

# Effects of Yellow Pigment Content on the Properties of Bamboo Flour/High-Density Polyethylene Composites

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Effects of iron oxide yellow pigment content were investigated relative to the properties of wood-plastic composites (WPCs) based on bamboo flour and high-density polyethylene (HDPE). Samples with pigment contents of 0%, 5%, 10%, and 15% were prepared, and the structure–property relationships were systematically examined. The incorporation of pigment significantly enhanced surface hydrophobicity, with the static water contact angle increasing from 79.41° to 109.15°. This was attributed to the inherent hydrophobicity of the pigment and its physical shielding of wood fibers, thereby reducing surface energy and limiting the exposure of hydrophilic groups. The composite with 5% pigment exhibited the optimum mechanical performance, whereas higher pigment loading ( $\geq 10\%$ ) resulted in reduced mechanical properties, with flexural strength decreasing by up to 14.8%. SEM analysis revealed that excessive pigment led to agglomeration, causing interfacial defects and stress concentration. The 10% pigment formulation showed a relatively uniform and well-bonded interface, while the 15% sample contained noticeable fiber exposure and voids. FTIR spectroscopy confirmed that the pigment primarily served as a physical filler without introducing new chemical functionalities. In conclusion, an appropriate amount of pigment (5%) can effectively improve the hydrophobicity and mechanical properties of bamboo flour/HDPE composites.

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## INTRODUCTION

Wood-plastic composites (WPCs) are a new class of environmentally friendly materials composed of renewable biomass fibers and thermoplastic resins (Yang 2024; Jiang *et al.* 2024). These materials combine the natural texture of wood with the excellent processability and durability of plastics. They are widely used in construction, furniture, landscape design, and other fields. However, due to the presence of natural fibers in their composition, WPCs are susceptible to environmental factors such as light exposure, humidity changes, and microbial erosion during long-term use (Hong *et al.* 2025). These factors can lead to surface degradation, color fading, and deterioration of mechanical properties, thereby affecting their service life and structural safety. Among various influencing factors, pigments—used primarily as coloring agents—not only impart rich colors to WPCs but may also significantly affect their physical, chemical, and aging resistance properties (Badji *et al.* 2017; Andrady *et al.* 2019). Therefore, it is important to investigate the mechanisms by which pigment types and contents influence the overall performance of WPCs, and to explore their aging behavior and protective strategies under

different environmental conditions. By such means it is possible to enhance the durability and application value of these materials (Fu 2024; Qi 2024). In recent years, researchers have conducted systematic studies on the effects of pigments on WPC performance. Niu *et al.* (2024) optimized the ratio of bamboo fiber (BF) to high-density polyethylene (HDPE), preparing a bamboo-plastic composite (BPC55) with optimal mechanical properties. They further introduced KH550-coupling agent-modified  $\text{SiO}_2@\text{TiO}_2$  particles for reinforcement. The results showed that the flexural strength and modulus of the modified composite increased by 31.1% and 52.3%, respectively, while its resistance to UV aging was improved by 77.8%, effectively enhancing the load-bearing capacity and environmental friendliness of pallet products. Wan (2024) investigated the effects of organic pigments (*e.g.*, phthalocyanine blue, phthalocyanine green, permanent yellow) and inorganic pigments (*e.g.*, iron oxide red, iron oxide yellow, iron oxide blue), both individually and synergistically, on the performance of bamboo fiber/HDPE composites through wet-heat aging tests. It was found that after adding organic pigments, the  $\Delta E$  value and water absorption rate decreased by 84.4% and 43.4%, respectively, within 20 days of aging, while the tensile and flexural strengths increased by up to 41.5% and 41.4%. The introduction of inorganic pigments also helped reduce surface fading and water absorption, and the combined use of pigments further enhanced the wet-heat stability and mechanical properties of the composites. Xiao *et al.* (2020) compared the chemical groups, mechanical properties, color changes, and microstructural differences of eucalyptus wood/PE composites in yellow, green, and silver colors under simulated acid rain corrosion. The results indicated that the silver-colored composite exhibited the best corrosion resistance. Additionally, Chen (2019) studied the effects of three inorganic pigments on the performance of wood fiber (WF)/polyvinyl chloride (PVC) composites. After 50 days of accelerated UV aging, the 24-h water absorption rate of the red AM/PVC composite decreased by 17.3%, while the tensile, flexural, and impact strengths increased by 11.2%, 10.7%, and 21.4%, respectively, demonstrating excellent aging resistance and reinforcing effects.

