

EFFECTS OF ETHYLENE VINYL ACETATE CONTENT ON PHYSICAL AND MECHANICAL PROPERTIES OF WOOD-PLASTIC COMPOSITES

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To investigate the effects of different ethylene vinyl acetate (EVA) contents on the performance of wood plastic composites (WPCs) made from poplar wood flour (PWF) and high density polyethylene (HDPE), physical properties tests, mechanical properties tests, and scanning electron microscope (SEM) tests were employed. The thermal stability and functional groups of PWF treated by EVA were evaluated by thermogravimetric analysis (TGA), differential thermal analysis (DTA), and Fourier transform infrared spectroscopy (FTIR), respectively. The results showed that the hardness, water uptake, and thickness swelling of the WPCs was reduced with increasing content of EVA. The MOR and tensile strength of the WPC treated by 15% EVA content were enhanced by 17.48% and 9.97%, respectively, compared with those of the WPC without EVA. TGA results showed that the thermal stability of PWF treated by EVA was improved. FTIR analysis indicated that PWF was reacted and coated with EVA. SEM results showed that gaps and voids hardly existed in the sections of the WPCs treated by EVA. This research suggests that the flexibility and mechanical properties of WPCs could be improved by adding EVA. The best condition of EVA content could be 15%.

Keywords: Wood plastic composites; Ethylene vinyl acetate; Thermogravimetric analysis; Physical properties; Mechanical properties

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INTRODUCTION

Wood-plastic composites (WPCs) are important environmentally friendly materials used in the construction industry. They are popular for residential and outdoor applications, because they combine favorable performance and cost attributes that come with the use of wood (and non-wood agricultural fibers) with the processability of thermoplastic polymers (Smith and Wolcott 2006). Increasing attention has been focused on their industrial production in China, after WPC products had been used in the various constructions for public facilities, such as in the 2010 World Exposition.

It is only recently that extruded WPCs have entered the mainstream of the wood product industry and thus improved the WPCs properties and manufacture (Smith and Wolcott 2006). In the extrusion process, either a single screw extruder or a twin screw extruder can be employed for pilot scale tests in order to study the process of WPC fabrication. Although the new machines require stricter controlled condition of processing and more precise formulation of WPCs in comparison with what hot-press

machines do, extrusion is becoming the preferred industrial processing method. This is because extruded WPC products exhibit excellent appearance during the continuous processing. Thus, in the present work, extruders were employed to make WPCs.

It has been found in many studies that wood-fiber-filled plastic achieved higher mechanical properties than unfilled plastics (Wolcott 2003; Stark *et al.* 2004; Clemons and Ibach 2004; Stark 2006; Bengtsson *et al.* 2007). However, added wood fiber also increases the modulus of elasticity (MOE) of plastic matrix and thus increases the difficulty of process steps in the manufacture of WPCs.

To improve the extrusion process, ethylene vinyl acetate (EVA) could be used to reduce the MOE of WPCs. This is due to a low softening point and excellent flexibility of EVA (Yang *et al.* 2009; Weng 2010; Li *et al.* 2010). EVA was used as a polymeric plasticizer and also as an impact modifier in the study of Marathe and Joshi (2010), because polymeric plasticizers can be reader-processed easier without the disadvantages of low-molecular-weight plasticizers, which include leaching over a period of time (Marathe and Joshi 2010).

In the meantime, various species of wood fibers have been considered for use as reinforcing fillers in WPCs. Such fibers include wood fiber, rice hull, wheat straw, corn stem, sisal, flax, hemp, kenaf, jute, and oil palm empty fruit bunches (Jayaraman 2003; Arbelaiz *et al.* 2005; Panthapulakkal and Sain 2006; Santiagoo *et al.* 2011; Ismail *et al.* 2011). The usage of varied fibers expands the range of raw materials and the market of WPC products. However, a basic problem still exists. Problems related to incompatibility and immiscibility within WPCs is due to the fact that the polyolefin matrix material is typically non-polar and hydrophobic, whereas the lignocellulosic material is typically polar and hydrophilic (Santiagoo *et al.* 2011). Many researchers have been attempting to solve this problem by using three main methods, *i.e.* modifying plastic, modifying wood powder, and adding coupling agents (Yin and Ren 2002). Considering the cost and scale of production and the recent technology, the latter two methods are easier to achieve.

More than 40 kinds of coupling agents have been researched to improve the bonding properties of WPCs. They include silanes, titanates, aluminate, polypropylene glycol (PPG), poly [methylene (polyphenyl isocyanate)] (PMPPIC), and maleic anhydride grafted polymer (Colom *et al.* 2003; Qin *et al.* 2005; Marti-Ferrer *et al.* 2006; Kim *et al.* 2007). Ly and his followers employed elemental analysis, Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy, scanning electron microscopy (SEM), and contact angle measurements to investigate the surface functionalization of cellulose fibers treated by six kinds of coupling agents. They found that coupling agents could be used to improve the bonding of wood fiber and polymer. The achievement of the aim was due to the fact that the functional groups of coupling agents react with the cellulose surface and the remaining moieties of coupling agents are compatible with the polymer matrix. So coupling agents provide a covalent linkage between the matrix and the reinforcing elements, which enable WPCs to obtain an improved stress transfer (Ly *et al.* 2008).

