EFFECTS OF COMPATIBILIZERS ON SELECTED PROPERTIES OF HDPE COMPOSITES HIGHLY FILLED WITH BAMBOO FLOUR

W. P. Zhang
Master Candidate
E-mail: weipengsh@163.com

Y. H. Lu
Doctor Candidate
E-mail: LuPhoebe_0@163.com

S. Khanal
Doctor Candidate
School of Materials Science and Engineering
East China University of Science and Technology
Shanghai 200237, China
E-mail: santoshkhanal2003@yahoo.com

*S. A. Xu**
Professor and Associate Director
School of Materials Science and Engineering
East China University of Science and Technology
Shanghai 200237, China
School of Chemical Engineering
Qinghai University
Xining 810016, China
E-mail: saxu@ecust.edu.cn

(Received December 2017)

Abstract. In this study, maleic anhydride–grafted high-density polyethylene (HDPE-*g*-MAH) and glycidyl methacrylate–grafted high-density polyethylene (HDPE-*g*-GMA) were synthesized by melting grafting reaction using styrene as a comonomer. These two functionalized HDPEs and three commercial functionalized polyolefins (Fusabond®M603, PE-*g*-MAH, and PEW-*g*-MAH) were used to compatibilize HDPE/bamboo flour (BF) composites. The morphologies and properties of compatibilized and uncompatibilized composites were compared to determine the optimal compatibilizer for HDPE/BF composites. Besides, the effect of HDPE-*g*-MAH and HDPE-*g*-GMA contents on the properties of HDPE/BF composites was also investigated. The results show that HDPE-*g*-MAH and HDPE-*g*-GMA can more effectively improve the mechanical properties of HDPE/BF composites than the three commercial compatibilizers (Fusabond®M603 resin, PE-*g*-MAH, and PEW-*g*-MAH). In addition, HDPE-*g*-MAH is more effective than HDPE-*g*-GMA because of the stronger interaction between anhydride and hydroxyl groups than that between epoxy and hydroxyl groups. The use of HDPE-*g*-MAH and HDPE-*g*-GMA contributes to improve the thermal stability and reduce the water absorption of HDPE/BF composites.

Keywords: Wood plastic composites, HDPE-*g*-MAH, HDPE-*g*-GMA, compatibilizer, mechanical properties.

INTRODUCTION

Wood plastic composites (WPCs) have attracted significant interest from both academics and practitioners in the architecture, garden, automotive, and marine industries since the beginning of the 21st century (Al-Salem et al 2009; Thompson et al 2009). Wood plastic composites are considered as a sustainable material because they can be produced from recycled plastics and

---

* Corresponding author

Wood and Fiber Science, 50(3), 2018, pp. 254-264
https://doi.org/10.22382/wfs-2018-026

forest or agricultural residues using conventional plastic manufacturing machines such as an extruder, intensive mixer, and injector (Michael et al 2010; Gozdecki and Wilczynski 2015; Kuang et al 2017). Wood plastic composites are mainly composed of matrix resin and wood flour, in which the matrix resin is mainly thermoplastics such as PE (Haque et al 2009; Michael et al 2010; Mansour et al 2016), polypropylene (PP) (Ashori 2008; Fang et al 2013), polystyrene (Sohn and Cha 2015), and polyvinyl chloride (Väntsi and Kärki 2015); whereas the wood flour is a natural plant powder consisting mainly of cellulose, hemicellulose, and lignin, such as bamboo flour (BF), polar flour, and pine and hemp fiber (Hoang et al 2013; Hosseinihashemi et al 2016). Therefore, WPCs have the advantages of easy manufacture, biodegradability, nontoxicity, low cost, and high strength and stiffness (Thompson et al 2009; Hosseinihashemi et al 2016).

A major problem of WPCs is the poor compatibility between the hydrophobic matrix resin and the hydrophilic wood flour, which can lead to agglomeration of wood flour, poor mechanical properties, and high water adsorption. Thus, the application of WPCs can be limited, especially when the content of wood flour exceeds 50 phr. Some physical and chemical methods have been developed to improve the interfacial compatibility of WPCs, such as silane coupling agent treatment (Deka and Maji 2012; Deka et al 2012), alkali treatment (Deka et al 2012), steam explosion treatment (Gao et al 2012), and graft copolymerization (Guo and Wang 2008; Xiong et al 2009; Lashgari et al 2011). The use of polyolefin grafted with reactive monomers as a compatibilizer has proven to be one of the most effective and environmentally friendly methods for this purpose (Kumar et al 2011; Kazemi 2013; Kaseem et al 2015), and the preparation of WPCs can be optimized by melt mixing raw wood flour, polymer and compatibilizers based on a twin-screw extruder or internal mixer.

In recent decades, polyolefin-*g*-maleic anhydride (MAH) has often been used as a compatibilizer for WPCs (Zhu et al 2015) because of the esterification reaction between anhydride groups of MAH and hydroxyl groups of wood flour and the entanglement between the matrix resin and the copolymer chain with similar polarities (Zhu et al 2015). Zhu et al (2015) investigated the effectiveness of PP-*g*-MAH/DAP (diallyl phthalate [DAP] as comonomer) as a compatibilizer for PP/recycled PET (rPET) (80/20, w/w) blends, and the results showed that the PP/rPET blends compatibilized with PP-*g*-MAH/DAP showed enhanced adhesion at the interface compared with the binary PP/rPET blend.