In summary, pigment type and formulation significantly influence key performance indicators of WPCs, including weather resistance, mechanical properties, and water resistance. This study aimed to prepare WPCs using maleic anhydride grafted high-density polyethylene (MA-g-HDPE) as the compatibilizer and BF as the reinforcing phase *via* compression molding. The effects of different pigment contents on the microstructure, mechanical properties, thermal expansion behavior, and water resistance of the composites were systematically investigated. This work provides a theoretical basis and technical support for the design and application of high-performance colored WPCs (Lv 2022).

## EXPERIMENTAL

### Raw Materials

Bamboo flour (200 mesh) was purchased from a mineral products factory; high-density polyethylene (HDPE), grade 700F, with a melt index of 0.94 g/10 min, was supplied by Shanghai XinXie Engineering Plastic Co., Ltd. (China); yellow pigment (which was Iron Oxide Yellow),  $\text{FeO}(\text{OH}) \cdot \text{H}_2\text{O}$  (100 mesh), was obtained from FengFeng Mineral Pigment Co., Ltd. (China); maleic anhydride grafted polyethylene (MAPE), grade 400A, was provided by Dongguan Lehua Plastic Raw Material Trading Co., Ltd. (China);

and polyethylene wax, grade 0020P, was supplied by Dongguan Shanyi Plastic Co., Ltd. (China).

### Sample Preparation

The bamboo powder was dried in an electric thermostatic convection drying oven at 90 °C for 24 h to remove moisture. Subsequently, according to the designed formulation (see Table 1), the dried bamboo powder, high-density polyethylene (HDPE), maleic anhydride-grafted polyethylene (MAPE), polyethylene wax (PE wax), and yellow pigment were accurately weighed. The raw materials were then loaded into a three-dimensional mixer for thorough blending to ensure uniform dispersion of all components. The well-mixed material was transferred to a preheated mold in a flat-plate vulcanizing press and compression-molded at 170 °C and 4 MPa for 10 min. The resulting specimens measured 120 mm × 100 mm × 10 mm. To meet the requirements of various performance testing standards, the specimens were further processed and cut into corresponding dimensions for subsequent microstructural observation, mechanical property testing, thermal expansion analysis, and water resistance evaluation.

**Table 1.** Designation and Composition of Bamboo Fiber/HDPE Composites

| Sample | Bamboo Fiber (%) | HDPE (%) | MAPE (%) | Pigment (%) |
|--------|------------------|----------|----------|-------------|
| S1     | 50               | 50       | 5        | 0           |
| S2     | 50               | 50       | 5        | 5           |
| S3     | 50               | 50       | 5        | 10          |
| S4     | 50               | 50       | 5        | 15          |

### Performance Characterization

#### *Mechanical testing*

Tensile and flexural strength tests were conducted using a computer-controlled electronic universal testing machine (CMT6104, MTS Industrial Systems Co., Ltd., Jinan, China) in accordance with Chinese National Standards GB/T 1447-2005 and GB/T 1449-2005, respectively. For flexural testing, specimens measuring 100 mm × 100 mm × 10 mm were employed with a support span of 64 mm and a loading speed of 2 mm/min. Five replicates were tested for each condition, with mean values calculated to ensure data reliability.

#### *Impact strength*

Impact strength was determined following ASTM D256-10 (2018) standard using a microcomputer-controlled cantilever beam impact tester (TM2101-T5, Asry Instrument Technology Co., Ltd., Guangdong, China). Specimens (100 mm × 100 mm × 10 mm) were tested with five replicates per condition, and average values were reported as final results.

### Microstructural Analysis

The fracture surface morphology of impacted specimens was examined using a FlexSEM 1000 scanning electron microscope (SEM, Hitachi High-Tech, Japan). Prior to observation, samples were sputter-coated with gold to enhance conductivity, and imaging was performed at an accelerating voltage of 15 kV for optimal resolution.