EVA also has a carboxyl group that can react with the hydroxyl of cellulose and a polyvinyl group which could associate in a cooperative manner with the long chains of high density polyethylene (HDPE). So, EVA might be used to treat wood flour for improving the bonding of poplar wood flour filled HDPE composites. This work aimed to

find whether EVA could be used to reduce the MOE of WPCs in order to ease processing and improve mechanical properties of WPCs. Detailed studies were carried out to evaluate the effects of EVA content on performance of WPCs.

EXPERIMENTAL

Materials

HDPE Grade 5000S was obtained from Daqing Company of China National Petroleum Corporation with a melt index of 1.2 g/10min at 133°C and a density of 0.953 g/cm³. Poplar wood flour was supplied by Gaocheng Xingda wood flour factory in Hebei with a size over 100 mesh. EVA Grade 40W was obtained from Japan Mitsui Petrochemical Corporation with a melt index of 65 g/10min at 58°C and 40% vinyl acetate content. Stearic acid and stearic zinc were lubricants obtained from Xilong Chemical Company in Shantou and Jinke Institute of Fine Chemicals in Tianjin, respectively. Calcium carbonate was supplied by Xilong Chemical Company in Shantou. Formulations of poplar wood flour filled HDPE composites are given in Table 1.

Table 1. Formulations of Poplar Wood Flour Filled HDPE Composites

| Sample | HDPE (wt%) | Poplar wood flour (wt%) | EVA (wt%) | Stearic Acid (wt%) | Stearic Zinc (wt%) | Calcium Carbonate (wt%) |
|--------|------------|-------------------------|-----------|--------------------|--------------------|-------------------------|
| PWF | 34.60 | 51.90 | 0 | 1.56 | 1.56 | 10.38 |
| EVA-5 | 33.72 | 50.59 | 2.53 | 1.52 | 1.52 | 10.12 |
| EVA-10 | 32.89 | 49.34 | 4.94 | 1.48 | 1.48 | 9.87 |
| EVA-15 | 32.10 | 48.15 | 7.22 | 1.45 | 1.45 | 9.63 |
| EVA-20 | 31.35 | 47.03 | 9.40 | 1.41 | 1.41 | 9.40 |

EVA Treatment

Prior to compounding, poplar wood flour was dried in an oven at 120°C for 3h to reduce moisture. Four levels of EVA content were 5, 10, 15, and 20 wt% relative to the poplar wood flour. After EVA and the poplar wood flour were mixed, the EVA treatment reaction for the poplar wood flour was carried out in a twin screw extruder (Giant SHJ-20B, China) at 15Hz. The temperatures of five zones in the twin screw extruder were 60, 80, 90, 90, and 65°C in sequence.

WPCs Processing

Firstly, HDPE, stearic acid, stearic zinc, and calcium carbonate were mixed together. Secondly, the five different kinds of untreated and treated poplar wood flour were mixed with them, respectively. Then, the five different kinds of mixture were respectively granulated by the twin screw extruder at 15Hz. The temperatures of five zones in the twin screw extruder were 125, 145, 155, 155, and 130°C in sequence. Next, the five different kinds of granulations were processed by a single screw extruder (Giant SJ-45, China) at 6Hz. The temperatures of five zones in the single screw extruder were

125, 145, 155, 155, and 130°C in sequence. The cross section of the samples was 50 mm × 5 mm. Finally, the samples were cut according to the requirements of different tests.

Thermogravimetric Analysis (TGA)

The thermogravimetric behaviors of the poplar wood flour untreated and treated by EVA were characterized by a TGA instrument (Shimadzu TGA-600, Japan). The samples were placed in an oven at 90°C for 5h. The test temperature ranged from 40°C to 840°C with a heating rate of 10°C/min. The test was carried out under nitrogen atmosphere (20 mL/min) in order to prevent poplar wood flour from thermal oxidative degradations.

Differential Thermal Analysis (DTA)

The differential thermal behavior of the pure poplar wood flour was characterized by a TGA device (Shimadzu TGA-600, Japan). The samples were placed in an oven at 90°C for 5h. The test temperature ranged from 40°C to 840°C with a heating rate of 10°C/min. The test was carried out under nitrogen atmosphere (20 mL/min) in order to prevent poplar wood flour from thermal oxidative degradations.

Fourier Transform Infrared Spectroscopy (FTIR) Test

The samples were placed in an oven at 105°C until a constant weight was obtained. FTIR spectra of untreated and treated poplar wood flour were recorded using an infrared spectrometer (Nicolet 6700 FT-IR, USA) over the range of 400 to 4000 cm⁻¹. 32 scans were accumulated at a resolution of 4 cm⁻¹.

