{a}	3956.14±84^{a}	14.77 ± 0.17^{a}	734.40 ± 8^{a}
NBC-BPC2	2.5	41.52 ± 0.24^{b}	4205.85±76^{b}	18.44 ± 0.21^{b}	1096.85 ± 11^{b}
NBC-BPC3	5	42.38 ± 0.31^{b}	4211.14±97^{b}	18.68 ± 0.34^{b}	1156.92 ± 10^{b,c}
NBC-BPC4	7.5	46.01 ± 0.41^{c}	4650.07±93^{b,c}	18.77 ± 0.27^{b}	1262.50 ± 13^{c}
NBC-BPC5	10	45.13 ± 0.39^{c}	4486.55±107^{c}	16.86 ± 0.16^{a,b}	1024.92 ± 9^{a,b}
NBC-BPC6	12.5	43.50 ± 0.37^{b,c}	4628.48±144^{c}	14.48 ± 0.13^{a}	847.54 ± 6^{a}
Values are expressed as mean ± standard deviation, n=5. Values with the same small letter for each property are not significant different. (P<0.05)					

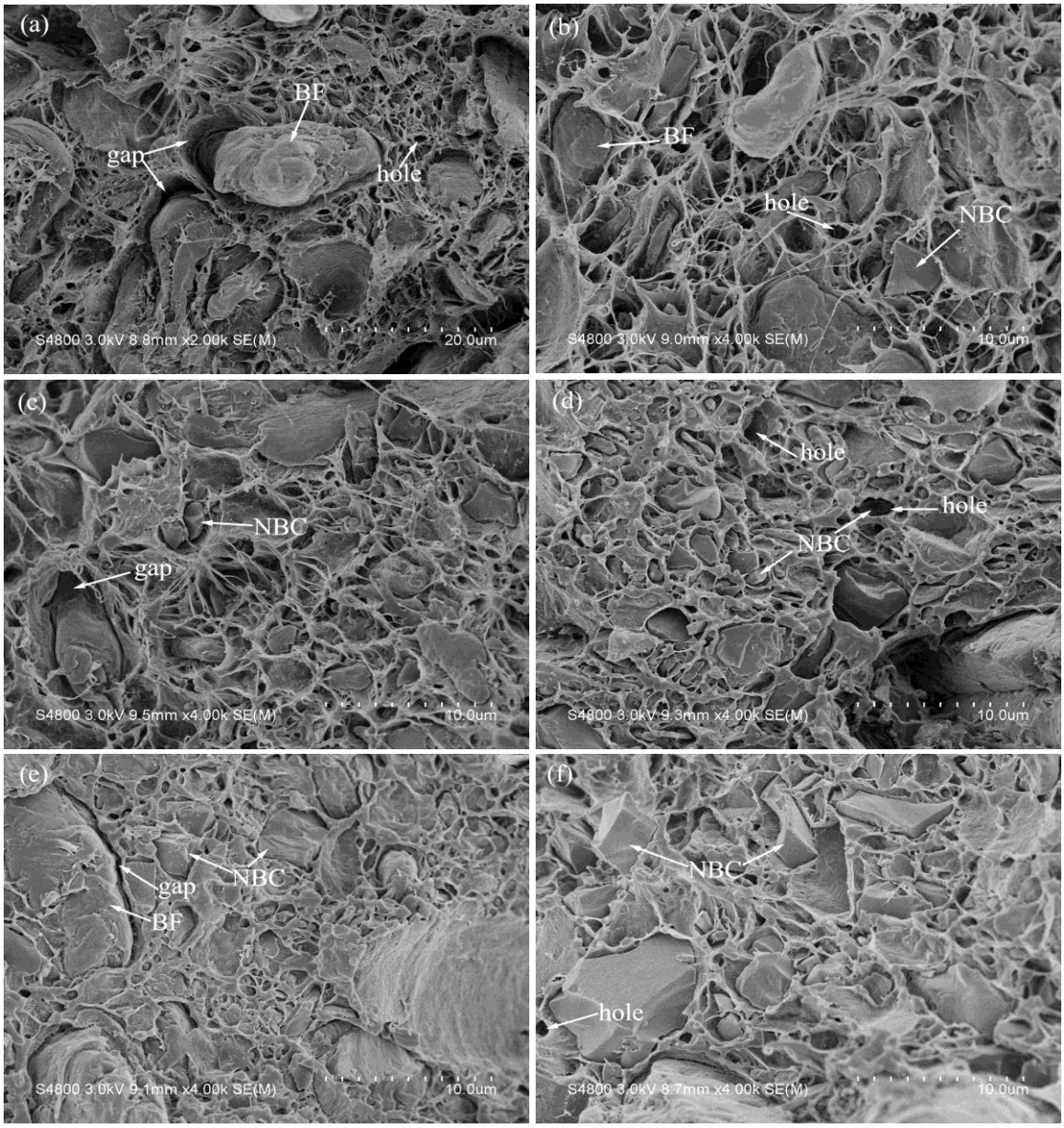

Fig. 1. SEM images of (a) NBC-BPC1, (b) NBC-BPC2, (c) NBC-BPC3, (d) NBC-BPC4, (e) NBC-BPC5, and (f) NBC-BPC6

As shown in Table 4. The flexural properties were improved at ≤ 7.5% NBC. When the volume of NBC was lower than 7.5%, the particles easily diffused into and filled gaps and holes in the BF-matrix bonding interface (see SEM images in Fig. 1). The well-dispersed phase resulted in a more compact and strong bonding interface between the fiber and matrix; meanwhile, the interfacial bonding force was increased, which improved the flexural properties of the composite. When excessive amounts of NBC were added, the NBC powder on accumulated the surface of the matrix, and the gaps and holes on the interface were not completely filled. Furthermore, a certain level of aggregation was observed. When the polymer molecule is restricted in its ability to twist and the cross-linking is reduced, the HDPE molecules cannot sufficiently coat the BF,

which results in a weak boundary layer; thus, the interfacial binding force is decreased, deteriorating the flexural properties of the composite, as previously reported (Deka and Maji 2011a; 2011b). In conclusion, the flexural moduli and flexural strength of the composites with NBC displayed enhanced properties relative to the composites without NBC, indicating that the presence of NBC had an enhancement effect on the flexural properties of the composites and displayed a reinforcing effect in BPC.