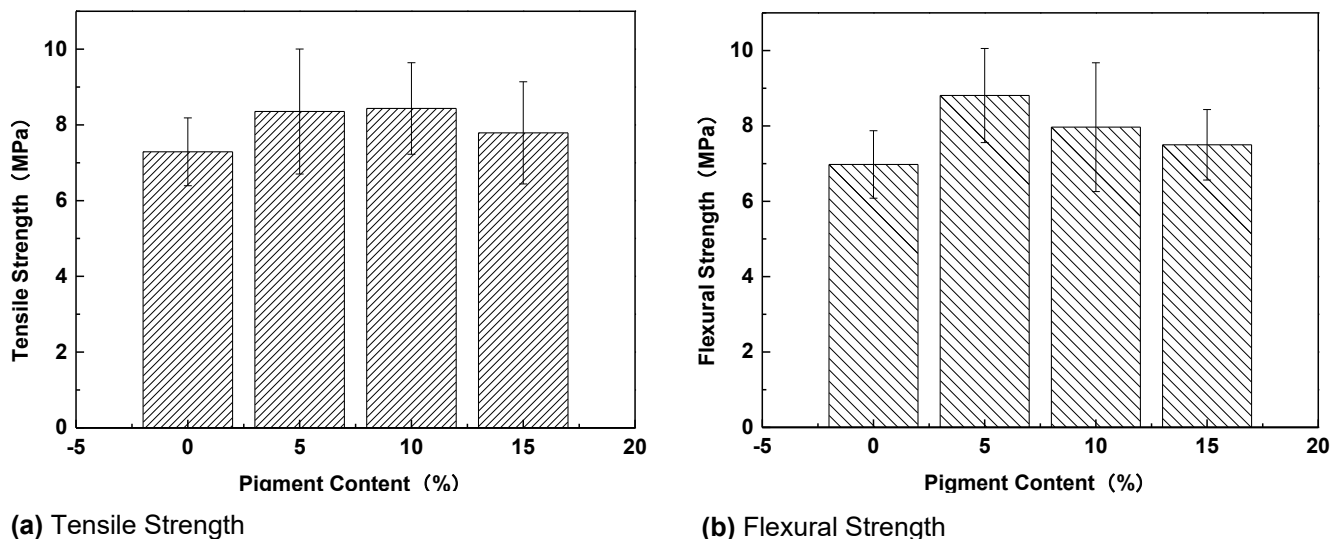
## FTIR Characterization

The chemical structures were characterized using a Nicolet iS20 Fourier transform infrared spectrometer (FT-IR, Thermo Fisher Scientific Inc.) with a wavenumber range of 400–4000  $\text{cm}^{-1}$  and a resolution of 4  $\text{cm}^{-1}$ .

## RESULTS AND DISCUSSION

### Mechanical Properties

Figure 1 illustrates the effects of different pigment contents (0%, 5%, 10%, and 15%) on the mechanical properties of wood-plastic composites (WPCs), where Figs. 1(a), 1(b), and 1(c) present the test results for tensile strength, flexural strength, and impact strength, respectively. All data are presented as mean values  $\pm$  standard deviation based on five independent replicates. Statistical significance was determined by one-way ANOVA followed by Duncan's multiple comparison test ( $p < 0.05$ ), and different letters above the bars indicate significant differences among groups. Data analysis reveals that the composite with 5% pigment content exhibited optimal overall mechanical performance. Beyond this threshold, most mechanical properties showed a declining trend. Specifically, no significant difference in tensile strength was observed between the 5% and 10% pigment groups, while the 15% pigment sample experienced a significant reduction of 6.74% compared to the 5% formulation.



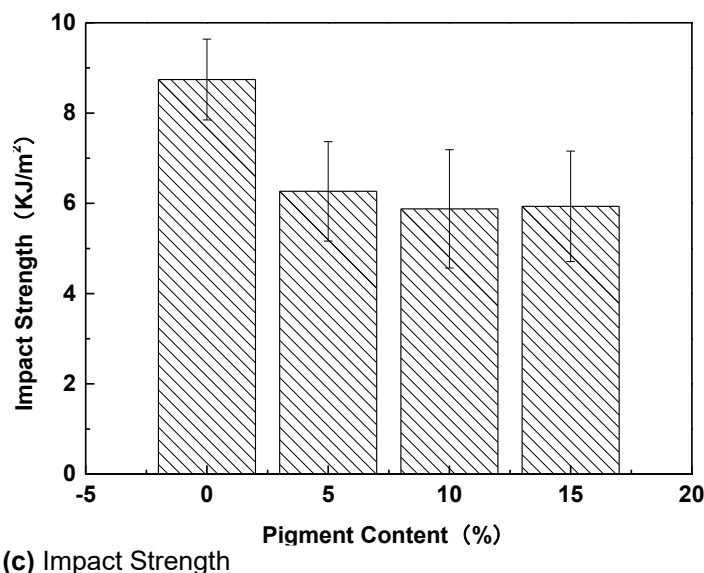
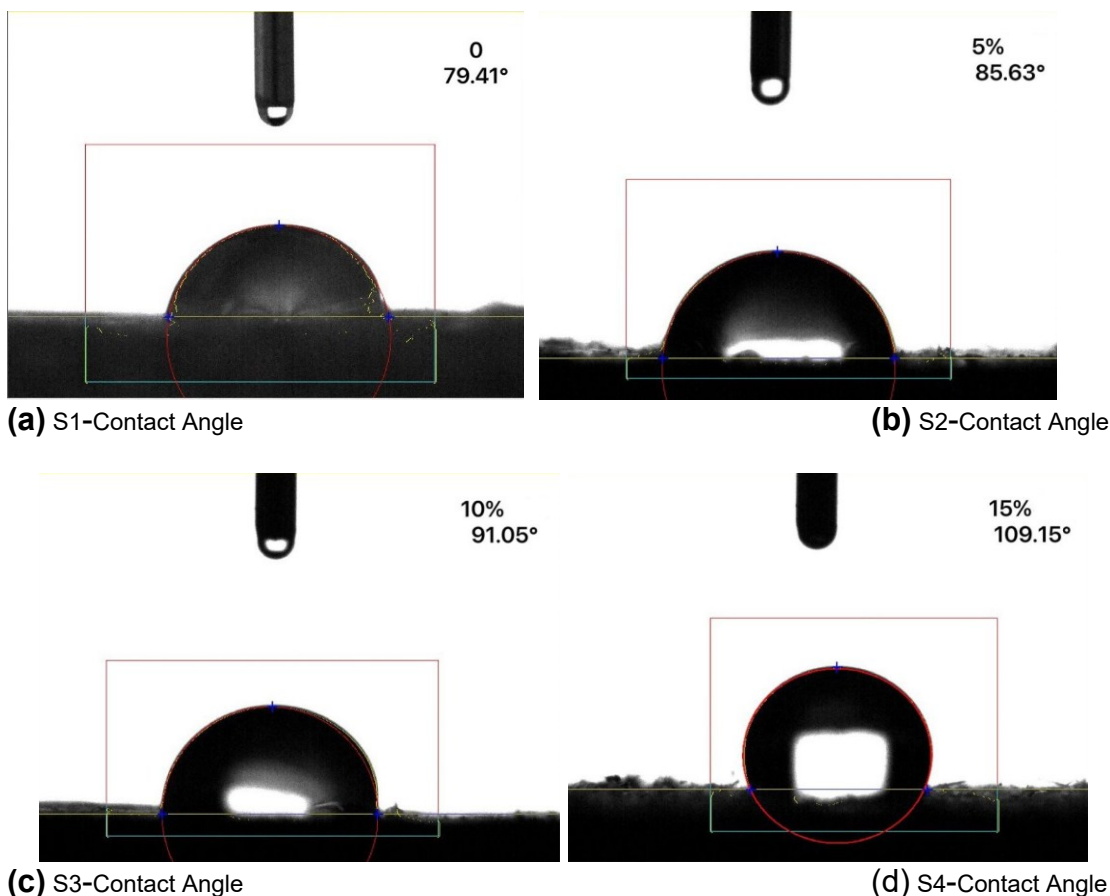


Fig. 1. Mechanical properties of colored wood-plastic composites

In contrast, flexural strength significantly decreased by 9.5% and 14.8% at 10% and 15% pigment contents, respectively. Impact strength also showed a significant decrease at 15% pigment loading (5.3% reduction), though the difference at 10% was not statistically significant. These results demonstrate that moderate pigment addition (5%) helped to maintain mechanical performance, whereas excessive loading ( $\geq 10\%$ ) led to notable deterioration in certain properties. Preliminary analysis attributes the negative effects to three main mechanisms: (1) pigment agglomeration at high concentrations causing interfacial defects and stress concentration; (2) restriction of polymer chain mobility due to excessive non-reinforcing fillers, reducing material toughness; and (3) encapsulation of wood fibers by pigment particles, compromising their reinforcement role and diminishing overall load-bearing capacity. Therefore, although pigments impart desirable coloration, their content should be controlled within 5% to balance aesthetic qualities and mechanical performance.

### Contact Angle

To determine the surface wettability of the WPCs, contact angle measurements were conducted using a goniometer. The sample was mounted on the instrument's stage, and a droplet of deionized water was deposited onto the material surface using a micro-syringe. After the droplet stabilized, an image was captured using a high-resolution camera, and the contact angle was analyzed with the corresponding software, as shown in Fig. 2.

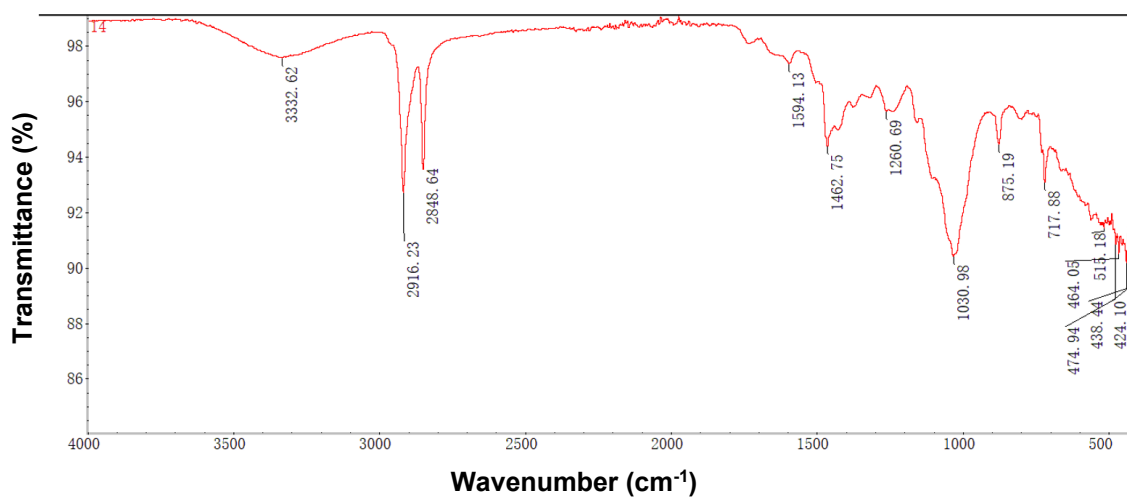


**Fig. 2.** Contact angle test

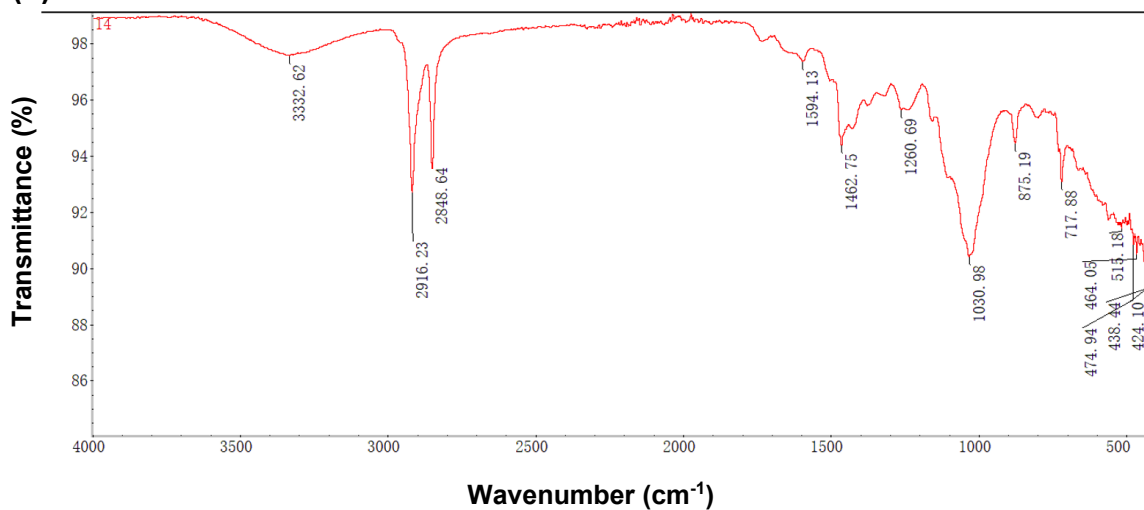
The results showed that as the pigment content increased from 0% to 15%, the static water contact angle significantly increased from 79.4° to 109.2°. This change indicates that the pigment enhanced the surface hydrophobicity of the material through two main mechanisms: first, pigment particles fill the micro-pores between the wood fibers and the matrix, reducing hydrophilic “recessed” areas and decreasing the contact area with water molecules; second, the pigment itself possesses low surface energy and inherent hydrophobic properties. As the pigment content increases, more hydrophobic particles accumulate on or near the surface, further lowering the overall surface energy. The synergistic effect of physical filling and intrinsic hydrophobicity leads to an increase in the contact angle, thereby enhancing the material’s water resistance and improving its application stability in humid environments. This not only improves the aesthetic appearance but also enhances the functional performance of the material.

### Fourier Transform Infrared Spectroscopy (FTIR)

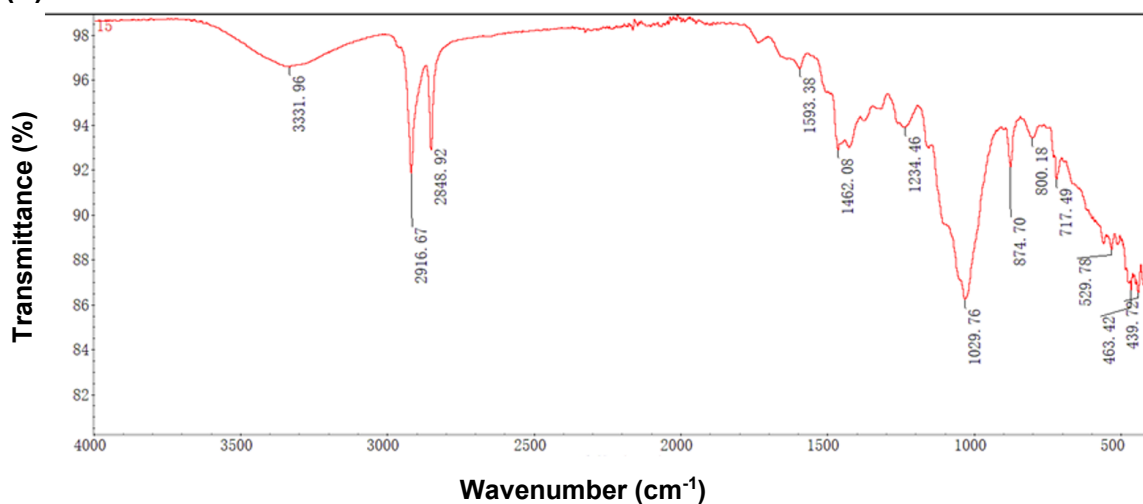
To investigate the influence of pigment addition on the molecular structure and functional groups of WPCs, FTIR analysis performed using the KBr pellet method was employed for characterization. The specific procedure involved accurately weighing 0.02 g of dried sample powder and thoroughly grinding it with 0.20 g of spectroscopic-grade KBr in an agate mortar. The mixture was then transferred into a mold and pressed into a transparent circular pellet with a diameter of 13 mm and uniform thickness using a TP-2 tablet press.



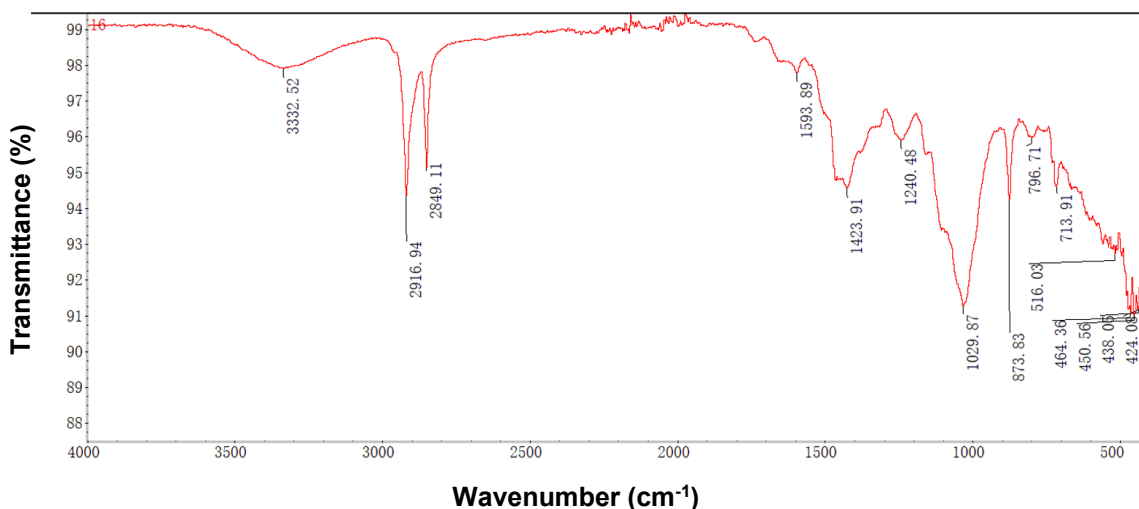
(a) S1- FTIR



(b) S2- FTIR



(c) S3- FTIR



(d) s4- FTIR

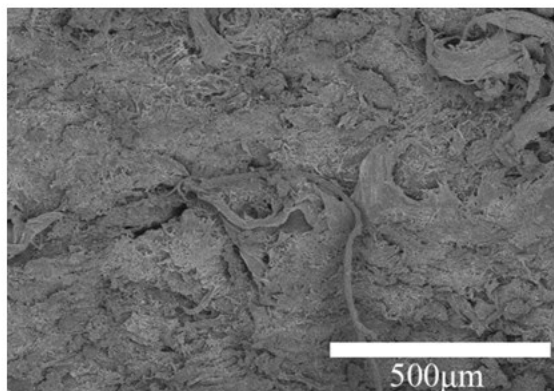
**Fig. 3.** Fourier transform infrared spectroscopy

Subsequently, the sample was placed in the FTIR spectrometer for testing under the following parameters: resolution of  $4\text{ cm}^{-1}$ , wavenumber range from  $4000\text{ to }400\text{ cm}^{-1}$ , and 16 scans, to obtain high-quality infrared spectra. Figures 3 show the FTIR spectra of WPCs containing 5%, 10%, and 15% pigment levels, respectively. These are compared with the sample without pigment (0%). The results indicate that all samples exhibited highly consistent characteristic absorption peaks, corresponding to typical vibrational modes of wood fibers (*e.g.*, cellulose, hemicellulose, lignin) and polymer matrices (*e.g.*, PE, PP, or PVC). This suggests that the introduction of pigment did not trigger new chemical reactions or generate new functional groups, indicating its presence mainly through physical filling. With increasing pigment content, some peak intensities change. Notably, the O–H stretching vibration peak ( $3300\text{ to }3400\text{ cm}^{-1}$ ) becomes weaker and broader, likely due to the pigment's hydrophobic nature reducing moisture absorption and partially shielding hydroxyl groups on the wood fiber surface. In the fingerprint region, the C–O stretching vibration peak (around  $1050\text{ cm}^{-1}$ ) also showed a similar decreasing trend, further supporting the shielding effect of pigment particles on the wood components. Overall, the degree of peak intensity variation correlated positively with pigment content—higher pigment levels ( $15\% > 10\% > 5\%$ ) result in more pronounced physical shielding effects on the wood fibers, leading to increasingly weakened IR signal responses. These findings provide molecular-level evidence of the physical dispersion behavior of pigment within the composite and its protective role toward the wood components.

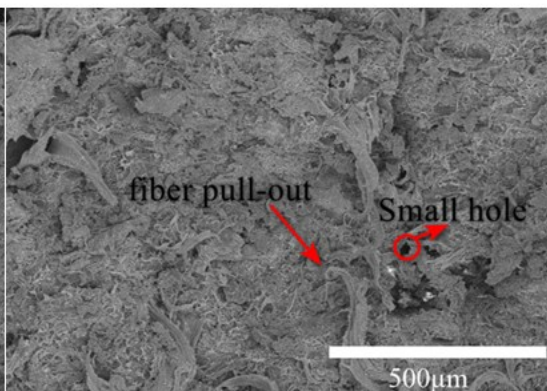
### Scanning Electron Microscopy Test

To further investigate the influence of pigment content on the interfacial bonding and microstructure of WPCs, scanning electron microscopy (SEM) was employed to observe the tensile fracture surfaces of the composite materials. Prior to SEM observation, the samples were coated with a thin layer of gold to enhance conductivity and improve image quality. Figure 4 shows the typical SEM micrographs of the tensile fracture surfaces of WPCs containing 5%, 10%, and 15% pigments, respectively. Microstructural analysis reveals significant differences in the interfacial bonding and fracture characteristics among the composites with varying pigment contents.