Glycidyl methacrylate (GMA) has emerged as an attractive active monomer for functionalization of polyolefins (Pracella et al 2006; Hosseinaei et al 2012). Glycidyl methacrylate is a bifunctional monomer consisting of active vinyl for free radical grafting onto polyolefins and epoxy functional groups which can react with other functional groups (Pracella et al 2006). Many studies have investigated the melt grafting of GMA onto polyolefins and the compatibilization of polyolefin-*g*-GMA through the reaction between the epoxy groups of GMA and the hydroxyl groups of wood flour. Pracella et al (2006) used GMA-functionalized PP (PP-*g*-GMA) as a compatibilizer in PP/hemp fiber composites. The results showed that the epoxy group of PP-*g*-GMA reacted with the hydroxyl group of hemp fiber, resulting in an increase in the mechanical and thermal properties of composites. Lashgari et al (2011) used various concentrations of PP-*g* -GMA as coupling agents to prepare PP/bagasse composites. The result showed that the heat deflection temperature, flexural properties, and impact strength of WPCs were improved with the incorporation of PP-*g*-GMA.

However, there have been very few studies comparing different compatibilizers for highly filled wood flour/high-density polyethylene (HDPE) composites. In this study, MAH-grafted HDPE (HDPE-*g*-MAH) and GMA-grafted HDPE (HDPE-*g*-GMA) were prepared with styrene (St) as a comonomer by melt grafting in a HAAKE mixer (Rheocord 300P, Haake, Karlsruhe, Germany). The two functionalized HDPEs and three commercial functionalized polyolefins were used for the compatibilization of HDPE/BF composites. The morphologies and properties of these composites were compared to determine the optimal compatibilizer for HDPE/BF composites. This study may provide some insights into the optimized formula of WPCs and the preparation of efficient WPCs.

EXPERIMENTAL

Materials

High-density polyethylene was purchased from Fushun Petrochemical Co., Ltd. (Liaoning, China) with a density of 0.93 g/cm^3 and a melt index of 8.5 g/10 min at 190°C/2.16 kg. Bamboo flour (60 meshes) was purchased from Fengle Co., Ltd. (Anhui, China). Fusabond®M603 resin was purchased from DuPont Co., Ltd. (Wilmington, DE). PE-*g*-MAH and PEW-*g*-MAH were purchased from Hangzhou Sea Polymer Material Co., Ltd. (Zhejiang, China). Glycidyl methacrylate, MAH, St, dicumyl peroxide (DCP), xylene, and acetone were purchased from Aladdin Reagent Co., Ltd. (Shanghai, China). All of these reagents were of analytical pure grade.

Synthesis of HDPE-*g*-MAH and HDPE-*g*-GMA

HDPE-*g*-MAH and HDPE-*g*-GMA were synthesized by using free radical grafting reaction in melt state in a HAAKE torque rheometer (Rheocord 300P, Haake, Karlsruhe, Germany), using DCP as a radical initiator and St as a comonomer (Hosseinaei et al 2012). High-density polyethylene granules were premixed with DCP, St, and a reactive monomer (MAH or GMA) and then charged into the mixer. The grafting reaction lasted for 10 min at 170°C at a rotor speed of 50 rpm.

Measurement of Grafting Degree

Grafted HDPE (2 g) was dissolved in 200 mL of xylene, stirred at 120°C for 3 h, and then precipitated with acetone. The precipitate was extracted with acetone for 72 h in a Soxhlet extractor to completely remove unreacted monomers, homopolymers, and other by-products, and the extracted products (HDPE-*g*-MAH or HDPE-*g*-GMA) were dried in a vacuum oven at 80°C for 24 h.

Nonaqueous titration method was used to determine the amount of grafted MAH or GMA on HDPE (Hosseinaei et al 2012; Yasemin et al 2012). The extracted sample (0.5 g) was dissolved in 100 mL of hot xylene, and excess potassium hydroxide (KOH) solution in methanol was added. The mixture was mechanically stirred at 110°C for 2 h to allow the reaction of anhydride or epoxide groups with the acid. The mixed solution was titrated with hydrochloric acid in isopropanol using phenolphthalein as indicator. The grafting degree of MAH or GMA was calculated by using the following formula:

$$\mathrm{MAH\%} = \frac{(C_1V_1 - C_2V_2)}{2w_{\mathrm{HDPE\text{-}g\text{-}MAH}} \times 1000} \times 98.08 \times 100\%, \tag{1}$$

$$\mathrm{GMA\%} = \frac{(C_1V_1 - C_2V_2)}{w_{\mathrm{HDPE\text{-}g\text{-}GMA}} \times 1000} \times 142.16 \times 100\% \tag{2}$$

where C_1 and C_2 (mol/L) are the concentrations of alcoholic KOH in isopropanol and KOH solution, respectively; V_1 and V_2 are the dropping amounts of alcoholic KOH in isopropanol and KOH solution, respectively; and $W_{\mathrm{HDPE\text{-}}g\mathrm{\text{-}MAH}}$ and $W_{\mathrm{HDPE\text{-}}g\mathrm{\text{-}GMA}}$ are the weights of HDPE-*g*-MAH and $W_{\mathrm{HDPE\text{-}}g\mathrm{\text{-}GMA}}$ sample, respectively. The molecular weight of MAH and GMA is 98.08 and 142.16 g/mol, respectively. The grafting degrees of the three commercial compatibilizers were also measured by using the same procedure. For each compatibilizer, at least three measurements were conducted and the average grafting degree was reported.