Similar to the flexural properties, the tensile properties of the composites were also affected by increasing NBC content. Below 7.5% NBC content, increasing the NBC increased the tensile strength and tensile modulus to their maximum values of 1262.50 MPa and 18.77 MPa, respectively, at 7.5% NBC. In comparison to the composites without NBC (NBC-BPC1), the tensile modulus and strength of NBC-BPC4 increased by 71.9% and 27.1%, respectively. The tensile properties of the composites were improved because of the reinforcement and toughening provided by the NBC powder, and the strengthening mechanism was identical to the flexural properties. At low NBC contents, NBC is well-dispersed on the matrix surface, filling the gaps and holes on the fiber-matrix bonding interface; this effect produces a strong interface layer that increases the interfacial bonding force and enhances mechanical performance. When NBC is higher than 7.5%, NBC particles restrict the motion of HDPE chains, and NBC particles become unevenly dispersed to the point of agglomeration. HDPE molecules are not capable of coating the BF, which produces a weak interface layer that degrades the performance of the composites. Meanwhile, the agglomeration of particles leads to weak spots that result in stress concentration under an applied external force, rapid destruction of the specimens, and deterioration of the tensile performance. In summary, the tensile properties of the composites increased with the incorporation of NBC at a certain volume, where it provided reinforcement for the composites (Li *et al.* 2014; You and Li 2014).