Shore Hardness Measurement

The shore hardness of the WPCs were measured by a durometer (TimeGroup TH210, China), according to GB/T 2411-2008 (Plastics and ebonite-Determination of indentation hardness by means of a durometer, China). Test specimen dimensions were 50 mm × 50 mm × 5 mm. At least 15 replicates of three samples were tested to obtain the average value for each sample, according to GB/T 24137-2009 (wood-plastic composites decorative boards, China).

Density Measurement

The dimensions of the WPCs were measured to 0.01 mm precision by use of a vernier caliper, and the mass of the WPCs was measured by balance with a resolution of 0.01 g, according to GB/T 17657-1999 (test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels, China). Test specimen dimensions were 150 mm × 50 mm × 5 mm. At least six replicates were tested to obtain the average value for each sample.

Density was calculated according to the following equation,

$$\rho = \frac{m}{a \cdot b \cdot h} \times 1000 \quad (1)$$

where ρ is the density of the sample (g/cm^3), m is the weight of the sample (g), a is the length of the sample (mm), b is the width of the sample (mm), and h is the thickness of the sample (mm).

Flexural Property Test

The flexural properties of the WPCs were measured by an electronic universal mechanical testing machine (ShiJin WDW-50D, China) controlled by a microcomputer, and the speed of the pressure-head was 10 mm/min, according to GB/T 1449-2005 (fiber-reinforced plastic composites-determination of flexural properties, China). Test specimen dimensions were 150 mm \times 27 mm \times 5 mm. At least six replicates were tested to obtain the average value for each sample.

Modulus of rupture (MOR) was calculated according to the following equation,

$$\sigma_f = \frac{3P \cdot l}{2b \cdot h^2} \quad (2)$$

where σ_f is the MOR of the sample (MPa), P is the maximum load of the sample (N), l is the span of the machine (mm), b is the width of the sample (mm), and h is the thickness of the sample (mm).

Modulus of elasticity (MOE) was calculated according to the following equation,

$$E_f = \frac{l^3 \cdot \Delta P}{4b \cdot h^3 \cdot \Delta S} \quad (3)$$

where E_f is the MOE of the sample (MPa), ΔP is the increment of the load in the initial straight segment (N), ΔS is the increment of the deflection in the same initial straight segment (mm), l is the span of the machine (mm), b is the width of the sample (mm), and h is the thickness of the sample (mm).

Tensile Property Test

The tensile properties of the WPCs were measured by an electronic universal mechanical testing machine (ShiJin WDW-50D, China) controlled by a microcomputer at the cross-head speed of 10 mm/min, according to GB/T 1447-2005 (fiber-reinforced plastic composites-determination of tensile properties, China). Test specimen dimensions were 150 mm \times 20 mm \times 5 mm. At least six replicates were tested to obtain the average value for each sample.

Tensile strength was calculated according to the following equation,

$$\sigma_t = \frac{F}{b \cdot d} \quad (4)$$

where σ_t is the tensile strength of the sample (MPa), F is the maximum load of the sample (N), b is the width of the sample (mm), and d is the thickness of the sample (mm).

Water Uptake Test

The water uptake tests of the WPCs were carried out by immersing the samples in distilled water at room temperature (20°C) for 24h, according to GB/T 17657-1999 (test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels, China). Test specimen dimension was 50 mm × 50 mm × 5 mm. At least six replicates were tested to obtain the average value for each sample.

Water uptake was calculated according to the following equation,

$$W = \frac{m_2 - m_1}{m_1} \times 100 \quad (5)$$

where W is the water uptake of the sample (%), m_1 is the original weight of the sample (g), and m_2 is the final weight of the sample (g).

Thickness Swelling Test

The thickness swelling tests of the WPCs were carried out by immersing the samples in distilled water at room temperature (20°C) for 72 h, according to GB/T 17657-1999 (test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels, China) and GB/T 24137-2009 (wood-plastic composites decorative boards, China). Test specimen dimensions were 50 mm × 50 mm × 5 mm. At least six replicates were tested to obtain the average value for each sample.

Thickness swelling was calculated according to the following equation,

$$T = \frac{h_2 - h_1}{h_1} \times 100 \quad (6)$$

where T is the thickness swelling of the sample (%), h_1 is the original thickness of the sample (mm), and h_2 is the final thickness of the sample (mm).

Scanning Electron Microscope (SEM) Test

The samples were placed in an oven at 105°C until a constant weight was obtained. The fracture surfaces of the untreated and treated WPCs were observed by a scanning electron microscope (Hitachi S-3400N II, Japan). Samples to be observed under the SEM were mounted on conductive adhesive tape, sputter coated with gold, and observed in the SEM using a voltage of 10 kV.

RESULTS AND DISCUSSION

Thermal Properties

Figure 1 shows the DTA and TGA curves of pure poplar wood flour. The TGA curve revealed that there were four main stages of the weight loss of the poplar wood flour. They were attributed to the loss of water, the thermal degradation of wood flour, the carbonization and calcination of wood flour, and the equilibrium of remainder.

