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***Article***

# Decorative Wood Fiber/High-Density Polyethylene Composite with Canvas or Polyester Fabric

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**Abstract:** Wood-plastic composite is an environmentally friendly material, due to its use of recycled thermoplastics and plant fibers. However, its surface lacks attractive aesthetic qualities. In this paper, a method of decorating wood fiber/high-density polyethylene (WF/HDPE) without adding adhesive was explored. Canvas or polyester fabrics were selected as the surface decoration materials. The influence of hot-pressing temperature and WF/HDPE ratio on the adhesion was studied. The surface bonding strength, water resistance, and surface color were evaluated, and observation within the infrared spectrum and under scanning electron microscopy was used to analyze the bonding process. The results showed that the fabric and WF/HDPE substrate could be closely laminated together depending on the HDPE layer accumulated on the WF/HDPE surface. The molten HDPE matrix penetrates canvas more easily than polyester fabric, and the canvas-veneered composite shows a greater bonding strength than does the polyester fabric-veneered composite. A higher proportion of the thermoplastic component in the substrate improved the bonding. When the hot-pressing temperature exceeded 160°C, the fabric-veneered WF/HDPE panels had greater water resistance, although the canvas fabric changed more obviously in terms of fiber shape and color, compared with the polyester fabric. For the canvas fabric, 140°C–160°C was a suitable hot-pressing temperature, whereas 160°C–180°C was more suitable for polyester fabric. The proportion of the thermoplastic component in the composite should be not less than 30% to achieve adequate bonding strength.

**Keywords:** wood-plastic composites; high-density polyethylene; polyester fiber; canvas; surface decoration

## 1 Introduction

Wood-plastic composites (WPCs) are mainly composed of wood fibers (WFs), thermoplastic polymers (such as high-density polyethylene and polypropylene) and small amounts of additives. Recycled woody materials and waste plastic are usually employed in their preparation and, for this reason, WPCs are considered to be environmentally friendly materials. These composites have great strength and stiffness, high dimensional stability and low toxic fume emission [1]. WPCs are increasingly used as outdoor building materials, such as for planking, door and window frames, guardrails, etc. However, these composites are rarely used in indoor spaces due to their lack of attractive surfaces.

The main problem in finishing WPC material is caused by nonporous and nonpolar nature of its surface. As a result of the processing technology, a thin layer of plastic is always accumulated on the surface of WPCs, resulting in low surface energy, non-polarity [2,3] and high hydrophobicity, features which are not conducive to bonding, painting or decoration. Physical [4,5] or chemical [6,7] treatment is usually required to achieve surface modification. Gupta et al. tried to use flame and plasma to treat the surface of WPC to increase the frequency of oxygen-containing groups [8,9]. Grubbström et al. found that coupling agents could help form silane bridges between wood and polyethylene [10], whereas Dimitriou et al. used hydrogen peroxide solution, hot air, and gas flame treatment to improve the adhesion properties [11]. In order to deal with the tendency to form agglomerates due to the high hydrophilic character of cellulose, Maria et al. used a resin of poly (styrene-methyl-methacrylate-acrylic acid) [12]. Nevertheless, it is difficult for known coupling agents (such as silane coupling agent) to be acceptable due to cost effectiveness in practical application. Simultaneously, some problems with other methods, such as spent liquor pollution and oxidation effectiveness, also occur. Guo et al. and Liu et al. introduced thermoplastic film as an intermediary between wood veneer and wood fiber/high-density polyethylene (WF/HDPE) substrate [13,14] to enhance bonding, which is a promising way to decorate WPC.

In these studies, wood veneers are commonly designated as surface decoration materials. However, attention has not been paid to another type of bulk material, textiles. A large volume of fabrics is discarded every year and, from a sustainability standpoint, it is increasingly important that appropriate ways are found to reuse them. Fabric is woven from a number of yarns which are made of natural and/or synthetic fibers. Physical gaps exist among yarns and fibers. This builds a favorable structure for the penetration of molten thermoplastic and adhesives. For example, Scida et al. made a composite material by hot pressing of non-woven natural-fiber and polypropylene, which is used to make vehicle interior parts [15]. Using textiles as surface materials with which to decorate WPCs could provide a more attractive surface and broaden the application of WPCs in the field of interior decoration.

