

Research Article

Mechanical and Thermal Properties of R-High Density Polyethylene Composites Reinforced with Wheat Straw Particleboard Dust and Basalt Fiber

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The effect of individual and combined particleboard dust (PB dust) and basalt fibers (BFs) on mechanical and thermal expansion performance of the filled virgin and recycled high density polyethylene (HDPE) composites was studied. It was shown that the use of PB dust had a positive effect on improving mechanical properties and on reducing linear coefficient of thermal expansion (LCTE) values of filled composites, because the adhesive of the particle board held the wheat straw fibers into bundles, which made PB dust have a certain aspect ratio and high strength. Compared with the commonly used commercial WPC products, the flexural strength of PB dust/VHDPE, PB dust/RHDPE, and PB dust/VHDPE/RHDEPE at 40 wt% loading level increased by 79.9%, 41.5%, and 53.9%, respectively. When 40 wt% PB dust was added, the crystallization degree of the composites based on three matrixes decreased to 72.5%, 45.7%, and 64.1%, respectively. The use of PB dust can help lower the composite costs and increase its recyclability. Mechanical properties and LCTE values of composites with combined BF and PB dust fillers varied with PB dust and BF ratio at a given total filler loading level. As the BF portion of the PB dust/BF fillers increased, the LCTE values decreased markedly, which was suggested to be able to achieve a desirable dimensional stability for composites. The process provides a useful route to further recycling of agricultural wastes.

1. Introduction

Recycling of waste plastics and agricultural residues is an effective solution to the sustainable development in the world and has already become a common practice in industry. Substituting virgin plastic composites with recycled plastic composites is proved to be a superior alternative in most environmental aspects and has achieved the highest environmental benefits [1]. Wood plastic composites (WPCs), which consist of thermoplastics and wood fibers, have become a successful commercial building material with a significant increase over the past decades due to their excellent mechanical properties especially when the low density and price are taken into account [2–4]. In recent years, due to the shortage

of raw material, WPCs enterprises and research institutions spared no effort to develop substitute biofillers. Previous studies showed that using crop residues such as rice straw, sugar cane, flax, hemp, jute, or tea residues to replace wood fibers improved notably mechanical and thermal properties of WPCs [5–7]. Wu et al. [8] prepared cotton stalk bark (CSB) filled polypropylene and characterized their morphology, mechanical, and thermal properties. The flexural properties and tensile modulus of cotton stalk bark plastic composites were increased with the increasing concentration of CSB. The tensile strengths exhibited a negative correlation with the CSB content, which reached 32.9 Mpa when the CSB added was 30%. Recently, Cholake et al. [9] investigated the effect of waste macadamia shell on enhancing mechanical properties

of WPC panel. It was shown that the addition of macadamia shell increased the comprehensive modulus 548 MPa for 75% macadamia shell WPC panel, and thermal property also indicated that the WPC panel has good flame retardant property compared to 100% plastic panel. However, limited information can be found on industrialized WPCs products from agricultural residues recycling, despite that they were much cheaper than wood. One of the lethal weaknesses is that they are very fluffy and very easily to be moldy, leading to high storage and transport cost in unit weight [10].

It is noteworthy that annually there are plenty of oriented strandboard (OSB) and plywood discarded in European and American and particle board (PB) and medium density fiberboard (MDF) abandoned in Asia [11, 12]. Utilization of these materials in manufacturing of WPCs can not only reduce production costs but also remove the problem of accumulating and discarding wood industry waste. Such postindustrial wooden products are available in huge quantities, quite consistent in moisture, and well-documented origin, which make it possible to be a consistent alternative source to wood fibers [13]. In a previous study, MDF/HDF based WPC showed significantly higher mechanical strength behaviors than standard WPC, which showed that using MDF dust in manufacturing WPC panel had more added worth [14–17]. The advantages of straw particleboard are its rigidity and strength, built-in insulation, and low cost [18, 19]. Since wheat straw particleboards are not as hard as OSB, they can be easily crushed into particle or powder, which may be used as raw material as natural fiber for WPC. In addition, recycling wheat straw particle board is a meaningful contribution for further recycling of agricultural wastes.

Although individual biofibers can contribute some desirable properties as reinforcement fillers, the mechanical and thermal properties of WPCs can be represented by the hybridization with inorganic fillers [20, 21]. Previous studies showed that hybridization of wheat straw reinforced recycled PP composites with different inorganic fillers such as heavy calcium carbonate, silicon dioxide, and fly ash improved notably their water absorption and thermal expansion properties. However, the flexural modulus and flexural strength were both reduced when reinforced with three kinds of inorganic fillers, respectively [22]. As a cost-effective and high-strength material for use in composites, basalt fibers (BFs) are gaining a great attention as an alternative to the use of glass fibers in polymer composites [23]. Also, an effective way to enhance the performance of WPCs while minimizing cost and agricultural residues would greatly improve the economic attractiveness of WPCs. Huang et al. [24] showed that incorporating BFs into the HDPE-Talc composites substantially enhanced the thermal expansion property, flexural, tensile, and dynamic modulus without causing a significant decrease in the tensile and impact strength of the composites. The combined filler system with BFs and Talc could offer a balance between cost and performance for WPCs. In this regard, this paper aims at evaluating the effect of individual PB dust and hybrid fillers (PB dust and BFs) filled virgin and recycled high density polyethylene (HDPE) composites.

