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Characterizing water sorption and diffusion properties of wood/plastic composites as a function of formulation design

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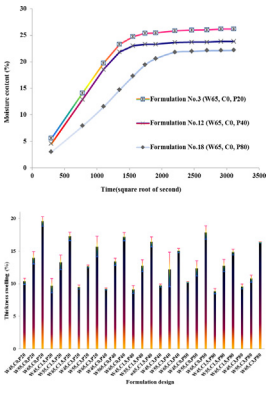
HIGHLIGHTS

- Water resistance of wood/plastic composite (WPC) depended on formulation design.
- WPC with low wood content and small wood particles required up to 84 weeks to reach its saturation point.
- Water sorption process in WPCs followed kinetics and mechanisms described by Fick's law.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the water sorption and diffusion properties of wood/plastic composites (WPCs) as a function of formulation design were investigated. Composites with different amounts of wood, coupling agent and high density polyethylene (HDPE) were produced by profile extrusion method. The time required to reach saturation point, moisture contents at saturation point, diffusion coefficients and thickness swelling were measured for all composites. The results showed that the response of WPCs towards water exposure is heavily dependent on formulation design. The time required to reach saturation point varied between four weeks and 84 weeks. Such a big difference reflected magnitude of formulation design on water resistance of WPCs. Composites with large particles demonstrated weak performance towards water. Any increase in wood content led to an increase in water absorption. Coupling agent reduced water absorption. Diffusion coefficients and thickness swelling were also affected by wood and coupling agent contents, and wood particle size. The highest diffusion coefficients and thickness swelling were found in composites with high wood contents and large particles. Studying the water sorption process in WPCs showed that the process follows kinetics and mechanisms described by Fick's law.

1. Introduction

Plastic and wood industries had never worked together before the introduction of wood/plastic composites (WPCs). The industries had seemed not to have any common ground. Economic and environmental issues made the industries work together and have a common ground. WPCs pose the features of both wood and polymer. High strength and stiffness, and long spans in built-up members of wood and, durability and protection in weather-exposed applications of the matrix (polymer) give WPCS unique properties. When the Mobile research team's efforts to find

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a way to recycle polyethylene grocery bags resulted in the introduction of WPCs (in early 1990s), nobody expected such a big market for natural fibers/plastic composites [1].

Wood and other natural fibers have some advantages over inorganic fibers enjoying a preeminent position in plastic industry currently. Low cost and density, renewable nature and high specific strength and modulus are just some to name. In spite of having considerable advantages, wood and other natural fibers have a big disadvantage, water absorption stemming from hydrophilic nature of natural fibers. The water absorption can potentially cause WPCs dimensional instability and mechanical properties loss. Such susceptibility to water led to extensive studies on improving the properties of WPCs through modification of the wood particles [2–8]. Although, composites filled or reinforced with natural fibers absorb water as reported by some researchers [9–16], the absorption is lower than for the conventional wood based composites like particleboard, fiberboard and OSB. The matrix (polymer) provides natural fibers with some kind of protection, but not entire protection.

In general, mechanical properties of WPCs decrease after water uptake, due to the effects of water molecules, which change the structure and properties of fibers, matrix and the interface between them. The absorbed water molecules reduce the intermolecular hydrogen bonding between cellulose molecules in fiber and establish intermolecular hydrogen bonding between cellulose molecules in fiber and water molecules, thereby reducing the interfacial adhesion between the fibers and matrix. The matrix structure can also be affected by the water uptake by process such as chain reorientation and shrinkage. When the fiber/matrix interface is accessible to moisture from the environment, the cellulose fibers tend to swell. This results in development of shear stress at interfaces that leads to the ultimate debonding of the interface [18–23].

Kaboorani et al. [16] found that mechanical loss caused by immersion in water was proportional to wood and coupling contents. The extent of mechanical loss was directly related to the amount of water absorption. Having high wood contents in the formulation could be translated to higher mechanical loss after water exposure.