In the present study, a new method was developed to beautify the surface of WPCs with fabric. We selected two common fabrics, canvas fabric and polyester fiber fabric, as decorative materials. The molten thermoplastic on the surface of WPC would be expected to penetrate into the fabric and to form a strong anchoring structure. No adhesive was applied, so that the bonding process was convenient, fast, and most importantly, without pollution. The result demonstrated great potential for the manufacture of sustainable and recyclable products by decorating wood/plastic composites with a variety of attractive fabrics.

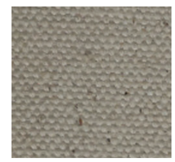
## 2 Experimental Methods

### *2.1 Materials*

The wood fiber/high density polyethylene (WF/HDPE) substrate, WF/HDPE panels (12 mm thick, 200 mm long and 100 mm wide), were made by the extrusion method in the laboratory (The HDPE pellets, oven dry WF, maleated polyethylene (MAPE), and PE wax were first mixed in a mixer for 20 minutes. Then these mixtures were compounded by passing through a co-rotating twin-screw extruder and reduced into small particles. Finally, these particles were extruded into WF/HDPE composite lumbers with 12 mm thickness and 100 width using a single screw extruder). Three ratios of WF to HDPE were used: 5:5, 6:4 and 7:3. Among the raw materials, wood flour (aspen wood, 40–80 mesh) was obtained from the local market. HDPE (5000 S, density of 0.949–0.953 g/L, melt flow index of 0.8–1.1 g/10 min, crystallinity of 71%) was obtained from Petrochina Daqing Petrochemical Company. MAPE (grafting percentage 0.9%) was obtained from Shanghai Sunny New Technology Development Co.

The fabrics used for veneering were purchased from the local wholesale clothing market. Their basic characteristics are listed in Tab. 1.

**Table 1:** Parameters of textile fabrics used for veneering in this study

| Fabric | Thickness (mm) | Melting (decomposition) Temperature (°C) | Chemical composition | Appearance |
|---|---|---|---|---|
| Polyester fiber | 0.48 | Melting: 205°C | HO-$CH_2$-$CH_2$-O<br>[-OC-Ph-$COOCH_2CH_2O$-]n |  |
| Canvas | 0.7 | Decomposition: 310°C | Mainly cellulose, Small amount of wax and pectin [16] |  |

### *2.2 Preparation of Fabric-Veneered WF/HDPE Panel*

As shown in Fig. 1, the fabric was spread on the surface of WF/HDPE composite board, then the fabric-WF/HDPE mat was placed in a thermo-compressor (SL-6; Harbin Special Plastic Production Co.,) for simultaneously heating and pressing. The mat was first hot pre-pressed before hot pressing. The parameters employed are listed in Tab. 2. After hot pressing, the fabric-veneered WF/HDPE panel was cooled down to ambient temperature under a pressure of 5 MPa.

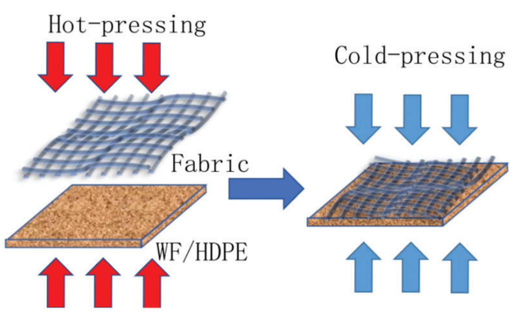



**Figure 1:** Preparation of a fabric-veneered wood fiber/high-density polyethylene (WF/HDPE) panel

**Table 2:** Production parameters for veneering WF/HDPE board with the fabrics

| WF/HDPE | Pressing temperature (°C) | Pre-pressing time (min) | Hot-pressing time (min) | Pre-pressing pressure (MPa) | Hot-pressing pressure (MPa) |
|---|---|---|---|---|---|
| 5/5 | | | | | |
| 6/4 | 140, 160, 180 | 3 | 2 | 2 | 10 |
| 7/3 | | | | | |

### *2.3 Property Test*

After conditioned at 25°C and 60% relative humidity, the veneered WF/HDPE panels were sawn into samples for testing (Fig. 2).