2. Materials Processing and Experiment Methods

2.1. Raw Materials and Experimental Design. Raw materials for the study included wheat straw particleboard dust (PB dust), basalt fiber (BF), virgin high density polyethylene (VHDPE), recycled high density polyethylene (RHDPE), maleic anhydride grafted polyethylene (MAPE), and lubricant. PB dust was from Dare Technology Co., Ltd., Zhenjiang, China. Basalt fibers were from Anjie Polymer Material Co., Haining, China. VHDPE was grade AD60 with an MFI at 190°C and 2.16 kg weight of 0.7 g/10 min and a density of 0.96 g/cm³ (ExxonMobil Chemical Co., Houston, TX, USA). MAPE was grade Epolene TM G2608 with an MFI at 190°C and 2.16 kg weight of 6~10 g/10 min, Mw of 65,000 g/mol, and acid number of 8 mgKOH/g from Eastman Chemical Co. (Kingsport, TN, USA). Lubricant was grade TPW 306 from Struktol Co. (Stow, OH, USA).

Experiment design included two factorial experiments. The first experiment was to investigate the effect of individual filler consisting of twelve blends covering one filler (PB dust) and four loading rates (10, 20, 30, and 40 wt% of total composite weight for PB dust pallets filler reinforced VHDPE, RHDPE, and VHDPE/RHDPE, resp.). The VHDPE/RHDPE ratio is 1:1. The second experiment was designed to study the effect of combined polymer and combined fillers system (VHDPE/RHDPE/basalt fibers/PB dust pallets), consisting of six blends covering one filler weight contents (50 wt%) and three basalt fibers/PB dust ratios (2:1, 1:1, and 1:2). The VHDPE, RHDPE, and VHDPE/RHDPE were used as a control.

2.2. Sample Preparation. Melt compounding was performed using a Leistritz Micro-27 corotating parallel twin-screw extruder (Leistritz Corporation, Allendale, NJ, USA) with a screw speed of 60 rpm. The temperature profile of barrels ranged from 150 to 175°C. The extrudates were air-cooled and then pelletized into granules. The granules were injection-molded into standard mechanical test specimens using a Battenfeld Plus 35 injection molding machine (Battenfeld, NJ). The injection temperatures were 190 and 180°C for HDPE-PB dust composites and neat HDPE, respectively. All specimens were then conditioned for 72 h at a temperature of 23 ± 2°C and a relative humidity of 50 ± 5% for later characterization.

2.3. Characterization

(1) Mechanical Properties. Flexural tests of samples were carried out according to ASTM D790-03, using a CMT6104 SANS Mechanical Testing Machine (Tesla Industrial systems Co., Guangdong, China). Notched Izod impact strengths were measured with XJJ-5 Impact Tester (Jinjian Testing Instrument Co., Chengde, China) according to the ASTM D 256-05. Four samples of each group were tested.

(2) Thermal Expansion Performance. Thermal expansion samples were machined with a miniature table saw along the long direction of samples with a dimension of 43.5 (length) × 12.7 (width) × 5.4 (thickness) mm. The linear

coefficients of thermal expansion (LCTE) value of each specimen were measured parallel to the long direction over a temperature range from 20 to -13°C and -13 to 60°C . They were conditioned at 60°C in an oven and -13°C in a freezer from their initial equilibrium temperature of 25°C prior to size measurements with a Mitutoyo digimatic indicator of ± 0.01 mm accuracy (Mitutoyo Co., Kanagawa, Japan). Five specimens were used for each group. The LCTE for each sample was calculated based on size changes before and after conditioning. The heating and cooling rates were kept constant at $5^{\circ}\text{C}/\text{min}$. The LCTE (α_L , $1/^{\circ}\text{C}$) was calculated as

$$\alpha_L = \frac{1}{L} \frac{dL}{dT}, \quad (1)$$

where L is the linear dimension of the test sample and dL/dT is the rate of change in the linear dimension per unit temperature.

(3) *Crystallization Behaviors.* The crystallization behaviors of HDPE in the blends and composites were measured using a differential scanning calorimeter (DSC Q100, TA Instruments, New Castle, DE). Samples of 4-5 mg were placed in aluminium capsules, heated from 40°C to 260°C at $10^{\circ}\text{C}/\text{min}$, and then melt annealed for 5 min to eliminate the heat history before being cooled down at $10^{\circ}\text{C}/\text{min}$. The crystallinity levels corresponding to the crystallization of HDPE in blends were normalized to the mass unit of specimens.

2.4. *Statistical Data Analysis.* Duncan's multiple range tests for pairwise comparisons were used to test the effect of various treatments on measured properties using Statistical Analysis Software SPSS 22. Statistical ranking at the 5% significance level was provided among the treatments for each property.

3. Results and Discussion

3.1. *Morphology.* Morphology of impact fractured surfaces of composites with PB dust is shown in Figure 1. Most PB dust appeared to be well dispersed in the VHDPE matrix, indicating that the PB dust was compounded well with VHDPE matrix (Figures 1(a), 1(b), and 1(c)). Agglomeration of PB dust was observed when PB dust content reached 40% (Figure 1(d)). In Figures 1(e) and 1(f), more fiber pullouts and increased gaps between two phases were observed compared to these shown in Figure 1(d). These features suggest that VHDPE/RHDPE and RHDPE matrix has a weaker interfacial bonding between wood filler and the matrix. Thus, further surface modification should be studied in the future, especially for the matrix which contained recycled plastic, which could help improve PB dust/polymer interfacial adhesion and play an important role in determining the efficiency of stress transferred from plastic matrix to the reinforcing fibers.

