



Alternative polymeric matrices for wood-plastic composites: Effects on mechanical properties and resistance to natural weathering

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HIGHLIGHTS

- Five types of plastic as the matrix phase in WPCs were compared.
- ANOVA, Tukey's multiple range comparison, and *t*-test were applied.
- The plastic type was found to significantly affect the mechanical properties of WPC.
- Mechanical property losses from weathering were the least for WPCs from PS and PP.

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ABSTRACT

The influences of plastic matrix on mechanical properties (flexural and tensile properties) of wood-plastic composites (WPCs) were investigated. WPCs were prepared with five types of plastic as the matrix phase, namely high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS). Rubberwood flour was used as reinforcing filler. Additionally, maleic anhydride, UV-stabilizer, and paraffin wax were used as coupling agent, ultraviolet stabilizer and lubricant, respectively. The WPCs were produced in two stages: mixing in an internal mixer, and compression molding. WPCs from PS and PP exhibited higher mechanical properties whereas LDPE, HDPE, and PVC gave lower values. In particular LDPE gave consistently the poorest mechanical properties to WPCs. Moreover, the WPCs with PS and PP had the smallest losses of mechanical properties from natural weathering, while LDPE would again be the poorest choice in this respect. These results indicate that WPCs from PP and PS are the best alternatives for applications requiring resistance to natural weathering (exposure to ultraviolet and humidity) or with high mechanical loading (stresses).

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1. Introduction

Wood-plastic composites (WPCs) are becoming popular materials in various industries, such as in construction industry (exterior decking, railing, fencing), automotive industry (seat backs and headliners), and in infrastructure applications (boardwalk) [1]. This is due to many advantages such as recyclability, low density, low cost, low maintenance, good mechanical properties, and environmental friendliness [2]. Several recent studies on this type of composites have sought to improve their properties. However, the mechanical properties of WPCs are dependent on many factors, such as wood flour content, wood species, coupling agent, and plastic matrix [3]. Najafi et al. [4] studied the mechanical properties of WPCs with high density polyethylene (HDPE) or polypropylene (PP) as the matrix phase, and reinforced with sawdust filler.

The results show that PP gave higher strength than HDPE due to its better strength and stiffness. The results of the flexural strength and modulus significantly increased 13% and 30%, when the HDPE content increased to 50%. In addition, the tensile strength statistically decreases 19% when the recycled PP content increases to 50%, whereas for HDPE composites this decrease is slight. Mijiyawa et al. [5] investigated the tensile properties of WPCs with PP matrix reinforced by 30 wt% birch and 40 wt% aspen fibers, with a view to gear applications. The composites exhibited higher tensile modulus than high-performance plastics for gears applications. Lisperguer et al. [6] studied WPCs with polystyrene (PS) and wood flour (*pinus radiata*). The results obtained show that in general, the mechanical properties, including flexural, tensile and impact properties, improved with wood flour content. The tensile modulus showed a decreasing trend with higher wood flour contents. The best results for the Izod impact strength were for the 30 wt% wood flour and 70 wt% recycled PS. Li et al. [7] studied the mechanical and thermal properties of WPCs from low density polyethylene

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(LDPE) reinforced with bamboo charcoal. The flexural and tensile properties were improved due to the full encapsulation of bamboo charcoal in the LDPE matrix, due to strong interfacial interactions, whereas the impact strength decreased with bamboo charcoal loading. Jeamtrakul et al. [8] studied the influences of wood content and glass fiber reinforcement on mechanical properties of WPCs from polyvinyl chloride (PVC). The flexural properties were found to improve with wood content. The addition of glass fiber also increased the flexural modulus and the flexural strength at 52–129 wt% and 21–93 wt% of WPCs, respectively.

In outdoor applications the WPCs are exposed to natural weathering by rain and ultraviolet sunlight, which degrades the physical and mechanical properties of WPCs [9]. Contributing factors include changing crystallinity in the matrix phase, oxidation of WPC surfaces, and interfacial degradation caused by moisture absorption and ultraviolet radiation [10,11]. Many studies have assessed the resistance of WPCs to natural weathering, in various applications. Te-Hsin et al. [12] investigated the optimal composition of PP and wood flour for different periods of outdoor exposure, and analyzed effects of the loading level on physical and mechanical properties. WPCs with 40 wt% plastic content had degraded physical and mechanical properties after natural weathering. In contrast plastic contents exceeding 50 wt% gave improved resistance to natural weathering. Taib et al. [13] investigated the effects of natural weathering for 2000 h on the properties of HDPE and wood flour composites. Loss of flexural modulus was observed after natural weathering due to micro-cracks on the WPC surfaces that degraded stress resistance. Lopez et al. [14] studied the effects of humidity, temperature, and ultraviolet light exposure on the performance of natural fiber and plastic composites. High humidity was the main determinant of loss of flexural properties.