The most important parameter for water sorption is the diffusion coefficient because it shows the ability of solvent molecules to penetrate inside the composite structure [19,24–25]. Recently published reports regarding the instability of wood/plastic composites (WPCs) towards water have raised some questions about the durability of WPCs [26–30]. Using WPCs on exterior applications is on the rise. As in the applications water exposure is highly expected, having knowledge on the topic of water sorption process and diffusion properties of WPCs are strongly felt.

More importantly, inclusion of more wood to the formulation of WPCs which is becoming common (up to 80%), renders the issue more problematic. Despite its importance, the topic has received less attention in comparison with mechanical properties. Any attempt to understand the role of formulation design (wood and coupling contents, and particle size) can lead to using proper formulation design with respect to the application of WPCs and using our resources more efficiently. The main objective of this study is to establish information concerning water sorption and diffusion properties of WPCs as a function of formulation design.

2. Materials and methods

2.1. Materials

High density polyethylene, Petrothene® LB 0100-00 with melt flow index of 0.50 g/10 min (measured according to ASTM D 1238) and density of 0.953 g/cc was supplied by Lyondell chemical company, Houston, TX. Wood flour (420, 250 and 177 μm maple flour) was purchased from American Wood Fibers Inc, Schofield, WI. Coupling agent polypropylene-maleic anhydride copolymer (MAPP), A-C® 950P was supplied by Honeywell Company, Morristown, New Jersey.

2.2. Methods

2.2.1. Compounding and processing

A 20-kg batch of each wood/HDPE composite formulation (Table 1) was mixed in a drum blender for 10 min. The mixture was then conveyed to the feed hopper of 55-mm counter-rotating conical twin-screw extruder (Cincinnati Milacron, Batavia, OH). A slit die, measuring 152.4 mm by 12.7 mm was attached to the extruder. During extrusion, the temperature of the barrel/screw and die were 163 and 171 °C and the screw rotational rate were 5 rpm for formulations No.1, 2, 4, 7,10,14,15 and 17, and 10 rpm for the others. After exiting the die, the extrudate was cooled with 20 °C water.

2.2.2. Water absorption

The water absorption test was conducted according to procedure described in ASTM D 570. Specimens required for the tests were cut from extruded materials. Specimens dimensions were: 76.2 mm long by 25.4 mm wide and 6.4 mm thick. Before immersion in water, the specimens were dried at 50 °C for 24 h to measure the dried weight. Intervals of water absorption and saturation point measurements were also according to ASTM D 570.

2.2.3. Thickness swelling

The thickness measurements were conducted by using the same specimens which were used in water absorption tests. The thickness of the specimens after spending 24 h in an oven with a temperature equal to 50 °C was considered as dried thickness. The thickness of the specimens was measured after 76 weeks in water. The thickness of specimens were measured by using a laboratory caliper with a precision of 0.1 mm. For calculation of thickness swelling the following equation was used:

$$TS\% = \frac{T_h - T_o}{T_o} \times 100$$

TS: thickness swelling
T_o: thickness of specimens in dry state
T_h: thickness of specimens after spending 76 weeks in water

2.2.4. Diffusion coefficients

Different models have been developed to describe moisture absorption of materials. As shown by Stamboulis et al. [22], Rangaraj and Smith [19], Espert et al. [8], Joseph et al. [15], Qingzheng and Shaler [31], and Ishak et al. [21], the process of water absorption by natural fibers/thermoplastic composites follows kinetics and mechanisms described by Fick's law. The characteristics of Fick's law of diffusion can be described as: (1) the absorption curves are linear in the initial stages, and (2) above the linear portion both absorption and desorption curves are concave to abscissa.

Moisture contents M_t as a function of square root of time for a typical Fickian process schematically given in Fig. 1 [21]. For a thin (thickness ≪ width) and long (thickness ≪ length) specimen, diffusion is actually one-dimensional.

The apparent diffusion coefficient (D_A) can be calculated according to Fick's law by using the following relation established by Springer [21]: