



Mechanical, thermal expansion, and flammability properties of co-extruded wood polymer composites with basalt fiber reinforced shells



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ARTICLE INFO

Article history:

Received 12 December 2013

Accepted 2 April 2014

Available online 12 April 2014

Keywords:

Basalt fiber

Co-extrusion

Mechanical properties

Thermal expansion

WPC

ABSTRACT

Basalt fiber (BF) filled high density polyethylene (HDPE) and co-extruded wood plastic composites (WPCs) with BF/HDPE composite shell were successfully prepared and their mechanical, morphological and thermal properties characterized. The BFs had an average diameter of 7 μm with an organic surfactant surface coating, which was thermally decomposed at about 210 °C. Incorporating BFs into HDPE matrix substantially enhanced flexural, tensile and dynamic modulus without causing a noticeable decrease in the tensile and impact strength of the composites. Micromechanical modeling of tensile properties for the BF/HDPE composites showed a good fit of the selected models to the experimental data. Compared to neat HDPE, BF/HDPE composites had reduced linear coefficient of thermal expansion (LCTE) values. The use of the pure HDPE and BF/HDPE layers over a WPC core greatly improved impact strength of core-shell structured composites. However, the relatively less-stiff HDPE shell with large LCTE values decreased the overall composite modulus and thermal stability. Both flexural and thermal expansion properties were enhanced with BF reinforced HDPE shells, leading to well-balanced properties of core-shell structured material. Cone calorimetry analysis indicated that flammability performance of core-shell structured composites was improved as the BF content increased in the shell layer.

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1. Introduction

During the past decades, wood plastic composites (WPCs) have become a successful commercial building material with an increasing market potential. WPCs consist of varying contents of wood, plastics and additives, and are processed by thermoplastic shaping techniques such as extrusion, injection molding, and compression molding. The main applications of WPCs are decking, railing, fencing, window and door frames, and playground equipment [1]. These outdoor applications expose WPCs to moisture, fungi, freeze–thaw actions, and ultraviolet light in sunlight, which strongly affect their durability. Some previous studies have examined the weathering, biological and fire resistance of WPCs and their associated degradation processes. The results showed that WPC degradation in outdoor environments occurred in forms of mechanical property loss, color change and loss in weight, and controlling moisture absorption was the key to control the

degradation that occurred during weathering and fungal attack [1,2]. Various fire retardant formulations and fiber treatment techniques have been developed to enhance fire resistance of WPCs and other natural fiber polymer composites e.g., [1,3,4]. Effort has been made to use natural fibers to replace the synthetic fibers in improving charring and thermal stability of polymer-based composites [4].

To meet the requirement for practical use especially in structural engineering, the fundamental performance of WPCs needs to be carefully investigated based on the chemical component changes and formulation optimization, as well as a design that fully takes advantage of these capabilities. Core-shell structure design achieved through the coextrusion technique is an effective way to provide a protective shell layer over regular WPCs, helping improve their durability and reduce material and production cost [5,6]. Coextrusion processing involves extruding two dissimilar materials into a single profile. Through combining molten multiple layers with various properties into one profile, coextruded products with better properties such as water resistance, air entrapment, oxygen barrier, and increased toughness can be

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obtained [6–8]. The shell or cap layer plays an important role in modifying the overall composite properties. For example, it has been shown that different shell thicknesses [6], and material compositions [9,10] had notable effects on mechanical and thermal properties of co-extruded WPCs.

The shell layer in co-extruded WPCs usually consists of thermoplastic matrix and reinforcing fillers. In general, the fillers in fiber-polymer composites help provide composites with relatively higher specific stiffness and strength, and lower the material cost at the same time. Glass fibers with good mechanical properties and carbon fibers with a high level of thermal resistance and strength are two main enhancing fibers for fiber reinforced polymer composites [1]. However, the disadvantages of skin irritation and high processing cost for glass and carbon fibers, respectively, have limited their extensive applications. Natural fibers offer significant environmental and processing advantages, but are very sensitive to thermal and hygroscopic loads with limited mechanical properties due to the difficulty in fiber alignment, small fiber dimension, and poor interface strength [11].

Application of basalt fibers (BFs) could be a possible solution for the problem due to the potential low cost of this fiber as well as good mechanical performance. BFs with basic chemical components of SiO_2 , Al_2O_3 , CaO , MgO , K_2O , Na_2O , Fe_2O_3 and FeO [12] are produced from common volcanic rock. BFs are biologically inert as well as environmentally friendly and can be used in composites and other materials for some aggressive environments [13,14]. Czigány [15] investigated the strength properties of short BFs in comparison with glass and carbon fibers. The results showed that the tensile strength of BF was 568 ± 267 MPa and its tensile modulus was 60.4 ± 18.9 GPa. With high mechanical performance, outstanding heat resistance, good sound insulation properties, excellent resistance to chemical attack and low water absorption, as well as lower cost, BFs have attracted more and more attentions as a potential reinforcing agent for fire-resistant thermoplastic and thermoset matrix composites, oil well casing cement, and drilling fluid for lost circulation control [16–18]. However, the use of BFs in co-extruded WPC has not been attempted so far.

