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Sandwich-structured wood flour/HDPE composite panels: Reinforcement using a linear low-density polyethylene core layer

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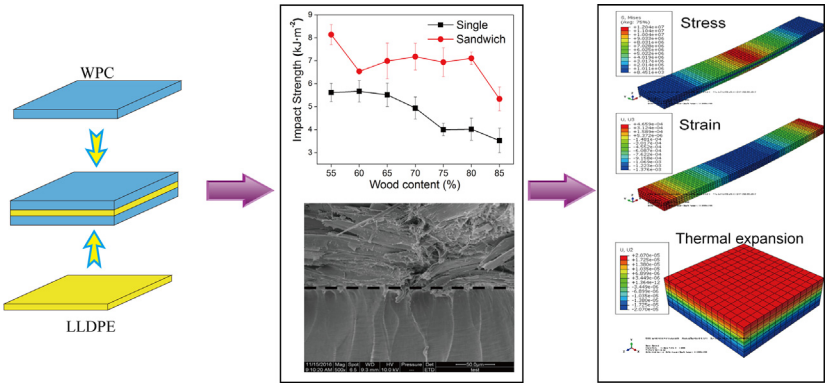
HIGHLIGHTS

- Sandwich-structured WPC panels were prepared comprising a linear LLDPE core layer.
- The LLDPE core layer improves the strength and toughness of the composites.
- Water uptake of the sandwich panels was half of the single layer panels.
- The LLDPE layer did not change the creep and relaxation behavior of the panels.
- Reinforcement of the LLDPE layer was more remarkable at high wood flour contents.

GRAPHICAL ABSTRACT



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ABSTRACT

Sandwich-structured panels, composed of two surface layers of wood flour/high-density polyethylene composite (WPC) and a core layer of linear low-density polyethylene (LLDPE), were prepared by hot-press. The single-layer WPC panels were used as controls, with wood flour contents ranging from 55 to 84%. The sandwich-structured panels showed an improvement in both flexural and impact strength of up to 42% and 77%, respectively, and water absorption was considerably reduced compared to the controls. The LLDPE core layer did not cause substantial change in creep and relaxation behavior, but resulted in an increase in the linear coefficient of thermal expansion.

1. Introduction

Wood flour/polymer composites (WPCs) have been widely utilized in construction, packaging, transportation and furniture products [1]. In the composite system, the use of stiff wood flour considerably improves the modulus of elasticity of the polymer matrix; however, the low-impact strength of the composites is problematic, due to insufficient interfacial adhesion between the polar wood flour and the non-polar polymer [2]. Consequently, this limits the applications of WPCs, such as in load-bearing items.

Strong hybrid fibers, such as glass fiber, Kevlar fiber and carbon fiber, have been incorporated in the structure of WPCs, substantially improving the impact strength of the resulting composites

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[3–5]. However, these hybrid fibers are not recyclable and may also damage the equipment during processing [2]. Coupling agents are another means of improving the impact strength, by enhancing the interfacial adhesion between wood flour and matrix [6–8]. Most established coupling agents, such as aminosilane and maleic anhydride grafted polyolefin, can limitedly improve (approximately 20–30%) the impact properties of the resulting composites [6,9,10].

Proper structural design can also improve the impact strength of materials. A well-known example is the sandwich-structured material comprising a lightweight core between two stiff surface layers [11,12]. For example, carbon fiber reinforced epoxy sandwich panels, with either polypropylene foam or aluminum honeycomb in-between, exhibited an increase in impact of approximately 10 and 20%, respectively, compared to the unfilled panels [13]. Another sandwich-structured material is bulletproof glass, laminated with glass/polymer composite. Bulletproof glass generally contains laminated glass layers, such as soda-lime silicate, borosilicate glass and sapphire windows, and a flexible polymeric core layer that can be polyvinyl butyral, polyurethane, polycarbonate or polyester [14–16].

According to the findings stated above, we hypothesized that a flexible polymeric thin layer as core layer may also improve the impact strength of WPC. In our beforehand work, we used both HDPE and LLDPE as the core layer of the sandwich-structured composites. The preliminary results showed lower reinforcement efficacy of HDPE than the LLDPE. Therefore, the objective of this study focuses on designing a sandwich-structured WPC panel composed of two surface layers of wood flour/high density polyethylene (HDPE) and a core layer of linear low-density polyethylene (LLDPE). The effects of the sandwich structure on the properties of the resulting composite, such as impact strength, creep and relaxation behavior, and water adsorption, were systematically determined, using single-layer WPC panels as comparison controls.