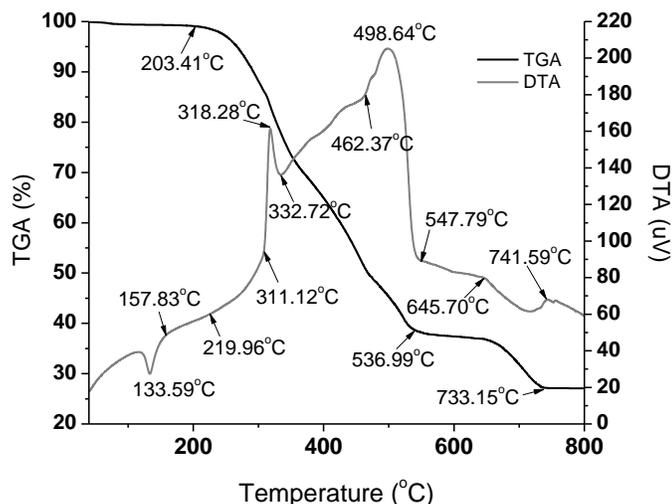


Fig. 1. DTA and TGA curves of pure poplar wood fiber (100 mesh)

According to Table 2, the range from 203.41°C to 536.99°C is a very important part for the thermal degradation of hemicellulose, cellulose, and lignin. In this study, poplar wood flour was treated by EVA. Because the poplar wood flour could be coated by EVA and the hydroxyl group of the poplar wood flour could be reacted with the carbonyl group of EVA, the thermal stability of the poplar wood flour treated by EVA would be improved. This hypothesis was also supported by results shown in Fig. 2 and Table 3.

Table 2. Characteristic Temperature of Wood Pyrolysis (Huang 1996)

| Type | Thermal Degradation | | Exothermal Reaction |
|---------------|---------------------|---------------|---------------------|
| | Initial Temp (°C) | End Temp (°C) | Reaction Temp (°C) |
| Hemicellulose | 200 | 260 | 220 |
| Cellulose | 240 | 350 | 275 |
| Lignin | 250 | 500 | 310 |

The DTA curve provided additional details related to the weight loss behaviors of the pure poplar wood flour. The poplar wood flour started the pyrolysis reaction at 157.83°C and reached equilibrium above 741.59°C. Below 157.83°C, the weight loss was mainly attributable to the loss of water containing absorption water and bound water in the wood flour. This interpretation is consistent with Huang's study in his book (1996). The observations in the range from 536.99°C to 733.15°C of the TGA curve might be reflective of the carbonization and calcination of poplar wood flour, because the residual of poplar wood flour was black at 550°C and was gray at 840°C in this research. And the range from 547.79°C to 741.59°C of the DTA curve also gave a fine correlative correspondence. Baileys and Blankenhorn (1982) also found that the woods of four species (red oak, southern yellow pine, black cherry, and hybrid poplar) were carbonized at final temperatures up to 700°C in a flowing nitrogen atmosphere at an average heating rate of 3°C/min.

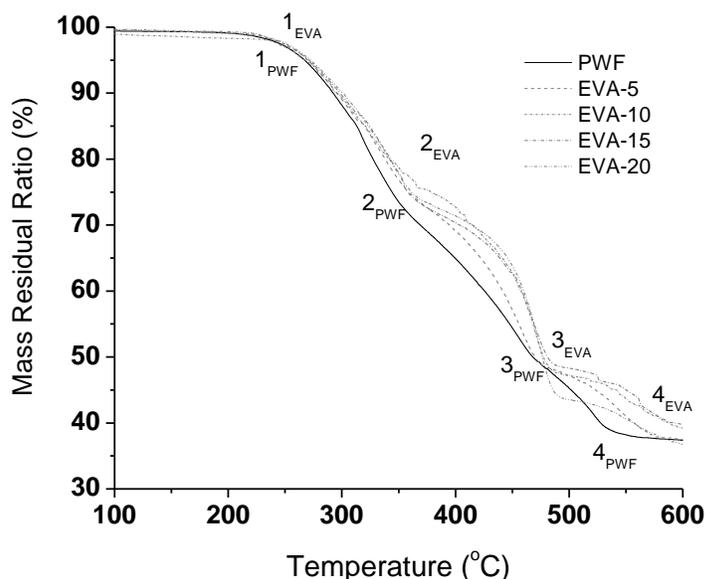


Fig. 2. Effect of EVA Content on thermal behavior of poplar wood flour

Figure 2 shows the pattern of the weight loss behaviors of the poplar wood flour with and without EVA. Both the curve of the poplar wood flour without EVA and the curves of the poplar wood flour with various EVA contents exhibited four inflection points. But, the TGA curves of the poplar wood flour treated by EVA had distinct difference during the thermal degradation of hemicellulose and cellulose compared with that of the pure poplar wood flour. Pyrolysis characteristic values of the poplar wood flour with and without EVA are shown in Table 3. The initial temperatures of the poplar wood flour with different EVA contents in the first weight loss process were delayed at least 22°C in comparison with that of the pure poplar wood flour without EVA. This suggested that the thermal stability of the poplar wood flour treated by EVA was improved.