The objectives of this study were: (a) to determine some basic properties of the selected commercial BFs; (b) to develop BF/HDPE shell materials and evaluate their thermal-mechanical properties as a function of BF weight content in the HDPE matrix; and (c) to study the effect of developed shell material on mechanical and thermal performance of co-extruded WPCs. It is important to analyze the influence of shell material formulation on overall composite performance in order to provide a fundamental guidance for designing high-performance co-extruded WPCs with reduced material costs.

2. Experimental details

2.1. Materials

BFs with a density of 2.6 g/m^3 were obtained from CETCO Co. The fibers were surface treated by a specially formulated surfactant during manufacturing process and specific formulation of the coating is, however, unknown. HDPE (AD60-007) pellets, which had a density of 0.963 g/cm^3 , a melt index of 0.73 g/10 min (190°C , 2.16 kg) and a softening temperature of 127°C , was provided by ExxonMobile Chemical Co. (Houston, TX, USA). Pine wood flour (WF) with a 40-mesh particle size was supplied by American Wood Fibers Inc. (Schofield, WI, USA). Lubricant (TPW 306) from Struktol Co. (Stow, OH, USA) was used to improve the processing of WPC profile. A maleated polyethylene (PE-g-MA) coupling agent (G2608) with melt index of 8 g/10 min (190°C , 2.16 kg) and an acid number of 8 mg KOH/g was purchased from Eastman Chemical Co. (Kingsport, TN, USA).

2.2. Sample preparation

2.2.1. BF reinforced HDPE

BF-filled high density polyethylene (BF/HDPE composites) was manufactured by one-step melt compounding. Experimental design included five blends with BF/HDPE ratios of 0/100, 10/90, 20/80, 30/70, and 40/60 wt%. A Leistritz Micro-27 co-rotating parallel twin-screw extruder (Leistritz Corporation, Allendale, NJ, USA) with a screw speed of 50 rpm was used to blend BF/HDPE composites. The extrusion temperature profile ranged from 160°C to 182°C . The extrudates were continuously drawn (through neck formation) with a BT 25 pelletizer (Scheer Bay Co., Bay City, MI, USA) and then pelletized into granules.

Standard test samples for mechanical properties were made through injection molding, using a Plus 35 injection system from Batenfeld of American Inc. (South Elgin, IL, USA). The blends were injection molded at injection temperatures of 180 – 185°C and mold temperatures of 73 – 80°C . Virgin HDPE control samples were directly molded at injection temperature of 180°C and mold temperature of 73°C .

2.2.2. Co-extruded WPCs with BF reinforced HDPE shells

The composites were formulated with the one core type in combination with different BF contents in the HDPE shells. The formulation for the core was Wood: HDPE: Talc: Lubricant: MAPE = 55: 33: 5: 5: 2 wt%. Four different BF loading levels (i.e., 0, 10, 20, and 30 wt% of the total weight of shell) were used to fabricate co-extruded WPCs with different shells. Extruded (core only) composites with the same formulation as the core material of the co-extruded composites were used as control group.

The composites were manufactured with a pilot-scale co-extruded system [6] consisting of a Leistritz Micro-27 co-rotating parallel twin-screw extruder (Leistritz Corporation, Allendale, NJ) for core and a Brabender 32 mm conical twin-screw extruder (Brabender Instruments Inc., South Hackensack, NJ) for shell. A specially-designed die with a cross-section area of $13 \times 50 \text{ mm}$ and a vacuum sizer were used in this system. The co-extruded profiles passed through a 2 m water bath with water spraying using a down-stream puller. Processing temperatures for core systems were controlled between 155°C and 170°C . Processing temperatures for shells varied from 150°C to 170°C according to different shell formulations.

3. Testing and characterization

3.1. Basic properties of BFs

The morphology of the original BF were studied by a Hitachi S4800 (Hitachi Ltd., Tokyo, Japan) scanning electron microscope (SEM). The surfaces of the selected BFs were coated with gold to improve the surface conductivity before SEM observation and observed at an acceleration voltage of 15 kV. Fiber diameter was determined using the Image J software based on 200 fibers randomly selected from the SEM pictures. To show the original surfactant coating on the fiber surface, BFs samples were heated at 450°C for one hour and Fourier Transform infrared spectroscopy (FTIR) analyses (Nicolet Nexus 670-FT-IR, Thermo Electron Corporation, Gormley, Canada) for both original and heat treated BFs were carried out at a resolution of 4 cm^{-1} and a minimum of 60 scans. Thermogravimetric analysis (TGA) was conducted using a TA Q50 analyzer (TA Instruments, New Castle, DE, United States) to study thermal decomposition of the coating and BFs. Samples of about 10 mg were heated from room temperature to 600°C at a rate of 10°C/min in a N_2 atmosphere. The weight-loss rate was obtained from derivative thermogravimetric (DTG) data. The onset

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