Despite the many studies in the field of WPCs the influences of various polymeric matrices on their natural weathering are not well understood. Therefore, the aim of this research was to study influences of choice of polymer matrix on the mechanical properties and weathering. The five alternative polymers included were LDPE, HDPE, PVC, PP, and PS. Additionally, rubberwood flour (RWF), maleic anhydride (MA), UV-stabilizer, and paraffin wax were used as reinforcement, coupling agent, ultraviolet stabilizer (UV), and lubricant (Lub), respectively.

2. Experiments

2.1. Materials

The WPCs were based on five alternative polymers as the matrix phase, namely LDPE, HDPE, PP, PVC, and PS purchased from Valence Hitech Co., Ltd (Pathumthani, Thailand). The RWF was obtained from a local rubberwood factory (Songkhla, Thailand) for reinforcing filler. The three main components in RWF are cellulose (39%), hemicellulose (29%), and lignin (28%) [15]. To eliminate moisture, the RWF was dried at 105 °C for 8 h in a hot air oven. Then, the particle size was controlled by sieving through a 50–70 mesh (210–297 µm) standard sieve. This particle size range reportedly provides near optimal mechanical properties to the WPCs [16,17]. Additionally, MA was supplied by Sigma-Aldrich (Thailand) Co., Ltd. The UV-stabilizer was supplied by TH Color, Ltd. (Samutprakarn, Thailand). Lastly, the paraffin wax was obtained from Nippon Seiro Co., Ltd. (Yamaguchi, Japan).

2.2. Wood-plastic composite preparation

The WPCs were produced in two stages, namely mixing in an Internal Mixer (Chareon Tut Co., Ltd., Thailand) and compression molding in a machine for that purpose (N.T. Engineer, Thailand).

The formulation of WPCs was done on the basis of prior literature, where the typical plastic content is in the range 40–60 wt% and 3–5 wt% of coupling agent is added [8,12,18,19]. However, Adhikary et al. and Hosseinihashemi et al. reported that using 3 wt% coupling agent improved the mechanical and physical properties of WPCs [20,21]. Also Mijiyawa et al. corroborate that 3 wt% level of coupling agent can enhance the mechanical properties of WPCs [5]. Therefore, the coupling agent content 3 wt% was selected in the current study. Furthermore, Homkhiew et al., found that the optimal composition of WPCs from recycled polypropylene and rubberwood flour had plastic content 50.3 wt%, UV 0.2 wt%, and Lub 1.0 wt% [22]. Based the reviewed literatures, the formulation and manufacturing conditions of this study were chosen as those tabulated in Table 1. In WPC manufacturing, all the ingredients were added into the chamber of the internal mixer to compound the materials, and after mixing were transformed to WPC pellets by a pelletizing grinder. Subsequently the WPC pellets were again dried to eliminate moisture, at 105 °C for 8 h in a hot air oven. WPC panels were then manufactured by compression molding at 140–200 °C, pressure 1000–2500 psi, and rotor speed 50–120 rpm for 10–20 min, depending on the plastic type [5,6,8,12]. Then the WPC panels were machined to test specimens conforming to standards of American Society for Testing and Materials (ASTM).

The three levels of plastic content used were 40, 50, and 60 wt% while the wood flour content also had three levels, namely 35.8, 45.8, and 55.8 wt%. The additive agents including MA, UV, and Lub were fixed at 3, 0.2, and 1 wt%, respectively. As an example of labelling of the WPC formulations, the specimen code 40LDPE55.8RWF indicates this sample had 40 wt% LDPE and 55.8 wt% RWF; and the fixed amounts 3 wt% MAPP, 0.2 wt% UV, and 1 wt% Lub that were not varied by case.

2.3. Testing

2.3.1. Flexural testing

The flexural properties of WPCs were determined according to ASTM D790-92 standard with an Instron Universal Testing Machine (Model 5582 from Instron Corporation, Massachusetts, United States of America), as shown in Fig. 1(a). Five specimens were prepared from each WPC panel, with dimensions of 4.8 mm × 13 mm × 100 mm. The cross-head speed was 2 mm/min with span length 80 mm. All specimens were conditioned in an incubator under controlled conditions at 23 °C and 50%RH for 40 h. The test conditions were similar, 23 °C and 50%RH. The flexural properties can be calculated using

$$\text{Ultimate flexural strength (MPa)} = \frac{3P_{\max}L}{2bd^2} \quad (1)$$

where P_{\max} is the maximum load (N), L is the span (mm), b is the width of the specimen (mm), and d is the thickness of the specimen (mm). The flexural modulus can be calculated from

$$\text{Flexural modulus (MPa)} = \frac{P_{pl}L^3}{4\delta_{pl}bd^3} \quad (2)$$

where P_{pl} is the load increment in the linear range (N), L is the span (mm), δ_{pl} is the distance increment from bending in the linear range (mm), b is the width of the specimen (mm), and d is the thickness of the specimen (mm).

2.3.2. Tensile testing

The tensile properties of WPCs were evaluated by an Instron Universal Testing Machine (Model 5582 from Instron Corporation, Massachusetts, United States of America) according to the standard ASTM D638-99, as shown in Fig. 1(b). The cross-head speed was 5 mm/min. Five specimens were prepared from each WPC panel

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