Table 3. Pyrolysis Characteristic Values of Wood Flour With and Without EVA

| Type | The first weight loss process | | | The second weight loss process | | |
|--------|-------------------------------|---------------|-------------------------|--------------------------------|---------------|-------------------------|
| | Initial Temp (°C) | End Temp (°C) | Mass Residual Ratio (%) | Initial Temp (°C) | End Temp (°C) | Mass Residual Ratio (%) |
| PWF | 203.14 | 360.52 | 27.91 | 360.52 | 466.64 | 29.59 |
| EVA-5 | 225.07 | 367.83 | 24.14 | 367.83 | 476.28 | 33.82 |
| EVA-10 | 230.42 | 362.35 | 23.92 | 362.35 | 483.74 | 35.38 |
| EVA-15 | 234.21 | 367.43 | 23.62 | 367.43 | 487.96 | 37.07 |
| EVA-20 | 238.49 | 364.02 | 23.21 | 364.02 | 484.64 | 39.02 |

In Table 3, from 220°C to 370°C, the weight loss of the treated wood flour decreased with the increment of the EVA content. So the weight loss of the poplar wood flour might contribute to the total weight loss of the treated poplar wood flour. From 380°C to 500°C, the weight loss of the treated wood flour increased with the increment of the EVA content. So the weight loss of EVA might contribute to the total weight loss of the treated poplar wood flour. This indicated that the poplar wood flour might have reacted with EVA. This hypothesis will be supported by infrared spectroscopy analysis. Similar findings were reported by Qi *et al.* who employed infrared, TGA, and SEM to investigate poplar wood flour treated by EVA (Qi 2008).

Chemical Properties

Specific absorption peaks can be used to identify particular chemical groups in the FTIR spectra. Figure 3 shows the spectra of the pure poplar wood flour (PWF), the poplar wood flour with 5% EVA content (EVA-5), the poplar wood flour with 15% EVA content (EVA-15), and pure EVA (EVA). In the spectrum of PWF there was a strong stretching vibration band of hydroxyl group at 3391 cm^{-1} , a moderate stretching vibration band of methylene group at 2912 cm^{-1} , an absorption band of C-O at 1024 cm^{-1} , and the weak absorption band of carbonyl groups from 1600 cm^{-1} to 1650 cm^{-1} , representing characteristic peaks of cellulose and lignin.

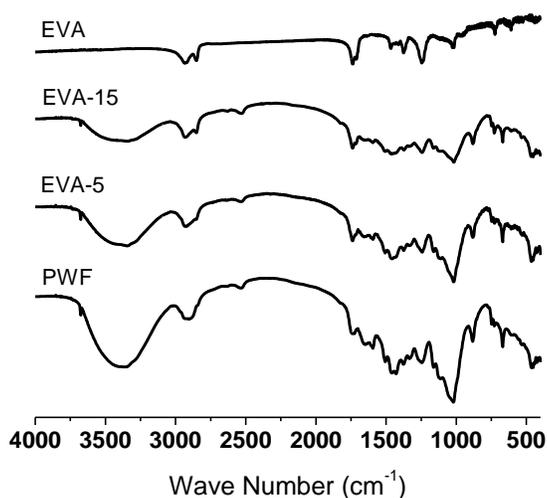


Fig. 3. FTIR of pure wood flour, wood flour with 5% EVA, and wood flour with 15% EVA

Compared to the spectra for PWF and EVA, the spectra for EVA-5 and EVA-15 showed that the strong stretching vibration band of carbonyl group at 1743 cm^{-1} , the absorption band of methyl group at 2940 cm^{-1} , and the absorption band of methylene group at 2850 cm^{-1} were related to characteristic peaks of EVA. It can be concluded that the poplar wood fiber was coated by EVA.

Compared to the spectrum of PWF, the spectra for EVA-5 and EVA-15 did not exhibit the strong stretching vibration band of hydroxyl group at 3391 cm^{-1} . This suggested that the hydroxyl group of the poplar wood flour was reacted with the carbonyl

group of EVA. This reaction would reduce the polarity of the poplar wood flour and increase the compatibility between the poplar wood flour and HDPE. It would be represented by the increasing mechanical properties and the decreasing water uptake properties.

Hardness

Figure 4 shows that hardness of the WPCs decreased with increasing content of EVA. Decreasing hardness was due to the soft and flexible property of EVA (Yang *et al.* 2009) and the decreasing weight fraction of poplar wood flour. In this experiment, the WPC products become easier to flex by increasing content of EVA. This suggests that the flexibility of the WPCs was improved by adding EVA.