3.2. Mechanical Properties

3.2.1. *Flexural Property.* Flexural properties of PB dust/HDPE composites with PB dust content from 0 to 40 wt% were shown in Figure 2(a). Compared with the mechanical

properties of commonly used commercial WPC products (GeoDeck™, Report number ESR-1369, manufactured by Green Bay Decking, LLC, WI, US), the flexural strength of PB dust/VHDPE, PB dust/RHDPE, and PB dust/VHDPE/RHDPE at 40 wt% loading level increased by 79.9%, 41.5%, and 53.9%, respectively, and modulus improved by 2~3%. The better flexural properties might be because the adhesive of the particle board held the wheat straw fibers into bundles as it can be seen from Figure 1(b), which made PB dust have a certain aspect ratio and high strength. Therefore, adding PB dust improved the stress transfer efficiency and enhanced the composite stiffness. Flexural modulus of the composite exhibited an increasing trend with increasing PB dust loading levels. With every 10 wt% rise of PB dust content, HDPE, RHDPE, and VHDPE/RHDPE based composite showed an average increase of 85%, 48%, and 72%, respectively. For HDPE, RHDPE, and VHDPE/RHDPE systems, the modulus, respectively, increased to 2.58 GPa, 2.22 GPa, and 2.55 GPa at the 40 wt% PB dust loading level. It can be inferred that flexural modulus of composite is affected by its component. The interfacial interaction existed between fiber and matrix by addition of PB dust to plastic matrix, which could make the transmission from matrix to stiff PB dust and consequently results in increasing the modulus of the composite. The flexural strength increased significantly from 0 to 30% PB dust content but decreased slightly at the 40% PB dust content level. The increasing PB dust content increased the possibility of stress concentration caused by fiber aggregation, which became the failure point of composite and resulted in lower strength (Figure 1(d)).

3.2.2. *Tensile Strength.* Tensile properties of PB dust/HDPE composite with different PB dust loading levels are plotted in Figure 2(b). Tensile modulus of the composite exhibited an increasing trend with increasing PB dust content in composites. For the neat virgin HDPE, recycled HDPE, and virgin and recycled HDPE, tensile modulus was 1.17 GPa, 0.71 GPa, and 0.96 GPa. When PB dust content was 40 wt%, composites in three kinds of system showed a notable increase to 3.23 GPa, 2.7 GPa, and 3.07 GPa, respectively. It can be seen that PB dust suggested a positive effect on tensile modulus, which might be due to the strength and stiffness of PB dust. For tensile strength, a decreased trend with increasing PB dust content in composite was observed. When composites were loaded with 40 wt% PB dust, tensile strength of VHDPE, RHDPE, and VHDPE/RHDPE based composite decreased to 18.14 MPa, 11.48 MPa, and 12.06 MPa from the neat VHDPE, RHDPE, and VHDPE/RHDPE of 22.36 MPa, 16.56 MPa, and 19.42 MPa, respectively. The constant reduction of tensile strength illuminated that MAPE did not work as a coupling agent leading to the interface adhesion between PB dust and matrix was very weak. The force of tensile will not be transported from matrix to filler effectively.

3.2.3. *Impact Strength.* The impact strength constantly decreased by increasing PB dust loading level among all three systems. This showed that the MAPE could not improve the interface adhesion between fibers and polymer, which