(a) (b) (c)

**Figure 2:** WF/HDPE samples for testing: (a) patterned canvas; (b) canvas; (c) polyester fabric

*2.3.1 Surface Bonding-Strength Test*

The surface bonding strength between the fabric and the WF/HDPE substrate was evaluated based on a procedure described in GB/T 17657-2013 [17]. The dimension of the sample was 50 mm × 50 mm × 10 mm, with a middle circle area of 1,000 $mm^2$. There were six replicate specimens in each group. The loading rate was 2 mm/s. The test was carried out on a universal test machine (RGT-20A; Reger Instrument Company).

*2.3.2 Water Resistance Test*

The dip stripping test was conducted to evaluate the water resistance of the adhesion between the fabric and the WF/HDPE substrate, according to the procedure specified in GB/T 17657-2013. Samples (veneered WF/HDPE panel, 75 mm × 75 mm × 10 mm) were immersed in water at 63 ± 3°C for 3 h and then dried in an oven at 63 ± 3°C for 3 h. The delaminated length at each of the four edges of each of the dried samples was measured. Six replicate samples were tested in each series.

*2.3.3 Microstructure of the Canvas and Polyester Fabric*

The fiber morphology of the canvas and polyester fabric surface before and after hot pressing was observed under a scanning electron microscope (FEI Quanta 200; FEI Company). The samples were first sputter coated with gold and then examined under an accelerating voltage of 5 kV.

*2.3.4 Surface Chemical Characterization*

The chemical characteristics of the textile surface before and after hot pressing were analyzed by attenuated total reflection−Fourier transform-infrared (ATR−FTIR) spectroscopy (Magna-IR 560 ESP; Nicolet Company). Scans were recorded from 4000 $cm^{-1}$ to 400 $cm^{-1}$ at a resolution of 4 $cm^{-1}$.

### *2.4 Color Change Measurement*

A spectrophotometer (CM-2300 d; Konica Minolta) was used to measure any color change in canvas or polyester fabric surface before and after hot pressing, according to the CIE 1976 L*a*b* color space. The measurement area was 8 $mm^2$, the light source was set to D 56 and the light source angle of view was 10°. The total color change ($\Delta E^*$) was calculated according to Eq. (1), as in ASTM D2244 [17]. An increase in L* means the samples is lightening. The color coordinates a* and b* are defined as the red/green coordinate (+Δa* signifies a color shift toward red, −Δa* toward green) and yellow/blue coordinate (+Δb* toward yellow, −Δb* toward blue), respectively.

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2} \tag{1}$$

where ΔL*, Δa* and Δb* are the differences between initial (before hot pressing) and final (after hot pressing) values of L*, a* and b*.

## 3 Results and Discussion

### *3.1 Surface Bonding Strength between Fabric and WF/HDPE Substrate*

The test results (Fig. 3) show that the surface bonding strength of fabric-veneered WF/HDPE panel increased with increasing temperature during pressing. When the temperature reached 180°C, the surface bonding strength reached a maximum. Higher temperatures promoted HDPE melting and penetration.