Preparation of HDPE/BF Composites

HDPE/BF composites were prepared in a HAAKE torque rheometer. Before melt mixing, BF was dried at 105°C for 24 h, and then HDPE, BF, and the compatibilizer were melt mixed at 50 rpm at 170°C for 10 min. The blend was crushed and hot compressed into a plate of 10 × 15 × 4 mm^3 on a panel vulcanizer (BL-6170-A, Baolun Co., Ltd., Guangdong, China) and then fabricated into standard test samples. The preparation process is shown in Figure 1. The BF content was fixed at 60 wt.% of the total mass of the composites in all samples. The composites containing 7 wt.% of compatibilizers were prepared to compare the compatibilizing effects of the five compatibilizers. Besides, the composites with 3, 5, 7, 9, and 11 wt.% of HDPE-*g*-MAH or HDPE-*g*-GMA were also prepared to investigate the effects of HDPE-*g*-MAH or HDPE-*g*-GMA contents on the mechanical properties of the composites. Bamboo flour/high-density polyethylene composite without any compatibilizer was also prepared as control.

Measurements

Structure characterization. The Fourier transform IR (FTIR) spectra of HDPE-*g*-MAH and HDPE-*g*-GMA were recorded using a Nicolet 6700 FTIR spectrometer at a scan number of 32 and a resolution of 4 cm^{-1}.

Mechanical properties. Tensile tests were performed on a universal testing machine (E44.204, Meitesi Industry Co., Ltd., Tianjin, China) according to GB/T 1040.2-2006, where the samples were dumbbell shaped (150 × 10 × 4 mm^3) and the cross-head speed was 1 mm/min. Flexural tests were performed on an universal testing machine (CMI4024; Shenzhen Sans Co., Ltd., Shenzhen, China) at a crosshead speed of 2 mm/min with a 50 N load cell according to GB/T 9341-2008. The sample dimensions were 80 × 10 × 4 mm^3 and the span length was fixed at 64 mm. Notched Izod impact strength was measured on an Izod testing machine (CEAST 9050; CEAST Co., Ltd.) operating with a pendulum weight of 5.5 J. Rectangular samples (80 × 10 × 4 mm^3) with a V-shaped notch were prepared using an automatic sample notcher (model ASN-230-M, Dynisco, Braunschweig, Germany) at least 24 h before testing according to GB/T 9341-2008. All tests were performed at room temperature. At least five samples were measured for each composition, and the averages and deviations were reported.

Scanning electron microscopy (SEM). The impact-fractured surfaces of the composites were observed by the S-4800 SEM instrument (Hitachi Co., Tokyo, Japan). Before observation, all samples were dried at 60°C for 24 h and then the impact fractured surface was sprayed with a layer of gold.

Thermal properties. The thermal properties of BF, pure HDPE, and HDPE/BF composites were measured by using thermogravimetric analysis ([TGA], STA409PC; Netzsch, Bavaria, Germany). Samples were heated from room temperature to 800°C at a heating rate of 10°C/min in a nitrogen atmosphere.

Water resistant performance. Samples were dried in an oven for 24 h at 60°C and then soaked in distilled water and kept at room temperature. After that, samples were taken out from water at regular intervals, and weighed after wiping off the water on the sample surface using blotting paper. Then, samples were soaked in water again, and

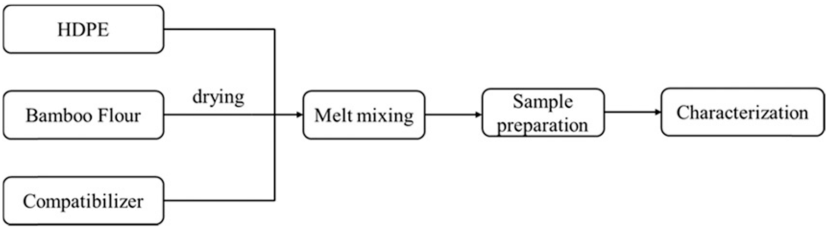

Figure 1. Preparation of high-density polyethylene (HDPE)/bamboo flour (BF) composites.

the operation was repeated until the water absorption equilibrium was reached. The water absorption in percentage was calculated using the following equation:

$$\text{Water adsorption } (\%) = \frac{W_t - W_0}{W_0} \times 100\% \quad (3)$$

where W_0 is the original weight of the sample after drying, and W_t is the weight of the sample after soaking for a given time.

RESULTS AND DISCUSSION

FTIR Analysis and Nonaqueous Titration

The FTIR spectra of HDPE, HDPE-*g*-MAH, and HDPE-*g*-GMA are shown in Figure 2. A pair of very strong absorption bands are observed at 2850 and 2920 cm^{-1} in all spectra, which could be assigned to the symmetric and asymmetric CH_2 stretching vibrations, respectively. The peaks at 1469 and 720 cm^{-1} are due to the deformation and skeletal vibrations of the CH_2 group (Dai et al 2016). Some new peaks are observed in the two synthesized compatibilizers. For HDPE-*g*-MAH, the new absorption peak at around 1784 cm^{-1} is assigned to the stretching vibration of the carbonyl group C=O of MAH. For HDPE-*g*-GMA, while that at 1741 cm^{-1} is attributed to the C=O stretching vibration. All of these results indicate that the two HDPE compatibilizers grafted with different active groups have been successfully prepared, which is consistent with the report of Dai et al (2016). The grafting degrees of both synthesized and commercial compatibilizers were determined by using nonaqueous titration method (Hosseinaei et al 2012). The grafting degrees of HDPE-*g*-MAH and HDPE-*g*-GMA are 2.35% and 2.21%, respectively, which is close to that reported by Dai et al (2016), whereas those of Fusabond®M603, PE-*g*-MAH, and PEW-*g*-MAH are 1.21%, 0.98% and 1.45%, respectively.