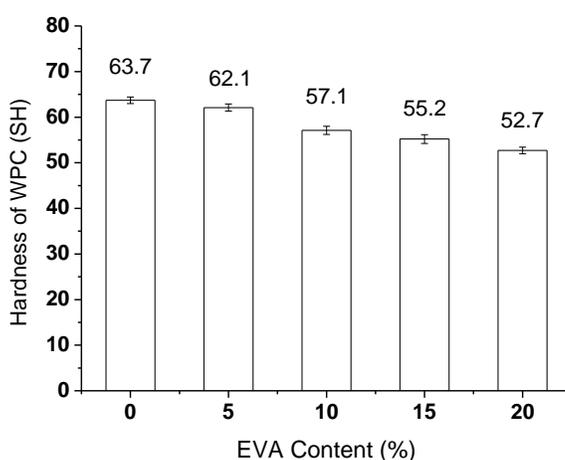


Fig. 4. Effect of EVA content on hardness of WPCs

But, it could not be concluded that the process of extrusion also followed the same tendency. Since EVA is a strong adhesion resin (Weng 2010), the extruding pressure became higher by increasing content of EVA in this research. An attempt was made to process WPC with 25% EVA content, but the process could not be completed successfully. Because the extrude pressure was so high, the machine ceased to run.

Density

Figure 5 shows that the densities of the WPCs were hardly influenced by the change of EVA contents. Bledzki and Faruk (2004) found a similar result when they compared injection and extrusion WPCs made from hardwood powder and a polyethylene matrix. In their study, the tensile strength of the injection products was higher than that of the extrusion products. However, the densities of both products were similar (Bledzki and Faruk 2004). Therefore, it might be concluded that the density of WPCs was only affected by the formulation, especially the ratio of wood flour to plastic. The density of WPCs with the same formula under the same process condition would have no obvious difference. Also, the density of WPCs would be decreased by the decreasing weight fraction of wood flour.

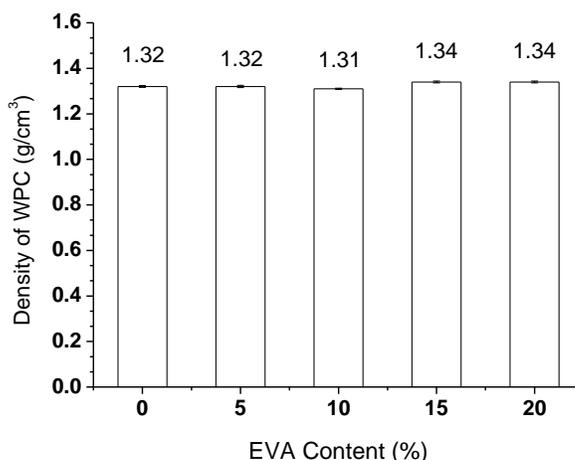


Fig. 5. Effect of EVA content on density of WPCs

In this study, although the weight fraction of poplar wood flour was decreasing, the density of the WPCs showed a tiny increase. It might be concluded that gaps and voids between the poplar wood flour and HDPE were decreased by increasing content of EVA. This hypothesis will be supported by the decreasing water uptake properties and the SEM results of the WPCs.

Flexural Property and Tensile Property

The molecular formula of EVA (Fig. 6) shows that there are two main parts of EVA. One part is a polyvinyl chain, which could wind in parallel with a long chain of HDPE; the other part is carboxyl, which could react with the hydroxyl of cellulose. Therefore, it could be concluded that the mechanical properties of WPCs could be improved by adding EVA. And this hypothesis will be supported by Figs. 7 and 9.

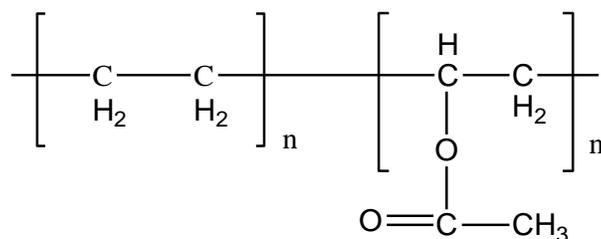


Fig. 6. The molecular formula of EVA

The MOR (Fig. 7), the MOE (Fig. 8), and tensile strength (Fig. 9) of the WPCs with various EVA contents showed a similar tendency in that they were all increased initially and then decreased by increasing content of EVA. And there was a maximum in the mechanical properties at 15% EVA content.