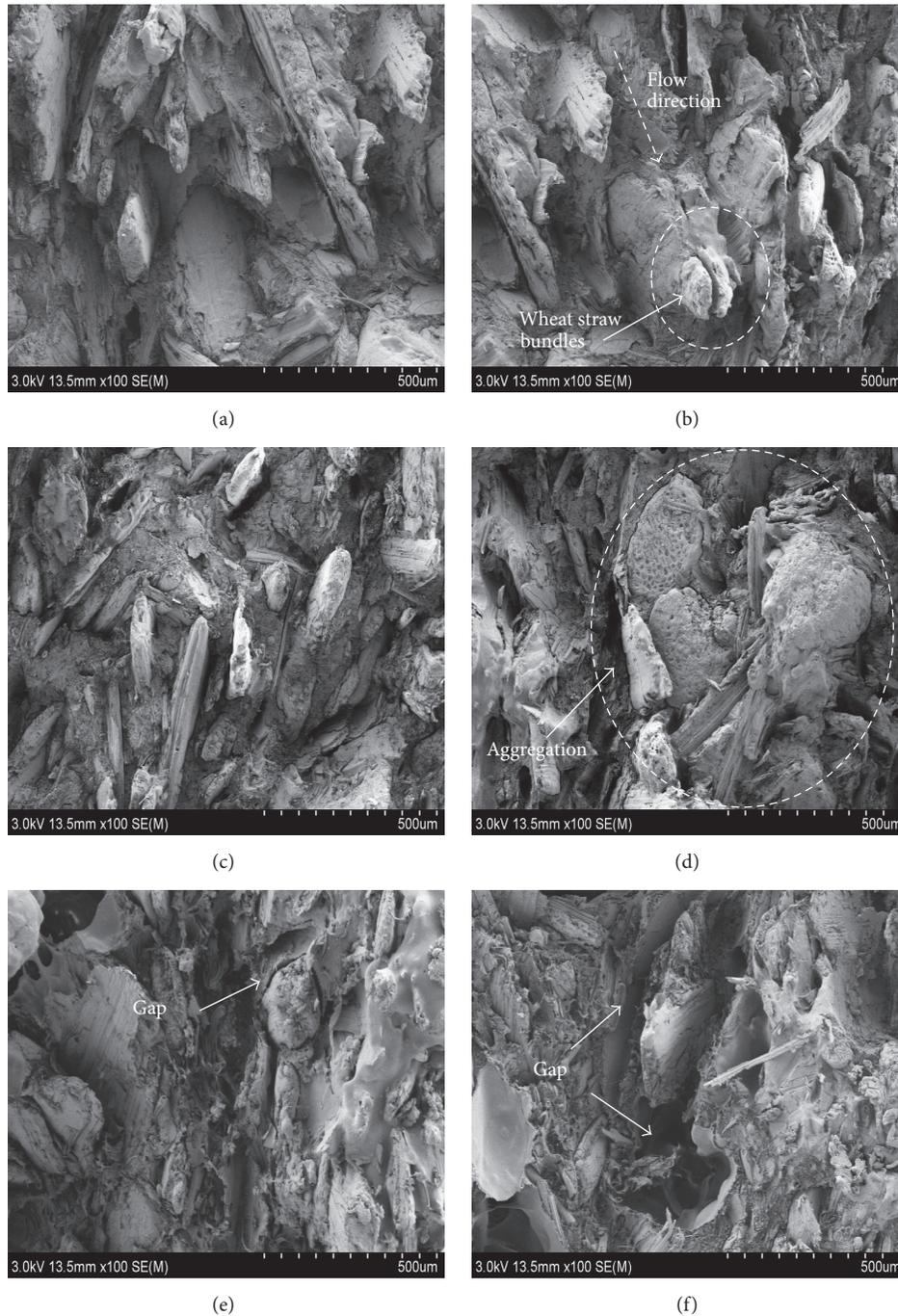


FIGURE 1: Morphology of fractured surfaces of WPCs: (a) VHDPE system with 10% PB dust, (b) 20% PB dust, (c) 30% PB dust, (d) 40% PB dust, (e) VHDPE/RHDPE system with 40% PB dust, and (f) RHDPE system with 40% PB dust.

contributed to an assumption that PB dust might be wrapped in adhesive so that there was few hydroxyl groups on the surface, and consequently it was difficult for MAPE to have graft reaction. On the other hand, the addition of stiffness PB dust reduced the toughness of the composite.

3.3. Thermal Expansion Properties. In the process of actual use, WPCs are often subjected to more complex service conditions and wider-ranging working temperatures, which

made thermal expansion properties as important as mechanical properties become a crucial engineering performance indicator. A lower LCTE value is one of the most desired properties for WPCs used in outdoor application in order to improve their thermal stability and optimize thermomechanical properties. Table 1 showed measured LCTE values as a function of PB dust content for PB dust filled HDPE polymer. Among three temperature ranges, the first heating cycle (20 to 60°C) had the largest LCTE, and the second