Mechanical Properties

Figure 3 and Table 1 show the effects of different compatibilizers on the mechanical properties of HDPE/BF composites containing 60 wt.% of BF, 33 wt.% of HDPE, and 7 wt.% of compatibilizer. Fusabond®M603 resin is a random ethylene copolymer modified by MAH, and PE-*g*-MAH is a commercial compatibilizer. Maleic anhydride-grafted polyethylene wax (PEW-*g*-MAH) could act as lubricant and compatibilizer. Obviously, those composites compatibilized by HDPE-*g*-MAH or HDPE-*g*-GMA have better mechanical properties than those compatibilized by Fusabond®M603 resin, PE-*g*-MAH and PEW-*g*-MAH, and uncompatibilized composites, indicating

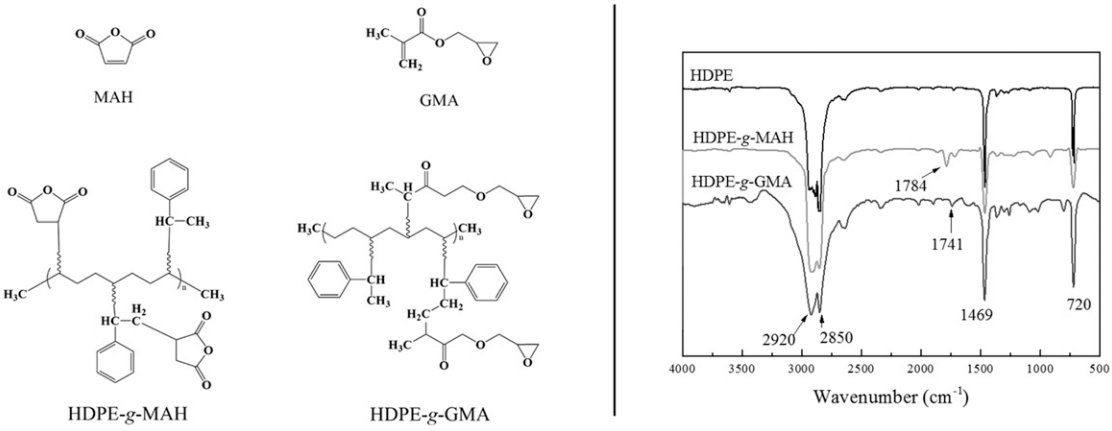

Figure 2. Structural formulas and Fourier transform IR (FTIR) spectra of pure high-density polyethylene (HDPE), maleic anhydride–grafted high-density polyethylene (HDPE-*g*-MAH), and glycidyl methacrylate–grafted high-density polyethylene (HDPE-*g*-GMA).

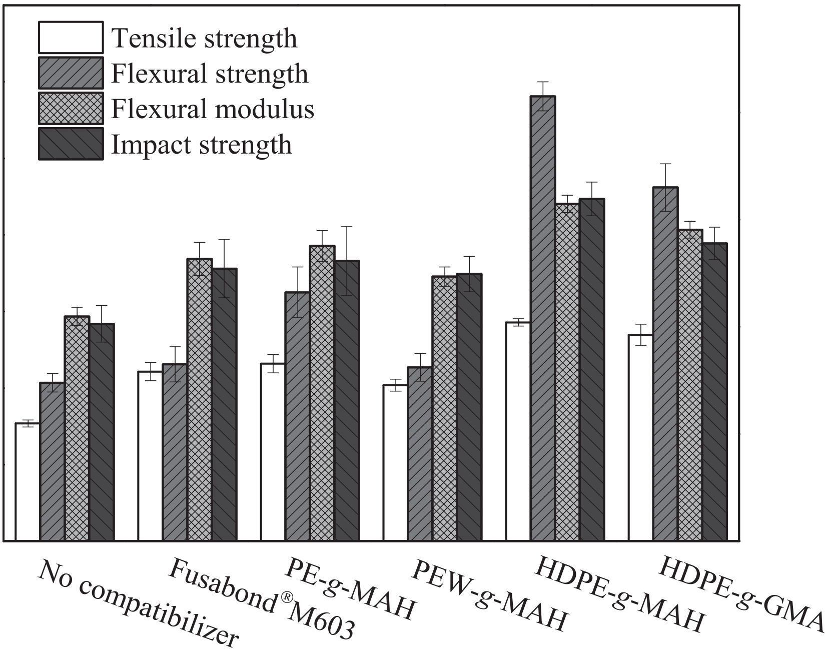

Figure 3. Effects of various compatibilizers on the mechanical properties of high-density polyethylene/bamboo flour composites.

that the synthesized compatibilizers are effective in improving the mechanical properties of HDPE/BF composites. As the functionalized compatibilizer with a higher grafting degree has better compatibilization, it is deduced that HDPE-g-MAH is more effective than PE-*g*-MAH. Similar results have also been reported by Dai et al (2016) and Ihemouchen et al (2013).

Figure 4 shows the effects of HDPE-*g*-MAH and HDPE-*g*-GMA contents on the mechanical properties of the HDPE/BF composite. It is evident that the mechanical properties of the composites are greatly improved with the addition of compatibilizers. Compared with uncompatibilized composites, the incorporation of HDPE-*g*-MAH or HDPE-*g*-GMA results in an increase in tensile strength, flexural strength, flexural modulus, and impact strength in HDPE/BF composites. The strength of WPCs can be significantly affected by the interfacial adhesion between the hydrophobic fiber and the hydrophilic polymer (Väntsi and Kärki 2015) and the effective stress transfer at the interface between lignocelluloses and matrix resin (Dai et al 2016). For HDPE-*g*-MAH–compatibilized composites, the tensile strength, flexural strength, flexural modulus, and impact strength increase with increasing HDPE-*g*-MAH content until a maximum

Table 1. Effects of various compatibilizers on the mechanical properties of high-density polyethylene (HDPE)/bamboo flour composites.