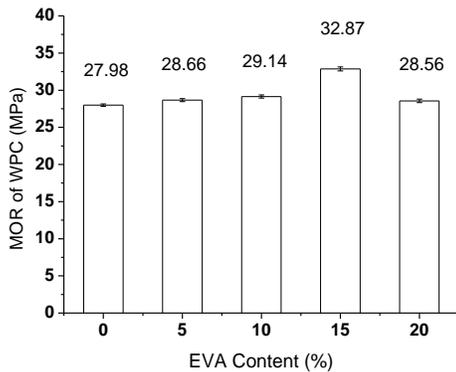


Fig. 7. Effect of EVA content on MOR of WPCs

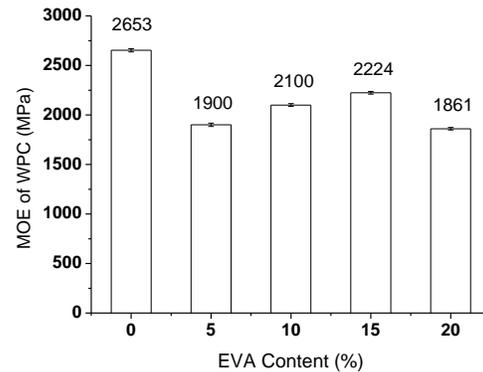


Fig. 8. Effect of EVA content on MOE of WPCs

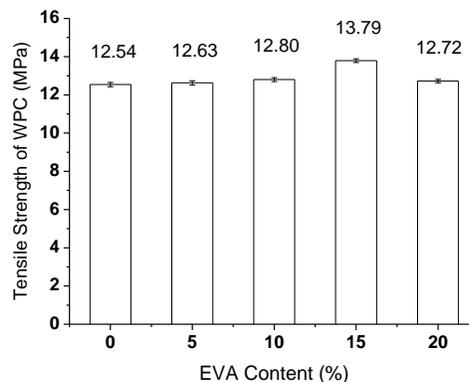


Fig. 9. Effect of EVA content on tensile strength of WPCs

Figures 7 and 9 show that the MOR and tensile strength of the WPCs added EVA were improved compared with that of the WPC without EVA. The MOR and tensile strength of the WPC treated by 15% EVA content were enhanced by 17.48% and 9.97%, respectively. By contrast, Chen *et al.* (2010) used poplar wood flour treated by EVA to fill polypropylene (PP) and found that 10% EVA content might be the best. That disagreement implied that EVA content should be adjusted according to the different plastic matrix.

The MOR and tensile strength of WPC is increased by decreasing weight fraction of wood flour. In this experiment, the decreasing weight fraction of the poplar wood flour also had influence on the mechanical properties. But WPC with 20% EVA had the least weight fraction of the poplar wood flour and did not achieve the highest mechanical properties. It might conclude that the different content of EVA was the main reason for the change of the mechanical properties of the WPCs.

Figure 8 shows that MOE of the WPCs treated by EVA was lower than that of the WPC without EVA. This was due to the soft and flexible nature of EVA. The result was consistent with the hardness data, which suggested that the flexibility of the WPCs was improved by adding EVA.

Water Uptake and Thickness Swelling

Figures 10 and 11 exhibit dimensional stabilities of the WPCs with and without EVA, including water uptake and thickness swelling. It was found that water uptake and thickness swelling were decreased with increasing content of EVA. Because hydroxyl groups of cellulose were reacted with the carboxyl of EVA, the hydrophilic behavior of the poplar wood flour was weakened. Similar results were found by using other coupling agents, such as silanes, titanates, aluminate, and maleic anhydride-grafted polymer (Qin *et al.* 2005; Xu *et al.* 2006; Song *et al.* 2011). Furthermore, the poplar wood flour was coated by EVA. The polarity of the poplar wood flour was decreased by the increasing content of EVA. So water uptake and thickness swelling of WPCs were decreased by the increasing content of EVA.

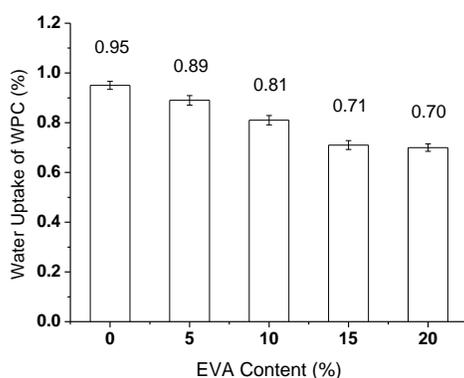


Fig. 10. Effect of EVA content on water uptake of WPCs

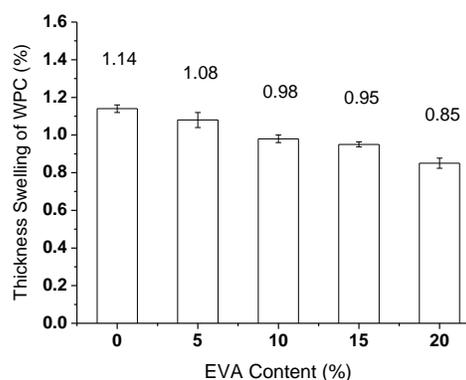


Fig. 11. Effect of EVA content on thickness swelling of WPCs

Morphology

Figure 12(a-c) presents SEM micrographs of the WPCs untreated and treated by EVA (1000 \times), respectively. In Fig. 12a, some fiber fragment and many gaps and voids were noticeable between the HDPE matrix and the poplar wood flour on the section of the WPC without EVA, and there was almost no filament of the polymer on the surface of the poplar wood flour. These observations constituted evidence of poor bonding between HDPE and the poplar wood flour untreated by EVA.

Figures 12b and 12c show almost no gap or void between the HDPE matrix and the poplar wood flour on the sections of the WPCs with EVA. The difference between the two pictures involved whether filaments of the polymer existed. Figure 12b shows some filaments of the polymer on the section of the WPC with 15% EVA content, but Fig. 12c does not show similar phenomena on the section of the WPC with 20% EVA content. This indicates that the bonding between HDPE and the poplar wood flour treated by 15% EVA was enhanced. So the MOR and tensile strength of the WPC with 15% EVA content was increased. And it can imply that the poplar wood flour with 20% EVA content was excessively coated. This might be due to the fact that the force transmission from HDPE to the poplar wood flour was weakened. So the MOR and tensile strength of the WPC with 20% EVA content was decreased in comparison with that of WPC with 15% EVA content. But the polarity of the poplar wood flour was decreased with the

increasing content of EVA. So water uptake and thickness swelling of the WPCs were increased by increasing content of EVA.