Table 5. Mechanical Properties of Various Biocomposites

Fiber	Matrix	Molding method	% Fiber	Flexural Strength (Mpa)	Flexural Modulus (Mpa)	Tensile Strength (Mpa)	Tensile Modulus (Mpa)	Ref.
Bamboo fiber	PP	compression moulding	50	49.56±0.64	2867±4	28.95±0.34	1721±10	Chattopadhyay et al. 2011
Bamboo fiber	PP+MA-g-PP	compression moulding	50	68.85±0.33	4127±5	50.26±0.39	1633±11	Chattopadhyay et al. 2011
Wood flour	PVC	Extrusion	60	52.09	3940	30.86	3820	Fang et al. 2013
Jute fiber	PP+MAP P	Extrusion	30	63.4(4.2)	6329 (388)	32.3 (1.5)	2793 (184)	Ranganathan et al. 2015
Viscose fiber	PP	Extrusion	30	38.8 (2.1)	2996 (71)	18.3 (0.6)	1426 (93)	Ranganathan et al. 2015
Hemp fiber	Wheat gluten	compression moulding	20	——	——	4.8 (0.7)	149.6 (33)	Wretfors et al. 2010
Wood flour	LDPE	Injection molding	50	14.1±0.1	1010±10	10.4±0.2	338±20	Li et al. 2014
Wood flour+Bamboo charcoal	LDPE	Injection molding	50+8	16.9±0.1	1120±13	11.9±0.2	523±18	Li et al. 2014
Bamboo charcoal	UHMWPE	Extrusion	80	——	——	61.2±2.7	2088±96	You and Li 2014
Wood fiber	PLA+Bioadimide	Injection molding	20	109.78±1.35	3940±10	68.00±1.84	3840±80	Awal et al. 2015
Bamboo fiber+NBC	Recycled HDPE	Extrusion	50+7.5	46.01 ±0.41	4650.07±93	18.77 ± 0.27	1262.50 ± 13	——

As can be seen in Table 5, the mechanical properties of various biocomposites are illustrated while compared to NBC-BPC. There were significance differences among various biocomposites. These results may contribute to the different application of the material. In addition, the types of fiber and matrix, molding method and the proportion of fiber also have an effect on mechanical properties of the composites. For instance, in comparison to the studies of Li *et al.* (2014), because of the difference of fiber and matrix types, as well as the molding method, the differences in tensile properties and flexural properties were more significant. The NBC-BPC composite showed more excellent mechanical properties. What's more, the selection of auxiliary agents (cross-linker, coupling agent, compatibilizer and lubricants, *etc.*) and mixing procedure may also have affected the mechanical properties of the composites. According to the research of Wretfors *et al.* (2010), higher-speed grinding yielded a better distribution of fibers and a more polymerized protein structure compared to lower-speed grinding; the addition of cross-linker increased the strength of the composites. Among these biocomposites, the flexural properties and tensile properties of NBC-BPC was not absolutely outstanding. This mainly attributed to the matrix used in NBC-BPC is recycled HDPE, but it also can be used for non-specific field, such as fencing, railing, decking, and landscaping timbers. Moreover, the development of proportional optimization design and the dispersion of BF, NBC required deep-going research at current.

Thermal Properties

The thermogravimetric analysis (TGA) and digital thermogravimetry (DTG) curves of NBC-BPC provided essential information about their thermal properties and degradation behavior (Figs. 2 and 3). The DTG curve of BF showed a peak from 278 °C to 367 °C that is associated with the degradation of hemicellulose and cellulose (Yao *et al.* 2008). The TGA and DTG curves of HDPE showed only a single decomposition step between 453.4 °C and 486.5 °C. The NBC-BPC1 composites presented intermediate thermal stability between neat HDPE and BF, which suggests that the addition of BF only slightly improved the thermal stability, as previously noted (Chattopadhyay *et al.* 2011). The NBC-BPC1 composite demonstrated two decomposition stages. The first step (281.5 to 357.7 °C) was attributed to the degradation of BF, while the second step (449.9 to 485.9 °C) corresponded to the degradation of HDPE.

TGA and DTG curves for NBC-BPC with varying amounts of NBC are shown in Figs. 4 and 5, respectively. The degradation of the composite materials was divided into two stages. Table 6 shows the initial decomposition temperature ($T_{initial}$), maximum pyrolysis temperature (T_{max}), decomposition temperature at different weight loss (%) (T_D), and residual weight (*RW*) of the composites. $T_{initial}$ values slightly decreased with the incorporation of NBC. A possible explanation is that with the reduction of HDPE, the BF is not completely wrapped and is therefore exposed, which makes it easily degraded by heat. The composite materials with mass losses of 10% and 30% had slightly lower degradation temperatures after the addition of NBC, while for composite material with mass losses of 50% and 70%, the degradation temperature was slightly increased. For instance, the 10% and 30% weight loss temperatures of NBC-BPC1 composites without NBC were 293.9 °C and 350 °C, respectively, which decreased to 291.9 °C and 344 °C when the NBC volume reached 12.5%. However, the 50% and 70% weight loss temperatures of NBC-BPC1 composites were 455.9 °C and 473.7 °C, respectively, and the degradation temperature of NBC-BPC6 composites with 12.5% NBC increased to 459.2 °C and 484.9 °C, respectively.

Table 6. Thermogravimetric Analysis under Pure Nitrogen Conditions

Sample	$T_{initial}$ (°C)	T_{max1} (°C)	T_{max2} (°C)	Temperature of decomposition (TD) in °C at different weight losses (%)				RW% at 800 °C
				10%	30%	50%	70%	
NBC-BPC1	281.6	339.6	471	293.9	350	455.9	473.7	11.53
NBC-BPC2	280.6	336.2	471.7	292.9	349.7	456.5	475	14.17
NBC-BPC3	281.2	338.3	470.4	292.9	349.4	457.2	476.2	16.86
NBC-BPC4	280.8	336.6	473.1	293.4	348.9	460.4	481	18.91
NBC-BPC5	279.9	331.8	471.4	291.6	345	456.7	479.6	20.03
NBC-BPC6	279.9	332.8	471.3	291.9	344	459.2	484.9	23.38
$T_{initial}$, value for initial degradation; T_{max1}, value for first step; T_{max2}, value for second step								

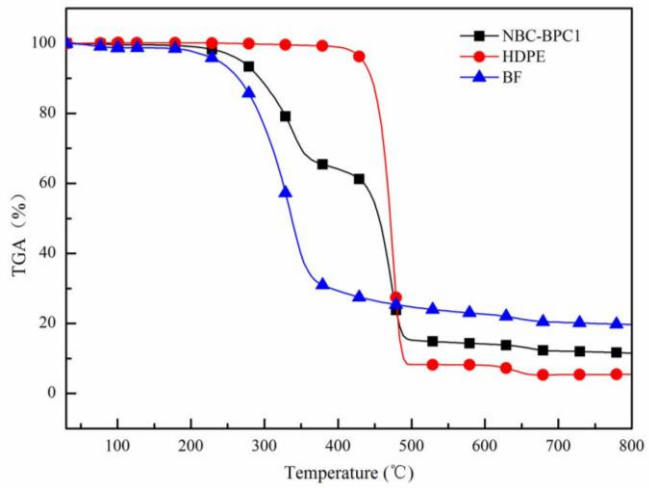

Fig. 2. TGA curves for NBC-BPC1, HDPE, and BF

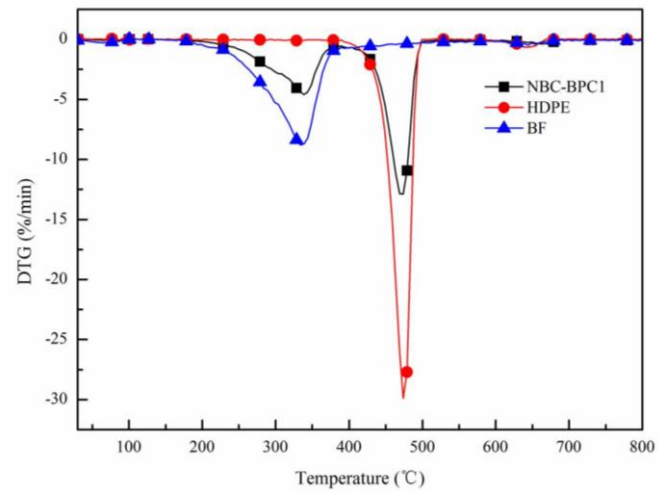

Fig. 3. DTG curves for NBC-BPC1, HDPE, and BF

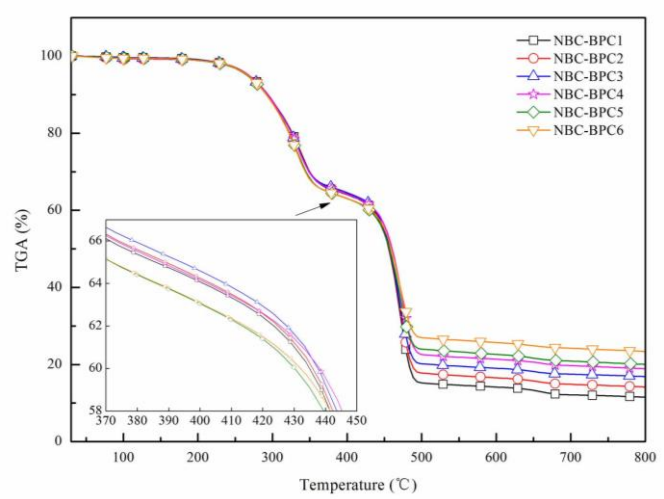

Fig. 4. TGA curves for NBC-BPC1, NBC-BPC2, NBC-BPC3, NBC-BPC4, NBC-BPC5, and NBC-BPC6 composites

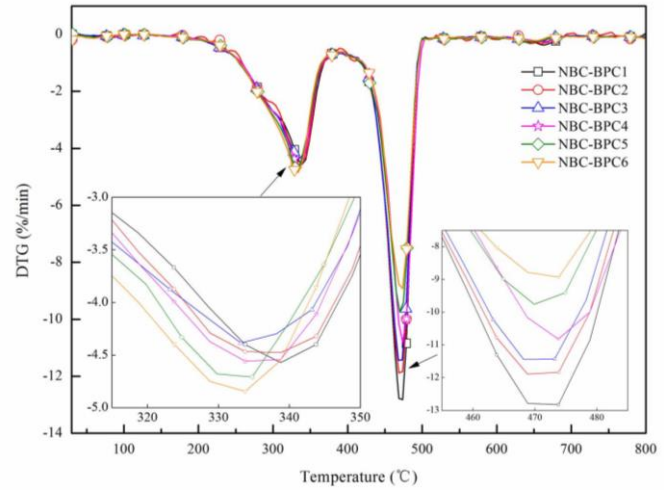

Fig. 5. DTG curves for NBC-BPC1, NBC-BPC2, NBC-BPC3, NBC-BPC4, NBC-BPC5, and NBC-BPC6 composites

The weight percentage of char residue at 800 °C for composites increased with increasing NBC volume, which is indicative of the improved thermal stability of the composite due to the thermal insulation effect of the charcoal residues and the limiting degradation reaction rate of the composite (Fang *et al.* 2013).

CONCLUSIONS

1. NBC demonstrated good dispersion in the polymer matrix, and a filling effect was observed when the volume of NBC was moderate. In addition, the interfacial adhesion increased, the structure of the composites was more compact, and water access to the composite was blocked.
2. The tensile and flexural strengths increased with increasing NBC content, with a trend of decreasing after the first increase, and achieved maximum values of 18.77 MPa and 46.01 MPa, respectively, at a volume of 7.5% NBC. Due to the low volume

of NBC, adequate dispersion was acheived, and the NBC particles filled and strengthened the gaps in the BF-matrix interface while enhancing the performance of the composite. However, poor dispersion, accumulation, and agglomeration occurred with high volumes of NBC. These high volumes influenced the cross-linking and twisting of the polymer molecular chain, forming weak spots in the composite where stress was concentrated under applied stress.

3. The addition of NBC improves the 50% and 70% weight loss temperature and the percentage of char residue at 800 °C. This result indicated adequate incorporation of the NBC, which enhanced the thermal properties of BPC.

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