	Tensile strength (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m^2)
No compatibilizer	15.4 ± 0.5	20.7 ± 1.2	2936 ± 119	2.84 ± 0.24
Fusabond®M603	22.2 ± 1.2	23.1 ± 2.3	3676 ± 216	3.56 ± 0.38
PE-*g*-MAH	23.2 ± 1.2	32.5 ± 3.3	3857 ± 201	3.66 ± 0.45
PEW-*g*-MAH	20.4 ± 0.8	22.7 ± 1.8	3456 ± 126	3.49 ± 0.23
HDPE-*g*-MAH	28.6 ± 0.5	58.1 ± 1.9	4406 ± 113	4.47 ± 0.22
HDPE-*g*-GMA	26.9 ± 1.4	46.2 ± 3.1	4069 ± 109	3.89 ± 0.21

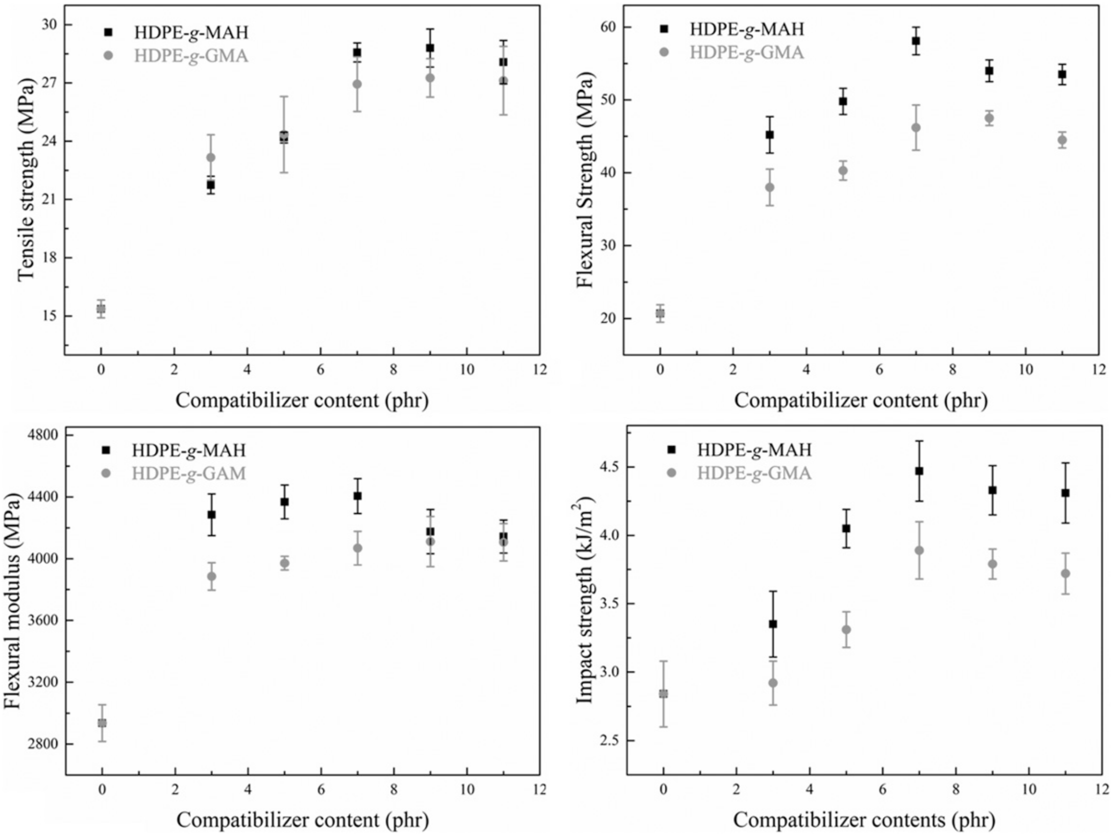

Figure 4. Effects of maleic anhydride–grafted high-density polyethylene (HDPE-g-MAH) and glycidyl methacrylate–grafted high-density polyethylene (HDPE-g-GMA) contents on the mechanical properties of high-density polyethylene/bamboo flour composites.

is reached at 7 wt.% of HDPE-*g*-MAH, and then decrease thereafter. However, for HDPE-*g*-GMA –compatibilized composites, the tensile strength and flexural modulus continue to increase slightly as the HDPE-*g*-GMA content increases, whereas the tensile strength and impact strength reach a maximum at 7 or 8 wt.% of HDPE-*g*-GMA.

The MAH of HDPE-*g*-MAH or the epoxy group of HDPE-*g*-GMA can react with the hydroxyl group of BF, resulting in the grafting of HDPE-*g*-MAH or HDPE-*g*-GMA on the surface of BF. This can improve the dispersion of BF in HDPE and the interfacial adhesion between them, the mechanism of which is shown in Figure 5. However, it is important to note that the composite compatibilized by HDPE-*g*-MAH has better comprehensive properties than that compatibilized by HDPE-*g*-GMA despite the similar grafting degree of HDPE-g-MAH and HDPE-g-GMA, indicating that MAH has a higher reactivity than epoxide. This is probably because of the lower reactivity of hydroxyl group with epoxy group than that with anhydride group.

The flexural strength and modulus of the HDPE/BF composites compatibilized by HDPE-*g*-MAH are increased as compared with that of uncompatibilized composites. This is particularly pronounced for flexural strength. For instance, the incorporation of 7 wt.% of HDPE-*g*-MAH results in a 180.7% increase in flexural strength and a 50.1 % increase in flexural modulus. The flexural strength of the composites depends strongly on the interfacial adhesion of the BF and

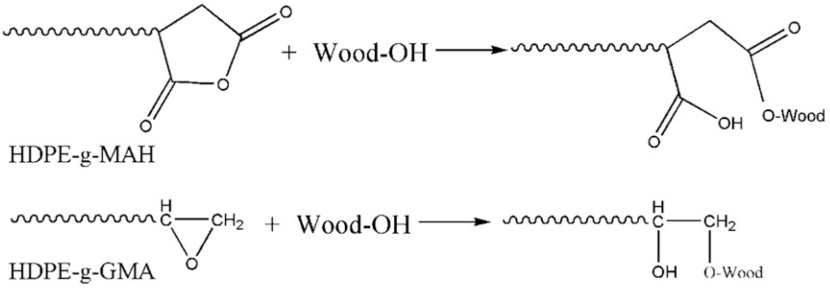

Figure 5. Reaction mechanism of maleic anhydride (MAH) or glycidyl methacrylate (GMA) grafting compatibilizer with wood fibers.

the HDPE matrix, which can be significantly affected by the compatibilizer. However, the stiffness is mainly governed by the stiffness of the components of the composites.

SEM Morphologies of HDPE/BF Composites

Figure 6 shows the SEM morphologies of the impact fracture surfaces of HDPE/BF composites. Bamboo flour granules, distinct boundaries, and gaps can be easily observed on the fracture surface of the uncompatibilized composite Figure 6(a), indicating low affinity and weak interfacial interaction between BF and the polymer matrix (Migneault et al 2009). As a consequence, the uncompatibilized HDPE/BF composite has poor mechanical properties and high water absorption. Figures 6(b) and (c) show the impact fracture surfaces of HDPE/BF composites compatibilized by 7 wt.% of HDPE-*g*-MAH and HDPE-*g*-GMA, respectively. It shows that BF is more homogeneously dispersed in the matrix and tightly bonded to the HDPE matrix and, thus, there are no distinct interface boundaries and gaps between them, indicating that the addition of HDPE-*g*-MAH or HDPE-*g*-GMA can significantly improve the interfacial adhesion between BF and the HDPE matrix and, thus, the stress can be effectively transferred from the matrix to BF particles.

Water Absorption of HDPE/BF Composites

The water absorption properties of WPCs depend on the available hydroxyl groups on the surface of wood flour and the interfacial bonding between the matrix and the wood flour. The water absorption of HDPE/BF composites and pure HDPE as a function of time is shown in Figure 7. It is evident that the HDPE matrix resin has almost no water absorption capacity because of the high hydrophobicity of HDPE. Compared with the composites without a compatibilizer, the addition of HDPE-*g*-MAH or HDPE-*g*-GMA can

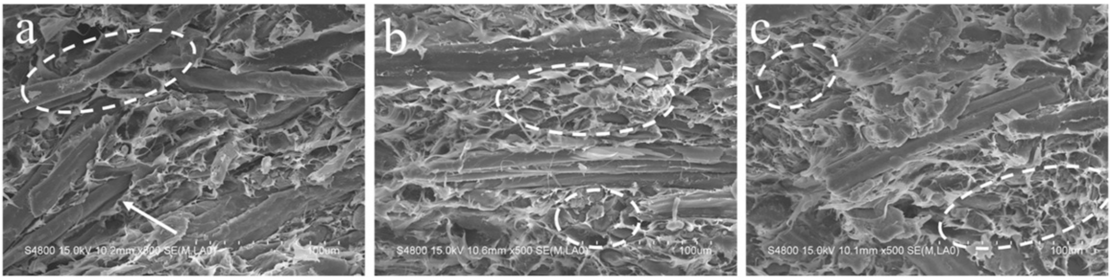

Figure 6. Scanning electron microscopy morphologies of the impact fracture surfaces: (a) no compatibilizer, (b) 7 wt.% maleic anhydride–grafted high-density polyethylene, (c) 7 wt.% glycidyl methacrylate–grafted high-density polyethylene.

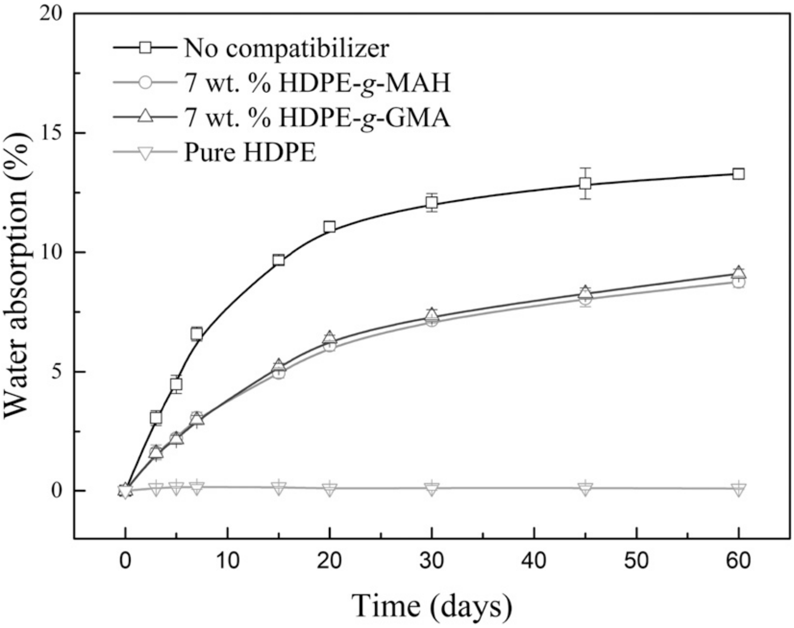

Figure 7. The water absorption properties of high-density polyethylene (HDPE)/bamboo flour composites with different compatibilizers.