2. Materials and methods

2.1. Materials

HDPE (5000s) and LLDPE (7042) were obtained from Petrifaction Company (Daqing, China). HDPE had a density of 0.95 g cm^{-3} and a melt flow rate of 0.90 g $(10\ min)^{-1}$. LLDPE had a density of 0.92 g cm^{-3} and a melt flow rate of 2.0 g $(10\ min)^{-1}$. Dry poplar wood flour (*Populus adenopoda* Maxim.) was prepared in-house, with particle size ranging between 40 and 80 mesh. Both maleic-anhydride grafted polyethylene (MAPE) and lubricant (stearic acid), as additives, were supplied by Rizhisheng Company (Nantong, China). MAPE had a maleic anhydride grafting ratio of approximately 1% and melt flow rate of 1.7 g $(10\ min)^{-1}$. The stearic acid (#1801) had a density of 0.85 g cm^{-3} and a melt point of 65 °C.

2.2. Preparation of the single layer and sandwich structural panels

Prior to blending, wood flour was dried in an oven at 103 °C for 24 h and the dried wood flour had a moisture content of 1–2%. HDPE, dry wood flour, MAPE and lubricant were compounded, in a specific ratio, using a twin-screw extruder, at temperatures of 145 to 165 °C, to produce granules (Table 1). The WPC granules and LLDPE were individually hot-pressed into a 1.5 and 1 mm layer, respectively. Two WPC layers, as surface layers, and one LLDPE layer, as core layer, were laminated and hot-pressed into a 4 mm-thick sandwich panel. As comparative controls, 4 mm WPC panels were also prepared. The temperatures of hot-press for WPC surface and core layers were 185 °C and 165 °C, respectively, and the pressure was 12.5 MPa. The final size of the target panels was 160 mm × 160 mm × 4 mm (length × width × thickness).

Table 1
Weight fraction of the WPC panels (wt%).

Sample[a]	Wood flour	HDPE	MAPE	Lubricant
WP55	55	40	3	2
WP60	60	35	3	2
WP65	65	30	3	2
WP70	70	25	3	2
WP74	74	20	4	2
WP79	79	15	4	2
WP84	84	10	4	2

[a] W and P represent the wood flour and HDPE, respectively, and the number behind P indicates the weight content of the wood flour.

2.3. Characterization of the sandwich structural panels

2.3.1. Scanning electron microscopy (SEM) analysis

The samples were frozen in liquid nitrogen and then quickly impact-fractured. The fractured surfaces were sputtered with a thin layer of gold and observed using a scanning electron microscope (Quanta 200; FEI Co., USA), operated at an acceleration voltage of 12.5 kV.

2.3.2. Mechanical test

Samples, measuring 80 mm × 10 mm × 4 mm, were cut from the panels and used to test the impact strength in the unnotched mode according to ASTM D6110, using an impact tester (JC-5; Chengde Jingmi Testing Machine Co., Ltd, China). The flexural properties of samples measuring 80 mm × 13 mm × 4 mm, were tested according to ASTM D790, using a universal electromechanical testing machine (CMT5504; MTS Systems Co., Ltd, China); the specific strength and specific modulus were also calculated based on the sample density. For each formulation, 10 replicates were tested.

2.3.3. Finite element analysis

The finite element software Abaqus 6.13 was used for the numerical analysis of flexural stress and thermal expansion behavior of the single-layer and sandwich-structured samples. For simplicity, top WPC layers and the LLDPE core layer were assumed to be the isotropic material, respectively. The dimensions of samples used in the geometrical model were identical to those used for flexural and thermal expansion testing. The parameters of WPC surface layers and LLDPE core layer, used for finite element analysis, were given in Table 2. Young's modulus (tensile mode) and shear modulus were measured using a universal electromechanical testing machine according to ASTM D638. Poisson ratio was calculated by Young's- and shear-modulus according to a reported method [17]. Density of WPC and LLDPE was calculated by the weight dividing volume. Linear coefficient of thermal expansion (LCTE) was measured using a thermal mechanical analyzer (Q400; TA Instruments Inc, USA).

Table 2
The measured parameters of WPC layer and LLDPE core layer at 25 °C used for the finite element analysis.

Type	Young's modulus (GPa)	Poisson ratio –	Density (g cm^{-3})	LCTE (30 → 60 °C) (10^{-6} $°C^{-1}$)
WPC layer	2.0	0.30	1.2	160
LLDPE layer	0.11	0.39	0.92	392