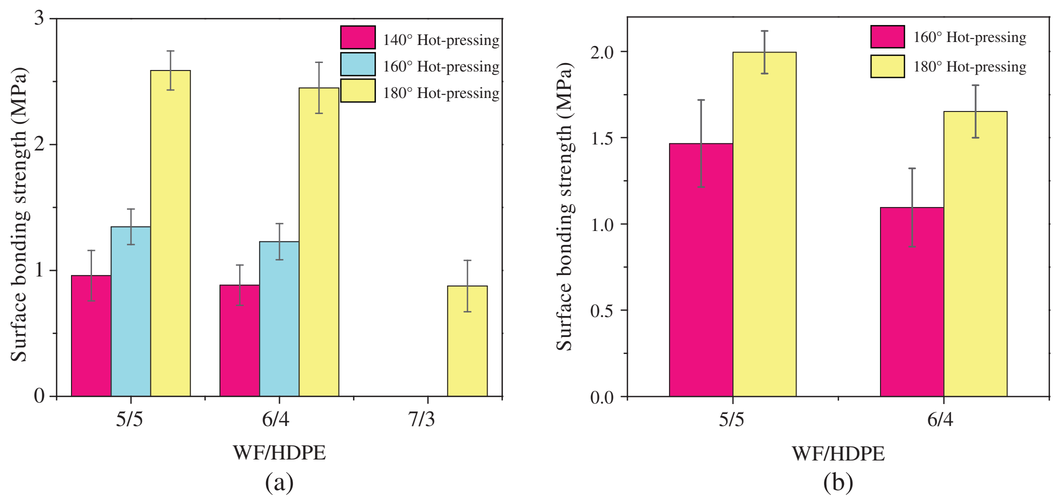



**Figure 3:** Bonding strength of wood fiber/high-density polyethylene (WF/HDPE) board covered by canvas fabric (a) or polyester fabric (b)

The adhesion between the surface fabric and the WF/HDPE substrate board depends on the performance of the HDPE film accumulated on the WF/HDPE surface. As the proportion of the plastic component contained in the substrate board increased, the surface bonding strength also increased. When the HDPE content reduced to 30%, the surface bonding strength from the polyester fabric was too low to withstand sample preparation. Thus, no testing result was obtained.

The melting point of HDPE is approximately 140°C [19]. At temperatures of 140°C and 160°C, although the HDPE film on the surface of the WF/HDPE substrate would not be fully molten during the limited pressing period, it softens and partly melts. This partially melted HDPE is compressed or partly penetrated into the gaps between the warp and weft yarn and among the fibers. When the composite cooled down, anchoring was achieved. Therefore, the canvas-veneered WF/HDPE composites can obtain high surface bonding strength at 140°C and 160°C hot-pressing temperatures. When the temperature rose to 180°C, the surface HDPE fully melted and it was easier to penetrate into the gaps in the canvas, greatly improving the surface bonding strength. However, for substrate with a high wood content (70%), there was too little HDPE on the surface of the WF/HDPE composite, and it was difficult to achieve sufficient penetration, resulting in greatly reduced surface bonding strength.

Based on the same logic as applied to the canvas, polyester-veneered WF/HDPE composite board did not achieve sufficient surface bonding strength when heated at the lower temperature (140°C) or when the HDPE content in the substrate was low (30%). When pressed at 160°C, the polyester fabric exhibited a surface bonding strength greater than 1 MPa. When the temperature rose to 180°C, HDPE melted completely, becoming fully melted and highly flexible. The surface bonding strength of the polyester-veneered samples (WF/HDPE = 5:5, 6:4) improved significantly. However, compared with canvas fabric, polyester fabric exhibited a lower surface bonding strength. This could be related to the different microstructures of these two fabrics, as shown in Figs. 4 and 5. The texture of polyester fabric is denser than that of canvas and could hinder HDPE penetration.

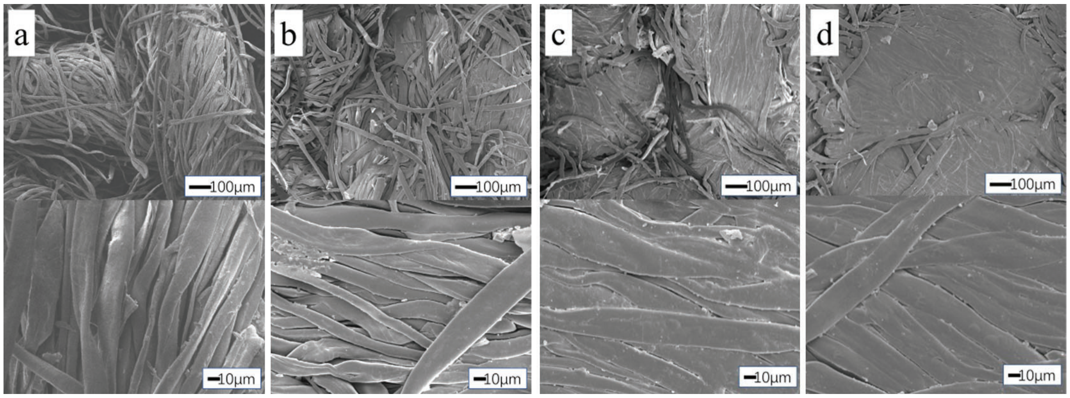



**Figure 4:** Electron microscopy studies at different magnifications of the fiber shape of a canvas surface under different hot-pressing temperature (WF:HDPE = 5:5, 6:4, 7:3): (a) unpressed; (b) hot pressed at 140°C; (c) hot pressed at 160°C; (d) hot pressed at 180°C