result in lower water absorption, indicating that HDPE-*g*-MAH or HDPE-*g*-GMA can effectively improve the water resistance. Hosseinaei et al (2012) showed that the better the interaction and adhesion between the matrix and wood flour, the better the water resistant properties. Migneault et al (2009) showed that the exposed wood flour in WPCs could easily absorb water

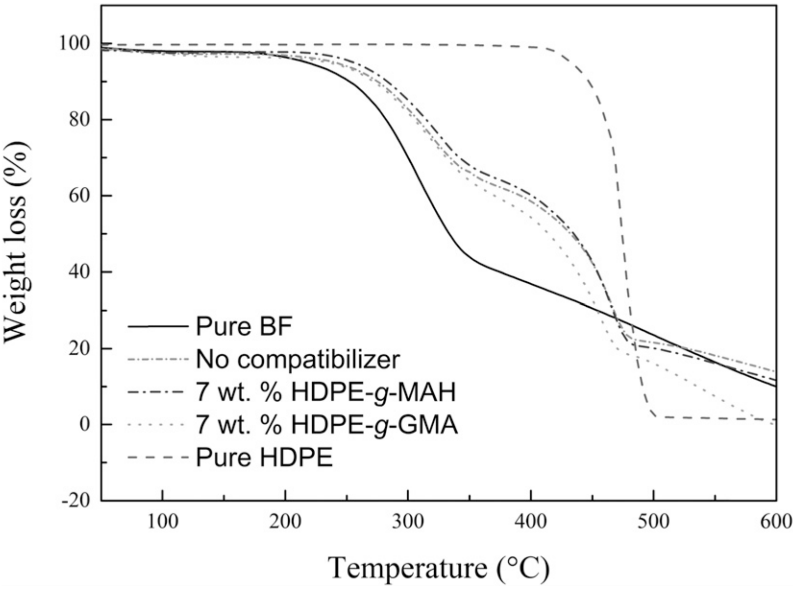

Figure 8. The thermogravimetric analysis curves of high-density polyethylene (HDPE)/bamboo flour (BF) composites with different compatibilizers.

Table 2. Decomposition temperature of pure bamboo flour (BF), pure high-density polyethylene (HDPE), and HDPE/BF composites.

	First stage			Second stage		
	$T_{\text{onset}(°\text{C})}$	$T_{\max(°\text{C})}$	$T_{\text{end}(°\text{C})}$	$T'_{\text{oeset}(°\text{C})}$	$T'_{\max(°\text{C})}$	$T'_{\text{end}(°\text{C})}$
Pure BF	261	306	341	—	—	—
No compatibilizer	265	318	343	438	464	475
7 wt.% HDPE-*g*-MAH	271	325	347	438	464	477
7 wt.% HDPE-*g*-GMA	266	323	346	425	455	470
Pure HDPE	—	—	—	459	474	489

and moisture. The chemical reaction between hydroxyl groups of wood flour and anhydride groups of HDPE-*g*-MAH or epoxy groups of HDPE-*g*-GMA can decrease the number of hydroxyl groups. Moreover, the strong interaction and adhesion layers formed by HDPE-g-MAH or HDPE-g-GMA can protect BF from water and eliminate the gaps between BF and HDPE. Thus, HDPE-*g*-MAH and HDPE-*g*-GMA can contribute to improve the water resistant properties. Similar results have also been reported by Hosseinaei et al (2012) and Najafi and Khademi-Eslam (2011).

Thermal Stability of HDPE/BF Composites

The TGA thermograms of pure HDPE, BF, and HDPE/BF composites are shown in Figure 8, and the TGA data are shown in Table 2. The maximum thermal degradation of HDPE/BF composites occurs at a lower temperature than that of pure HDPE, thus, indicating that the thermal stability of composites decreases in the presence of BF. However, for HDPE/BF composites with 7 wt.% of HDPE-*g*-MAH or HDPE-*g*-GMA, the maximum degradation temperature is shifted to a higher temperature than that of uncompatibilized composites, indicating the improvement of the thermal stability of compatibilized composites. Thus, adding compatibilizers to the HDPE/BF composites can improve the thermal stability of these composites, which is due to the better coupling effect between the BF filler and the HDPE matrix facilitated by HDPE-*g*-MAH or HDPE-*g*-GMA.

CONCLUSIONS

In this study, HDPE-*g*-MAH and HDPE-*g*-GMA were synthesized and used as compatibilizers for highly filled HDPE/BF composites. The results show that HDPE-*g*-MAH and HDPE-*g*-GMA can more effectively improve the mechanical properties of HDPE/BF composites than commercial compatibilizers (Fusabond®M603 resin, PE-*g*-MAH, and PEW-*g*-MAH). In addition, HDPE-*g*-GMA is more effective than HDPE-*g*-GMA because of the stronger interaction between anhydride and hydroxyl groups than that between epoxy and hydroxyl groups. The use of HDPE-*g*-GMA and HDPE-*g*-GMA contributes to improve the thermal stability and reduce the water absorption of HDPE/BF composite.

ACKNOWLEDGMENTS

This research was financially supported by the National Natural Science Foundation of China (U 1507123), the Foundation from Qinghai Science and Technology Department (2017-HZ-803) and Thousand Talents Program of Qinghai Province.

REFERENCES

Al-Salem SM, Lettieri P, Baeyens J (2009) Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Manage 29(10):2625-2643.

Ashori A (2008) Wood-plastic composites as promising green-composites for automotive industries! Bioresour Technol 99(11):4661-4667.

Dai BJ, Wang Q, Yan W, Guo WH (2016) Synergistic compatibilization and reinforcement of HDPE/wood flour composites. J Appl Polym Sci 133(8):42958-42967.

Deka BK, Maji TK (2012) Effect of nanoclay and ZnO on the physical and chemical properties of wood polymer nanocomposite. J Appl Polym Sci 124(4):2919-2929.

Deka BK, Mandal M, Maji TK (2012b) Effect of nanoparticles on flammability, UV resistance, biodegradability, and chemical resistance of wood polymer nanocomposite. Ind Eng Chem Res 51(37):11881-11891.

Fang Y, Wang Q, Guo C, Song Y, Cooper PA (2013) Effect of zinc borate and wood flour on thermal degradation and fire retardancy of polyvinyl chloride (PVC) composites. J Anal Appl Pyrol 100(100):230-236.

Gao H, Xie Y, Ou R, Wang Q (2012) Grafting effects of polypropylene/polyethylene blends with maleic anhydride on the properties of the resulting wood–plastic composites. Compos Part A 43(1):150-157.

Gozdecki C, Wilczynski A (2015) Effects of wood particle size and test specimen size on mechanical and water resistance properties of injected wood-high density polyethylene composite. Wood Fiber Sci 47(4):365-374.

Guo CG, Wang QW (2008) Influence ofm-isopropenyl-α,α-dimethylbenzyl isocyanate grafted polypropylene on the interfacial interaction of wood-flour/polypropylene composites. J Appl Polym Sci 109(5):3080-3086.

Haque MM, Hasan M, Islam MS, Islam MS, Ali ME (2009) Physico-mechanical properties of chemically treated palm and coir fiber reinforced polypropylene composites. Bioresour Technol 100(20):4903-4906.

Hoang T, Chinh NT, Trang NTT, Hang TTX, Thanh DTM (2013) Effects of maleic anhydride grafted ethylene/vinyl acetate copolymer (EVA) on the properties of EVA/silica nanocomposites. Macromol Res 21(11):1210-1217.

Hosseinaei O, Wang S, Enayati AA, Rials TG (2012) Effects of hemicellulose extraction on properties of wood flour and wood–plastic composites. Compos Part A 43(4):686-694.

Hosseinihashemi SK, Arwinfar F, Najafi A, Nemli G, Ayrilmis N (2016) Long-term water absorption behavior of thermoplastic composites produced with thermally treated wood. Measurement 86:202-208.

Ihemouchen C, Djidjelli H, Boukerrou A, Fenouillot F, Barres C (2013) Effect of compatibilizing agents on the mechanical properties of high-density polyethylene/olive husk flour composites. J Appl Polym Sci 128(3): 2224-2229.

Kaseem M, Hamad K, Deri F, Ko YG (2015) Material properties of polyethylene/wood composites: A review of recent works. Polym Sci Ser A 57(6):689-703.

Kazemi NS (2013) Use of recycled plastics in wood plastic composites-a review. Waste Manage 33(9):1898-1905.

Kuang FC, Xing Y, Wu ZH, Zhang JL (2017) Characteristics of screwdriving torques in wood-plastics. Wood Fiber Sci 49(2):206-218.

Kumar V, Tyagi L, Sinha S (2011) Wood flour–reinforced plastic composites: A review. Rev Chem Eng 27(5-6):253-264.

Lashgari S, Garmabi H, Lashgari S (2011) Improving the interfacial adhesion of highly filled PP—Bagasse composites designed by Taguchi method. J Thermoplast Compos Mater 24(4):431-446.

Mansour SH, El-Nashar DE, Abd-El-Messieh SL (2016) Effect of chemical treatment of wood flour on the properties of styrene butadiene rubber/polystyrene composites. J Appl Polym Sci 102(6):5861-5870.

Michael SG, Yadama V, Bender DA (2010) Effect of tie-layer on the bond strength between thermoplastic and borate-treated wood substrate. Wood Fiber Sci 42(4):1-10.

Migneault S, Koubaa A, Erchiqui F, Chaala A, Englund K (2009) Effects of processing method and fiber size on the structure and properties of wood–plastic composites. Compos Part A 40(1):80-85.

Najafi A, Khademi-Eslam H (2011) Lignocellulosic filler/recycled HDPE composites: Effect of filler type on physical and flexural properties. BioResources 6(3):2411-2424.

Pracella M, Chionna D, Anguillesi I, Kulinski Z, Piorkowska E (2006) Functionalization, compatibilization and properties of polypropylene composites with Hemp fibres. Compos Sci Technol 66(13):2218-2230.

Sohn JS, Cha SW (2015) Enhanced interfacial adhesion of polypropylene and waste wood from roadside trees composite materials. Int J Precis Eng Manuf 16(11): 2389-2393.

Thompson RC, Moore CJ, vom Saal FS, Swan SH (2009) Plastics, the environment and human health: Current consensus and future trends. Philos Trans R Soc Lond B Biol Sci 364(1526):2153-2166.

Väntsi O, Kärki T (2015) Different coupling agents in wood-polypropylene composites containing recycled mineral wool: A comparison of the effects. J Reinf Plast Compos 34(11):879-895.

Xiong C, Qi R, Wang Y (2009) Wood-thermoplastic composites from wood flour and high-density polyethylene. J Appl Polym Sci 114(2):1160-1168.

Yasemin A, Mehmet D, Erdal B (2012) Comparative study of maleated and glycidyl methacrylate functionalized terpolymers as compatibilizers for low-density polyethylene–wood flour composites. J Appl Polym Sci 127(2):1010-1016.

Zhu Y, Liang C, Bo Y, Xu S (2015) Compatibilization of polypropylene/recycled polyethylene terephthalate blends with maleic anhydride grafted polypropylene in the presence of diallyl phthalate. J Polym Res 22(3): 35-47.