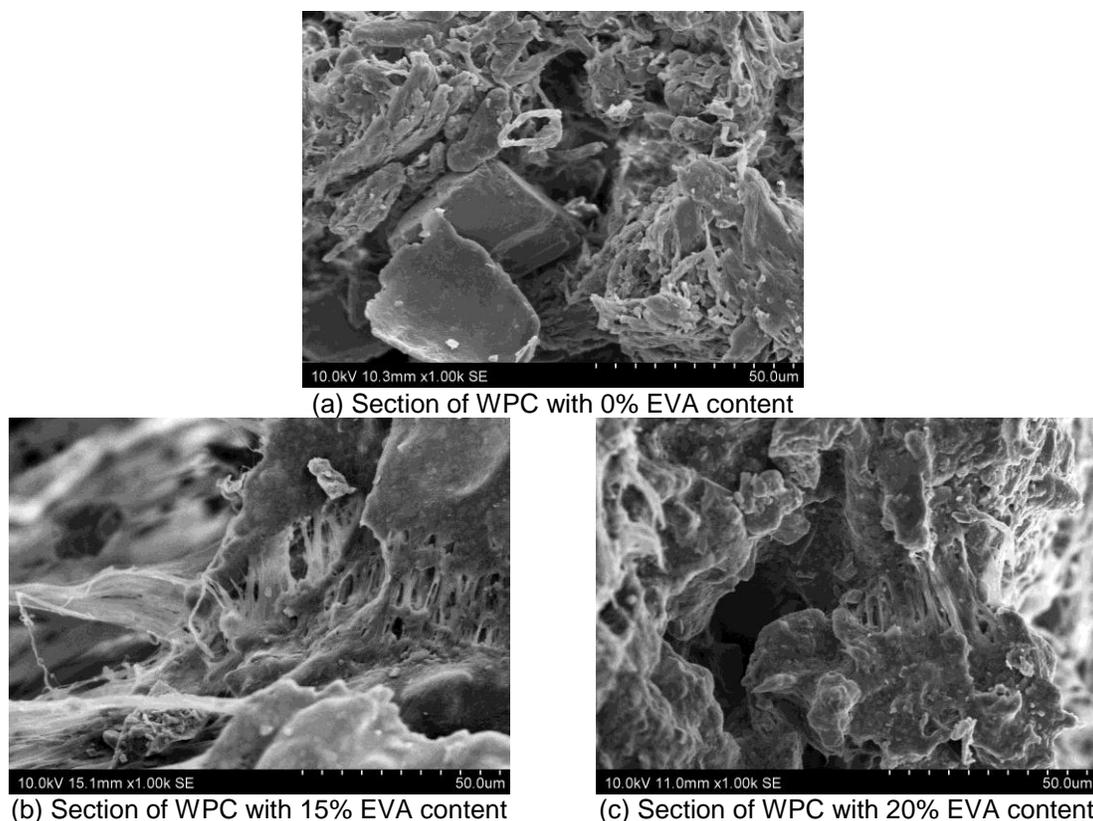


Fig. 12. Effect of EVA Content on Morphology of WPCs

CONCLUSIONS

1. The TGA results and the FTIR results indicated that the poplar wood flour was coated by EVA and the hydroxyl group of the poplar wood flour could be reacted with the carbonyl group of EVA. So the thermal stability of the poplar wood flour treated by EVA was improved, and the polarity of the poplar wood flour treated by EVA was reduced. This treatment contributed to a better interfacial bonding of WPCs.
2. The fact that the hardness of the WPCs was decreased with increasing content of EVA implied that the flexibility of the WPCs was improved by adding EVA. The similar conclusion was supported by the fact that MOE of the WPCs with EVA were lower than that of the WPC without EVA. The almost unchanged density of the WPCs suggested that the density of WPCs was only influenced by the formulation and the process condition of WPCs.

3. The MOR and tensile strength of the WPCs with EVA were enhanced in comparison with those of the WPC without EVA. This indicated that the mechanical properties of WPCs were improved by using EVA. The fact that the water uptake and thickness swelling of the WPCs was decreased by increasing content of EVA indicated that the water uptake properties of WPCs were reduced by using EVA.
4. The SEM results showed that there was almost no gap or void between the HDPE matrix and the poplar wood flour on the sections of the WPCs with EVA. This phenomenon explained the reason of increasing mechanical properties and decreasing water uptake properties of the WPCs with EVA. It also was found that the poplar wood flour with 20% EVA content was excessively coated. So the decreasing mechanical properties of the WPC with 20% EVA content was due to the fact that the force transmission from HDPE to the poplar wood flour was weakened.

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