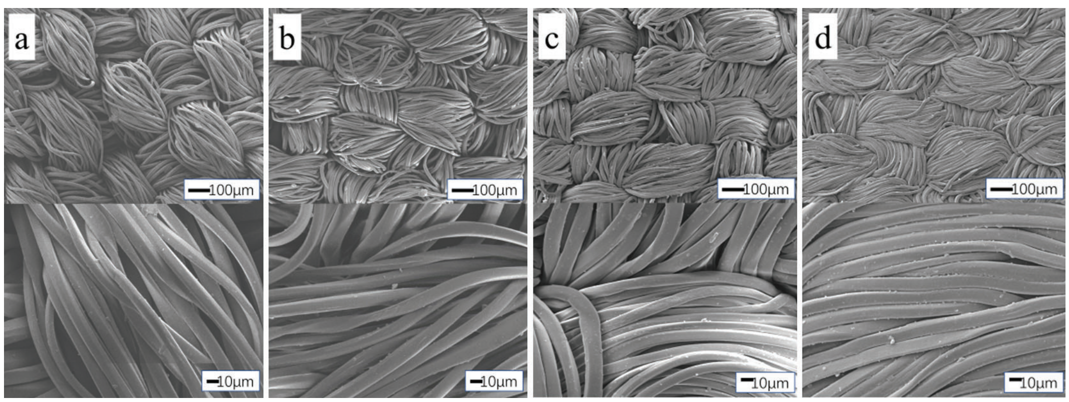



**Figure 5:** Electron microscopy studies at different magnifications of the fiber shape of a polyester surface under different hot-pressing temperature (WF:HDPE = 5:5, 6:4, 7:3): (a) unpressed; (b) hot pressed at 140°C; (c) hot pressed at 160°C; (d) hot pressed at 180°C

As the proportion of HDPE in the WF/HDPE substrate increased, more coupling agent, MAPE was emerged on surface. The grafted polar groups (carboxylic acid groups and circular anhydride groups) present in MAPE [13] can react with the hydroxyl group in the fabric. The main component of canvas is cellulose. It has higher hydroxyl content than polyester fiber, and thus has better compatibility with MAPE. Based on the above, under the same conditions, the surface bonding strength between canvas and the WF/HDPE substrate is higher than that between polyester fiber and WF/HDPE substrate.

As specified in Introduction, the surface of the wood-plastic composite material is non-polar and hydrophobic, which is not conducive to bonding with polar adhesives. Thus, comparing to isocyanate cross-linking polyvinyl acetate [20], the method in present study provided much higher bonding strength for the same WF/HDPE substrate board.

### *3.2 Influence of Hot Pressing on the Surface Morphology of Fabrics*

As shown in Figs. 4 and 5, the canvas used in the current study is thicker than the polyester fabric. The canvas has larger gaps between its warp and weft yarns, an irregular arrangement, a rough surface and randomly protruding tiny fibers. During the prepressing and hot pressing stages, the molten HDPE on the surface of the WF/HDPE substrate could penetrate deeply into these gaps, forming tight anchors. In addition, those tiny protruding fibers can also be embedded in the HDPE. As a result, the canvas-veneered WF/HDPE panel exhibits a greater bonding strength than the polyester-veneered WF/HDPE panel (Fig. 3). The polyester fiber is narrower than the canvas fiber, its surface is smoother (Fig. 5), and there are more warp and weft yarns per unit length in the polyester fiber, resulting in smaller gaps between the yarns and the polyester fibers. This compact structure of the polyester fiber makes molten HDPE more difficult to penetrate the fibers and anchor them, so that the bonding between the polyester fabric and the WF/HDPE panel is weaker than that with the canvas-veneered WF/HDPE panel.

The cotton fibers of canvas are poorly resistant to heat and deform easily at high temperatures, with the top surface of canvas (in contact with the pressing plate) appearing flat after hot pressing. There are abundant hydroxyl groups on the surface of cotton fibers, which form hydrogen bonds under hot-pressing conditions, with the space between the fibers being reduced. The higher the hot-pressing temperature, the flatter the fabric surface, with the canvas surface becoming almost a continuous plane after hot pressing at 180°C.

The melting point of polyester fiber is 205°C. Therefore, when pressing at 180°C, the fibers of the polyester did not melt and were still separate from one another (Fig. 5). The decomposition temperature of polyester is higher than that of cotton fiber. Hot pressing might result in less color change in polyester fabric.

### *3.3 Water Resistance*

The results of the dip stripping test are shown in Tab. 3. In the panel where the WF/HDPE composite was hot pressed with canvas at 140°C, delamination occurred in the dip stripping test. Although the canvas-veneered WF/HDPE panel exhibited satisfactory surface bonding strengths at 140°C, the HDPE was embedded into the canvas at a shallow depth due to the fact that it was only partly melted, with the interface bonding between the substrate and the fabric not being firm. Similarly, when the HDPE content in the substrate was low (30%), the WF/HDPE substrate and fabric are completely separated after the dip stripping test. The cotton fibers of the canvas fabric have a strong water absorption capacity due to the hydroxyl groups on their surface. Immersion in 63°C water and subsequent drying at 63°C caused expansion and shrinking of the canvas, facilitating breaks between the cotton fibers and HDPE. When hot pressed at 160°C or 180°C, HDPE melted more completely, which enhanced the HDPE fluidity and the depth of its penetration into the fibers. This promotes the formation of a firm bond after cooling and no delamination occurred in the dip stripping test.

**Table 3:** Delamination (mm) between fabric and WF/HDPE composites (hot pressed at different temperatures) after hot water treatment

| WF:HDPE ratio | Canvas | | | Polyester fiber fabric | |
|---|---|---|---|---|---|
| | 140°C | 160°C | 180°C | 160°C | 180°C |
| 5:5 | 3 | 0 | 0 | 0 | 0 |
| 6:4 | 5 | 0 | 0 | 0 | 0 |

Polyester is hydrophobic and their fibers changed little in response to hot water immersion and subsequent drying. No delamination occurred in the polyester-covered WF/HDPE composite board. When hot pressed at 140°C for veneering, the polyester fabric could not firmly stick to the WF/HDPE substrate surface due to the poor penetration by HDPE, and the test samples could not be obtained successfully.

### *3.4 Effect of Hot-Pressing Temperature on Fabric Color*

Compared with the un-pressed fabric, the hot-pressed fabric showed color changes, as listed in Tab. 4 and shown in Fig. 6. The ration of the WF/HDPE substrate has almost no effect on the color of the fabric. The total color change $\Delta E^*$ on the surface of the fabric clearly increased with increasing hot-pressing temperature, mainly resulting from changes in brightness values (L*). The brightness of the canvas fabric decreased faster and became darker than that of polyester fabric. This reflects the lower heat resistance of cotton fibers. When the hot-pressing temperatures were higher than 160°C, slight thermal degradation occurred to the canvas fabric. The other two coordinates, $a^*$ and $b^*$, changed little. The $\Delta E^*$ of polyester fiber was smaller than that of canvas fabric, which means the process of high-temperature pressing did not make an obvious change to its surface. As previously mentioned, polyester fabric exhibits good heat resistance and is able to withstand the hot-pressing temperature of 180°C.

**Table 4:** Color changes in canvas and polyester fabric in response to hot pressing

| Fabric | Temperature (°C) | $L^*$ | $a^*$ | $b^*$ | $\Delta E^*$ |
|---|---|---|---|---|---|
| Canvas | 140 | −2.200 | 0.364 | 0.193 | 2.238 |
| | 160 | −4.941 | 1.097 | 1.692 | 5.336 |
| | 180 | −8.680 | 1.681 | 2.541 | 9.199 |
| Polyester fiber | 140 | 1.836 | 1.250 | 1.785 | 2.850 |
| | 160 | 2.942 | 1.426 | 2.088 | 3.880 |
| | 180 | 2.501 | 1.636 | 3.692 | 4.750 |

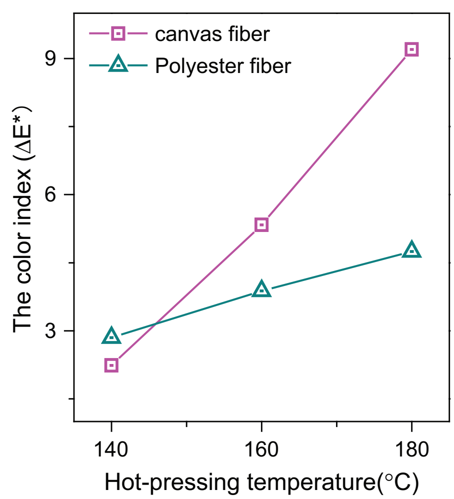



**Figure 6:** Color change in fabric at different hot-pressing temperatures

Pressing temperature plays an important role in WF/HDPE decoration. When the hot-pressing temperature rose to 180°C, both canvas- and polyester-veneered WF/HDPE panels exhibited the greatest bonding strength and could withstand water intrusion without delamination. However, high temperatures adversely affected the appearance of canvas. When the temperature decreased to 160°C, the adhesion strength of both decorative fabrics could withstand water intrusion, and the discoloration of the canvas was less obvious. Polyester fibers are so compact that the embedding of HDPE into the fibers is impeded when the temperature drops to 140°C, at which point the bonding strength was too low to be measured.

The structure of the canvas fiber is relatively loose, and it can provide an anchoring structure for HDPE at 140°C hot pressing. Although a slight delamination occurred after water treatment, the canvas-veneered WF/HDPE still met the requirements of GB/T 17657-2013. As a consequence, appropriate adjustment of the pressing temperature, based on the fabric type, could obtain an attractive decorative effect.

### *3.5 Effect of Hot Pressing on the Chemical Composition of the Fabric Surface*

In addition to the main component, cellulose (88%–96.5%), canvas cotton fiber also contains a small amount of non-cellulosic components, such as gum, waxy and inorganic substances [14]. Most of these non-cellulose components are concentrated in the outermost layer of the cotton fiber. C-C (waxy) and C-O (pectin) groups could be detected by infrared spectroscopy (IR). In Fig. 7, there were obvious characteristic peaks at 1728 $cm^{-1}$. This corresponds to the stretching vibration peak of C-O contained in the carboxylic acid of polygalacturonic acid in pectin [21,22]. With the increase in hot-pressing temperature, this peak decreased gradually and became very weak after hot pressing at 180°C. This indicates that pectin gradually decomposed during the heating process. The spectrum supports the conclusion that, the higher the temperature, the more pectin decomposes [23–25]. The characteristic peaks of -OH at 3200–3500 $cm^{-1}$ and -CH at 2855–2900 $cm^{-1}$ did not change significantly before and after hot pressing, indicating that cellulose did not degrade during the hot-pressing process.

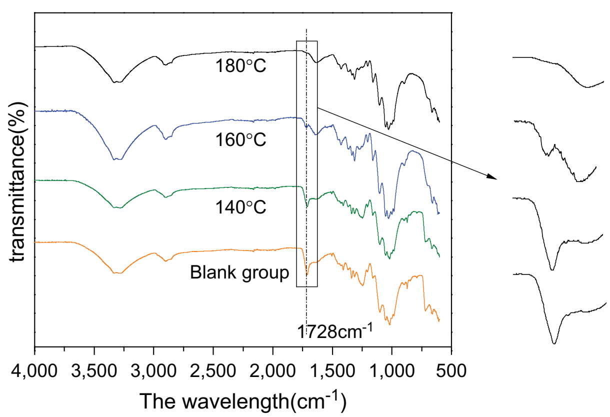



**Figure 7:** Infrared spectra of canvas fabric after hot pressing

The molecular chain structure of polyester is HO-$H_2$C-$H_2$C-O[-OC-Ph-COOC$H_2$C$H_2$O-]n. It contains only one hydroxyl group at the end of each molecular chain. The characteristic peak of the hydroxyl group is not obvious in Fig. 8. The chemical groups on the surface of the polyester fabric did not significantly change after hot pressing at different temperatures. The C-O stretching vibration peak at 1714 $cm^{-1}$, and the -COO- stretching vibration peak at 1409 $cm^{-1}$ are the characteristic peaks of the polyester fabric. The intensity and position of these peaks did not change before and after hot pressing, showing that the polyester fibers has good thermal stability and would not degrade under the hot-pressing temperatures used in this experiment.