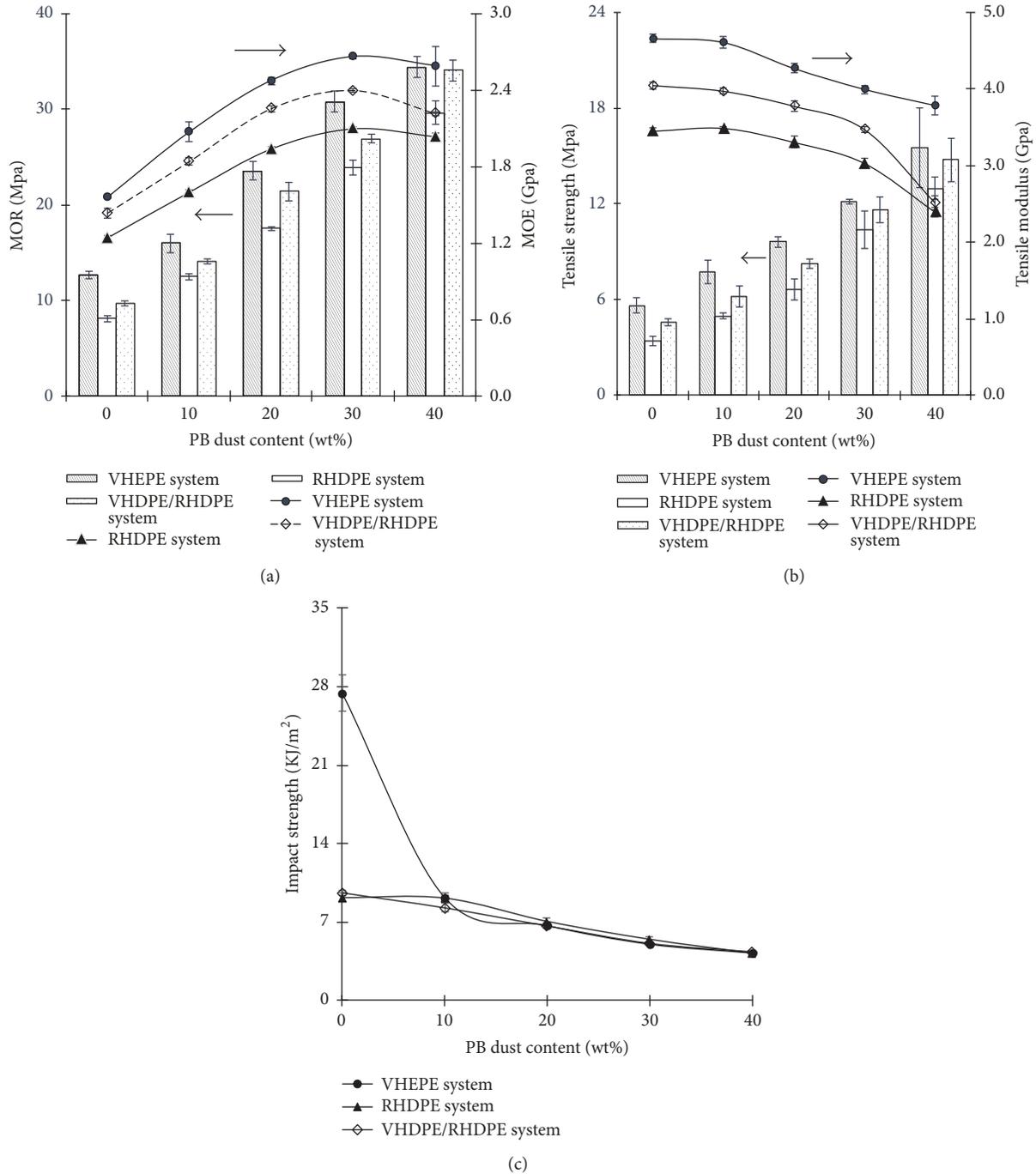


FIGURE 2: Mechanical properties of PB dust/HDPE composite: (a) flexural properties, (b) tensile properties, and (c) impact properties.

heating cycle (-30 to 20°C) had the smallest LCTE, which suggested that the thermal expansion behavior of composite was related to the thermal history built into the samples. As implied from the test results reported in Table 1, LCTE decreased with increased PB dust content among three plastic systems. Introducing 10 wt% PB dust in matrix, LCTE values among three plastic systems were observed to decrease by 10 to 15%. With 20 wt% PB dust loading, the LCTE showed a moderate decrease. The LCTE reduction rate increased greatly with the use of PB dust after the 30 wt% filling level.

Statistical ranking shows a significant effect of 40 wt% PB dust content on measured LCTE values among all systems, which indicated that the introduction of PB dust presented positive influences on LCTE of virgin and recycled HDPE, especially at higher loading level.

The LCTE showed an obvious decrease with respect to neat plastic. The LCTE reductions for the temperature ranges of 20 to 60, 60 to -30, and -30 to 20 are 49.2, 47.4, and 38.3%, respectively, for HDPE systems, and 27.5, 27.9, and 23.6% for the RHDPE system. The corresponding values are,

TABLE 1: Effect of PB dust content on thermal expansion coefficient of PB dust filled composites.

System	Filler content ^a (wt%)	Linear coefficient of thermal expansion ($10^{-6}/^{\circ}\text{C}$)		
		20 to 60 $^{\circ}\text{C}$ ^{bc}	60 to -30 $^{\circ}\text{C}$	-30 to 20 $^{\circ}\text{C}$
VHDPE	0	177.53 (5.36) ⁱ	168.40 (3.28) ⁱ	138.48 (1.35) ⁱ
	10	147.67 (3.24) ^{gh}	146.50 (3.35) ^g	129.64 (3.34) ^g
	20	143.73 (12.27) ^{fg}	136.07 (3.29) ^f	122.88 (3.39) ^f
	30	98.85 (1.04) ^b	97.80 (4.43) ^b	88.49 (3.10) ^a
	40	90.10 (5.69) ^a	88.57 (6.15) ^a	85.41 (0.42) ^a
RHDPE	0	151.17 (4.91) ^{gh}	146.40 (0.80) ^g	124.40 (1.14) ^f
	10	136.47 (2.87) ^{ef}	136.77 (0.58) ^f	119.3 (6.92) ^{ef}
	20	133.03 (6.85) ^e	131.63 (1.77) ^{ef}	113.60 (3.01) ^d
	30	117.20 (3.99) ^d	116.93 (6.07) ^d	100.04 (1.50) ^c
	40	109.60 (2.63) ^{cd}	105.53 (2.20) ^c	95.01 (0.66) ^b
VHDPE/RHDPE	0	155.67 (4.54) ^h	154.70 (7.32) ^h	129.47 (1.78) ^g
	10	134.90 (4.70) ^e	134.10 (7.86) ^{ef}	116.30 (3.03) ^{de}
	20	128.67 (0.57) ^e	127.90 (5.31) ^e	102.59 (4.61) ^c
	30	108.30 (1.50) ^c	108.27 (1.27) ^c	89.27 (0.94) ^a
	40	103.93 (1.36) ^{bc}	101.97 (0.81) ^{bc}	86.15 (0.74) ^a

^aThe content of each filler was based on the total composite weight. ^bMean values with the same lowercased letters for each property are not significantly different at the 5% significance level. ^cNumbers in the parenthesis are standard deviation based on five specimens. d, e, f, g, h, and i represent data statistics ranking in Duncan's multiple range tests.

respectively, 33.2, 34.1, and 33.5% for the VHDPE/RHDPE system. It was because of a small LCTE of PB dust and the reduction of plastic content in composites [25, 26]. Noticeably, though among three plastic matrices (i.e., HDPE, RHDPE, and VHDPE/RHDPE), neat RHDPE had the smallest LCTE value, RHDPE based composites did not impose an efficient effect on preventing the thermal expansion caused by heating and cooling cycles. It is because MAPE could not effectively enhance PB dust bonding to RHDPE matrix, so the interface adhesion between PB dust and matrix was very weak, which made the net effect hardly worked out [27, 28]. Thus, the declined LCTE of RHDPE based composite mainly contributed to the low LCTE of PB dust. Though it was reported that the introducing of coupling agent can improve thermal expansion of natural fiber filled composite, so much impurity in matrix may resist the covalently link with the PB dust [29–31]. This argument is further supported through previous tensile and impact properties, which suggested the weak interface adhesion between PB dust and RHDPE.

At the 40 wt% PB dust loading level, the LCTE values for HDPE system were, respectively, $90.1 \times 10^{-6}/^{\circ}\text{C}$, $88.57 \times 10^{-6}/^{\circ}\text{C}$, and $84.41 \times 10^{-6}/^{\circ}\text{C}$ from the cooling and heating cycles. These values are still higher than the reported LCTE values of WPC filled with natural fiber and other fillers. It is probably because during the manufacture of particleboard, wheat straw suffered from high temperature and high pressure, which may reduce the thermal and mechanical properties of WS fiber. On the other hand, the methylene diphenyl isocyanate (MDI) remaining on PB dust surface may resist MAPE to improve the thermal expansion behaviors of filled composites through enhancing surface adhesion.

3.4. Crystallization and Melting Behavior from DSC. Thermogravimetric analysis was performed to evaluate the behavior of the materials when subjected to the heating such as during thermomechanical processing. The cooling and second heating thermogram curves of PB dust/HDPE, PB dust/RHDPE, and PB dust/HDPE/RHDPE blends from DSC measurement are shown in Figure 3, and DSC results of three various types of matrix and composites are summarized in Table 2. T_c and T_m are peak temperatures of crystallization and melting, respectively. Peak heat flow of cooling run (H_p) presented peak crystallization rate of polymer. The crystallinity level, X_c , was evaluated from the following equation:

$$X_c = \frac{\Delta H_{\text{exp}}}{\Delta H} \times \frac{1}{W_f} \times 100\%, \quad (2)$$

where ΔH_{exp} is the experimental heat of crystallization, ΔH is the assumed heat of crystallization of fully crystalline HDPE (290 J/g), and W_f is the weight fraction of HDPE in the blends [32, 33].

As shown in Figure 3, compared with neat HDPE, HDPE, and HDPE/RHDPE, PB dust filled composites had lower melting peak temperatures, higher crystallization peak temperatures, much lower crystallization rates at crystallization peak temperatures, and wider crystalline temperature range, which implies an improvement on the processing temperature of composite.

PB dust content influenced crystallization degree of HDPE, RHDPE, and HDPE/RHDPE dramatically (Table 2). Crystallization degree results calculated from second heating run were fairly close to that from cooling run. The sample X_c decreased with the increased WSPB dust loading level.

TABLE 2: DSC result of VHDPE/fiber, RHDPE/fiber, and VHDPE/RHDPE/fiber composite.

System	Fiber loading (%)	Cooling			2nd heating	
		T_c	Hp	X_c	T_m	X_c
VHDPE	0	121.2	5.7	84.8	134.3	89.3
	20	121.8	5.2	79.4	134.0	84.7
	40	121.7	4.1	72.5	133.6	78.8
RHDPE	0	117.7	4.4	54.7	128.8	57.4
	20	118.1	3.7	52.0	128.4	55.3
	40	117.2	2.8	45.7	128.0	51.3
VHDPE/RHDPE	0	120.4	5.0	68.4	132.0	72.9
	20	120.4	4.3	65.4	131.8	70.8
	40	120.3	3.8	64.1	131.2	69.7

a, b, c, and d represent data statistics ranking in Duncan's multiple range tests.

When 40 wt% PB dust was added, the X_c of the composites based on three matrixes decreased to 72.5%, 45.7%, and 64.1%, respectively. It was because, by addition of natural fiber, the diffusion rate of HDPE chain was certainly reduced because matrix viscosity at the crystallizing temperature was increased [34, 35]. This phenomenon was more obviously found in composites based on RHDPE system due to their poor flow ability.

At the 40 wt% PB dust level, the crystallization degree for all HDPE systems was lower than that of WPC filled with wood fiber at the same loading level. It is probably because the consistence of PB dust was very complex, which contained low fibrous and miscellaneous awn and auricle fibers, with remaining MDI on WS surface. It was reported that so much impurity in matrix might hardly act as nucleation seeds and may greatly resist the crystal growth of polymer [36]. It was believed that the reduction of chain mobility of HDPE overwhelmed that of the nucleation resulting in the lowered crystallization degree. Similar results were reported by Lei et al. [35, 37].

As implied from the test results reported in Table 2, Hp showed a moderate decrease with 20 wt% loading and, then, decrease with further increase of PB dust content at 40 wt%, which are 28.1%, 35.3%, and 23.8% for HDPE, RHDPE, and HDPE/RHDPE systems, respectively. It indicated that the introduction of PB dust lowered the crystallization rate, and aggregation of PB dust at higher loading rate resisted the chain mobility of HDPE. As a result, the T_c shifted to a lower temperature, and the crystallization rate was obviously lowered.

3.5. Mechanical Properties of Composites with Combined Fillers. The results of Table 3 showed that the combined fillers affected the mechanical properties of composites. Here, both virgin HDPE and recycled HDPE were used to generate a mixed blend (50/50 wt%) as the matrix. The incorporation of BFs greatly improved mechanical properties. Flexural properties of PB dust/BF/VHDPE/RHDPE composites exhibited an increasing trend as BF portion of the PB dust/BF fillers (i.e., 2:1, 1:1, and 1:2) increased. Compared to the VHDPE/RHDPE, the flexural strength and modulus of PB dust/BF/VHDPE/RHDPE composites

increased by 150% and 247%, respectively, when PB dust/BF ratios reached 1:2, which exhibited the high strength and well-dispersed BFs play an important role in determining the flexural properties. Tensile strength and modulus of PB dust/BF/VHDPE/RHDPE composites increased by 46% and 255% when PB dust/BF ratio was 1:1. A slight decrease of tensile properties with the increasing BF content was observed. The decreasing trend could be associated with the insufficient interfacial adhesion between two fillers with different slenderness ratio.

Table 3 also shows test data of the notched Izod impact strength of PB dust/BF/VHDPE/RHDPE composites, which exhibited a significant decrease compared to that of VHDPE/RHDPE matrix. The stiffness of the hybrid composites increased with the addition of combined filler and possible strength concentration caused by fiber aggregation, thus resulting in the reduced toughness of the composites. On the other hand, the hydrophilic nature of the PB dust and BF and the contrasting hydrophobic nature of HDPE matrix exacerbate the agglomeration problem, thus resulting in the decrease of impact properties. Similar behavior for wheat straw fiber and inorganic filler reinforced PP composites was observed in the previous study [22].

3.6. Thermal Expansion Properties of Composites with Combined Fillers. The measured LCTE values of PB dust/BF/VHDPE/RHDPE composites over three temperature ranges (i.e., 20 to 60°C, 60 to -30°C, and -30 to 20°C) are listed in Table 4 at three PB dust/BF ratios. As the BF portion of the PB dust/BF fillers increased, the LCTE values decreased markedly, which was suggested to be able to achieve a desirable dimensional stability for composites. The LCTE value of PB dust/BF/VHDPE/RHDPE composites at PB dust/BF ratios of 2:1, 1:1, and 1:2 were, respectively, $56.6 \times 10^{-6}/^\circ\text{C}$, $50.2 \times 10^{-6}/^\circ\text{C}$, and $44.1 \times 10^{-6}/^\circ\text{C}$. These values are much lower than that of individual PB dust filler composites. Possible reasons for the decreasing trend of LCTE include the lower LCTE of BF than that of PB dust, which was able to pose a mechanical restraint on the opening of the polymer chain during the heat and cooling cycles and helped decrease the overall LCTE of composites [38].