Both polyester and cotton fibers have poor compatibility with HDPE. No chemical reaction occurred between them during the veneering process. It is supposed that the adhesion between the fabric and the WF/HDPE composite panel depended mainly on the anchoring of HDPE to the fibers, as shown in Fig. 9. Sufficiently deep penetration will result in strong surface bonding strength, which requires sufficient melted HDPE, for it to act as an adhesive.

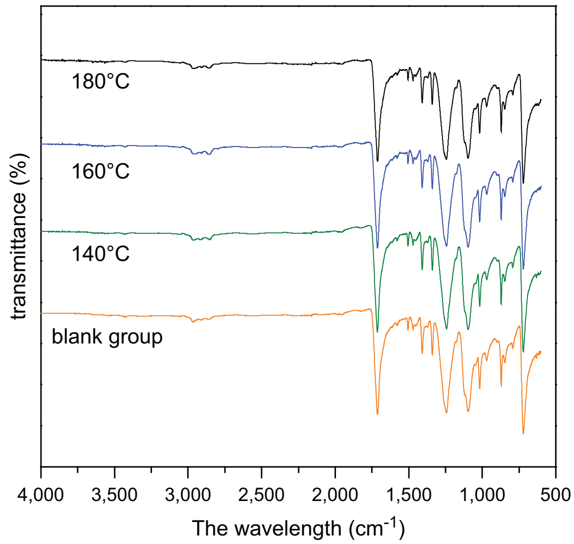



**Figure 8:** Infrared spectra of polyester fabric after hot pressing

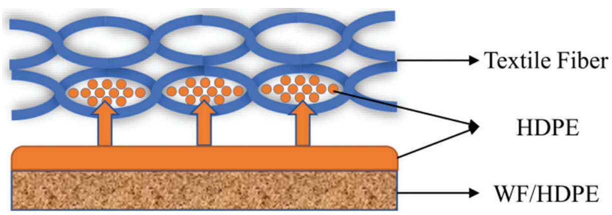



**Figure 9:** Adhesion mechanism between textile fabric fibers and WF/HDPE composite

## 4 Conclusions

In this study, the effects of three factors, namely hot pressing temperature, polymer content of the substrate, and the fabric material, on the surface bonding strength of fabric-veneered WF/HDPE composites are discussed. The results show that using canvas and polyester fiber textiles can achieve satisfying surface decoration and bonding strength under suitable hot-pressing temperatures. Specific relevant conclusions are as follows:

a) The fabric can be firmly bonded onto the surface of the WF/HDPE composite by means of the molten HDPE component of the composite self. No extra coating adhesive is needed, which maintains the environmentally sustainable performance of wood-plastic composite material.

b) Raising the hot-pressing temperature and increasing the HDPE proportion in the WF/HDPE composite substrate could increase the surface bonding strength. Cotton fibers in canvas are loosely aligned and easily penetrated by molten HDPE, achieving greater surface bonding strength than for polyester fabric. After hot pressing, greater changes occurred in the canvas fabric, such as fiber shape, chemical component, and color, than in the polyester fabric.

c) On the other hand, the thermostability of canvas is weaker than that of polyester fabric. Taking into account the surface bonding strength, water resistance and color change parameters, it was concluded that a hot-pressing temperature of 140°C–160°C is suitable for canvas, whereas a higher temperature of 160°C–180°C is appropriate for the denser polyester fabric.

Based on the above preliminary research findings, it would be worthwhile to further develop a more suitable thermoplastic intermediate film, with a lower melting point, to reduce the adverse effects on surface decoration of a high processing temperature. Such a decoration method would greatly promote the use of wood-plastic composite materials indoor in households.

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**Conflicts of Interest:** The authors declare that they have no conflicts of interest to report regarding the present study.

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