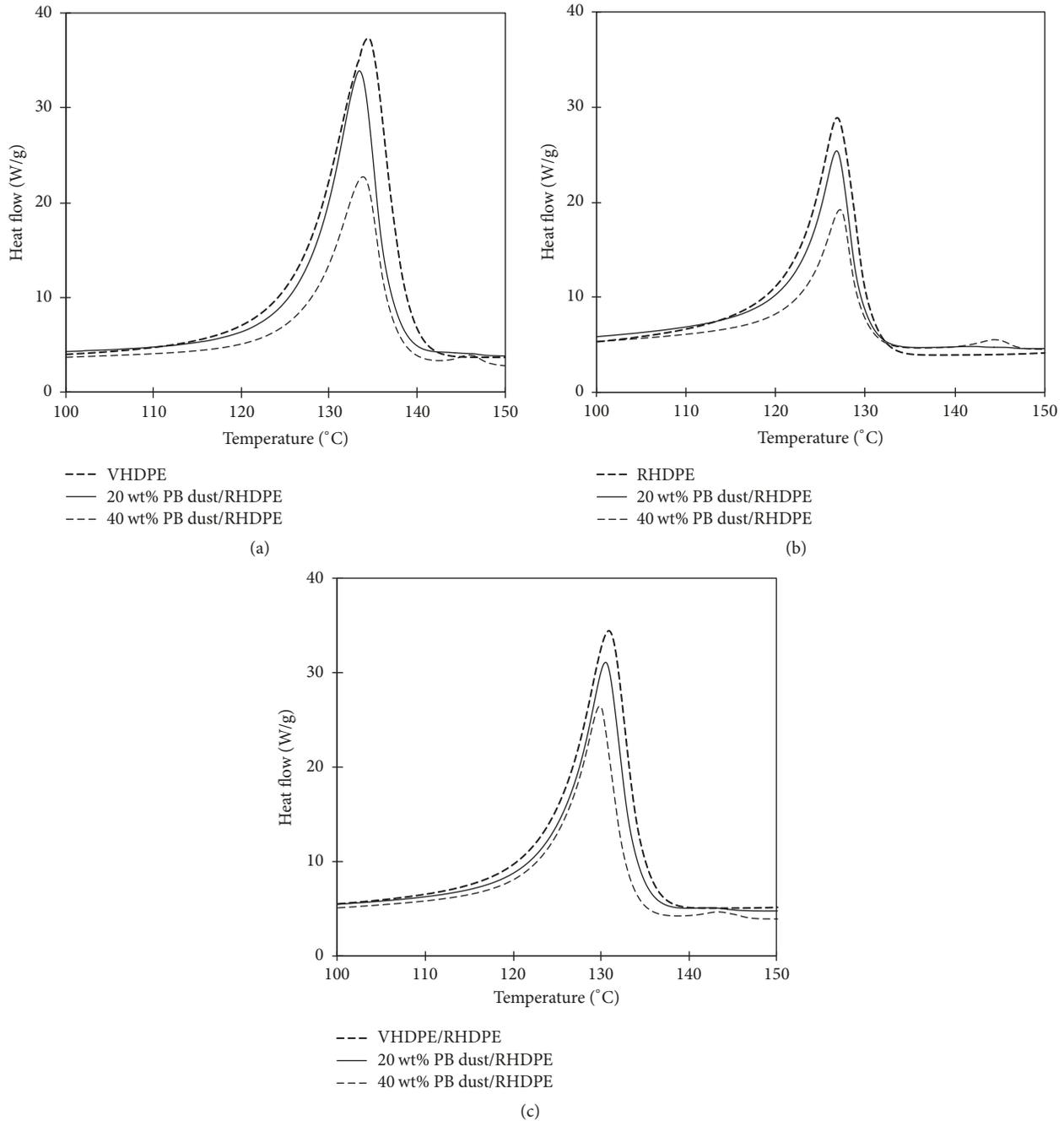


FIGURE 3: DSC curves of (a) PB dust/HDPE, (b) PB dust/RHDPE, and (c) PB dust/HDPE/RHDPE.

4. Conclusions

The effect of individual and combined PB dust and basalt fibers on mechanical and thermal performance of the filled VHDPE and RHDPE composites was studied. Application of PB dust could be a possible solution for the problem due to the potential low cost of this fiber as well as good mechanical performance. The following conclusions could be drawn from the results of the present study:

(1) The use of PB dust had a positive effect on improving mechanical properties and on reducing LCTE values of filled

composites, because the adhesive of the particle board held the wheat straw fibers into bundles, which made PB dust have a certain aspect ratio and high strength.

(2) At the 40 wt% PB dust level, the crystallization degree for all HDPE systems was lower than that of WPC filled with wood fiber at the same loading level, which it was believed that the reduction of chain mobility of HDPE overwhelmed that of the nucleation resulting in the lowered crystallization degree.

(3) As the BF portion of the PB dust/BF fillers increased, the LCTE values decreased markedly, which was suggested

TABLE 3: Mechanical properties of HDPE and filled HDPE composites with combined fillers.

System	Filler content (wt%)	PB dust/BF ratio	Strength			Modulus	
			Tensile (MPa)	Flexural (MPa)	Impact (KJ/m ²)	Tensile (GPa)	Flexural (GPa)
VHDPE/RHDPE	0	0	19.4 (0.2) ^a	19.1 (0.5) ^a	9.6 (0.2) ^d	0.96 (0.05) ^a	0.73 (0.02) ^a
VHDPE/ RHDPE/	50	2:1	24.1 (1.3) ^b	45.2 (0.9) ^c	6.3 (0.3) ^b	4.03 (0.16) ^d	2.15 (0.06) ^c
		1:1	28.3 (1.5) ^d	40.9 (1.3) ^b	6.7 (0.4) ^c	3.4 (0.09) ^c	2.01 (0.09) ^b
PB dust/BF		1:2	26.2 (1.4) ^c	47.8 (1.5) ^d	6 (0.4) ^a	3.15 (0.08) ^b	2.52 (0.07) ^d

a, b, c, and d represent data statistics ranking in Duncan's multiple range tests.

TABLE 4: Thermal expansion properties of HDPE and filled HDPE composites with combined fillers.

System	Filler content (wt%)	PB dust/BF ratio	LCTE (10 ⁻⁶ /°C)		
			20→60°C	60→30°C	-30→20°C
VHDPE/RHDPE	0	0	155.7 (4.5) ^d	154.7 (7.3) ^d	129.5 (1.8) ^d
VHDPE/ RHDPE/	50	2:1	118.1 (2.1) ^c	107.8 (5.5) ^c	97.2 (3.4) ^c
		1:1	77.3 (2.6) ^b	68.7 (1.1) ^b	60.7 (1) ^b
PB dust/BF		1:2	56.6 (1.0) ^a	50.2 (0.8) ^a	44.1 (2.6) ^a

a, b, c, and d represent data statistics ranking in Duncan's multiple range tests.

to be able to achieve a desirable dimensional stability for composites.

(4) The MDI remaining on PB dust surface could lead to the weak interface adhesion between combined fillers and matrix, resulting in a weak composite when PB dust is at a larger portion.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Haiyan Mao and Min Yu contributed equally to this work.

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