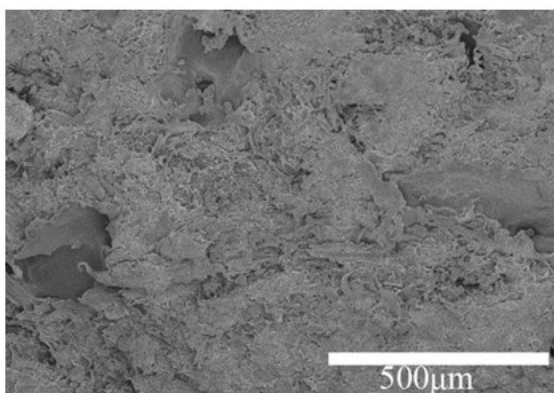
(a) S1-SEM



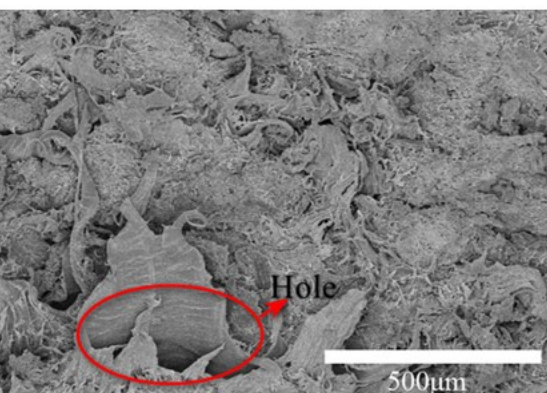
(b) S2-SEM



(c) S3 SEM



(d) S4 SEM

**Fig. 4.** Scanning electron microscopy test

As shown in Fig. 4(b), some degree of interfacial bonding between the wood fibers and polymer matrix was observed; however, fiber pull-out, debonding, and minor voids or defects were still evident. In contrast, Fig. 4(c) exhibits the relatively optimal interfacial condition, where the wood fibers were well embedded within the polymer matrix and surrounded by dispersed pigment particles. Fiber pull-out was significantly reduced, and the fracture surface appeared smoother and more compact, indicating improved compatibility and interfacial bonding strength. This microstructural feature aligns with the superior mechanical performance—particularly the impact strength—observed in this group. However, when the pigment content was further increased to 15% (Fig. 4(d)), the fracture surface became the roughest among all samples. It shows numerous exposed wood fibers, evident fiber pull-out holes, and pigment particle agglomeration. These features suggest that excessive pigment disrupts the effective bonding between the polymer matrix and the fibers, leading to deteriorated interfacial compatibility and the formation of numerous stress concentration zones and weak regions. The above microstructural observations are highly consistent with the results from the mechanical property tests. Specifically, the relatively flat and dense fracture morphology of the 10% pigment sample corresponded well with its favorable mechanical properties—especially its impact strength—indicating that good interfacial bonding is crucial for effective load transfer and enhanced toughness. Conversely, the rough fracture surface, pronounced fiber pull-out, and pigment agglomeration in the 15% pigment sample directly explain the significant decline

in mechanical performance—particularly in flexural and tensile strengths. The aggregated pigment particles and poor interfacial bonding act as stress concentrators and crack initiation sites, greatly weakening the material's load-bearing capacity.

Therefore, while an appropriate amount of pigment can improve interfacial bonding, excessive addition leads to performance degradation. This finding underscores the importance of optimizing pigment content to achieve the best overall performance in WPCs.

### Future Perspectives

While this study focused on a standard 50:50 formulation, future work will explore the interplay between pigment content and wood flour loading. Examining lower (*e.g.*, 30%) and higher (*e.g.*, 70%) wood content is crucial, as the hydrophilic nature of wood flour at high loadings may drastically alter the pigment's effect on hydrophobicity and mechanical properties. Additionally, investigating different pigment types (*e.g.*, organic vs. inorganic) and their cost–performance trade-offs would be highly valuable for industrial applications.

### CONCLUSIONS

This study systematically elucidated the threshold regulation effect and underlying mechanisms of pigment content on the performance of wood polymer composites (WPCs).

1. The results indicated that a pigment addition level of 5% achieved the optimal synergy between hydrophobicity and mechanical properties. The contact angle reached 85.6°, while all mechanical strengths peaked simultaneously. This improvement was mainly attributed to the effective encapsulation of wood fibers by pigment particles, which enhanced interfacial bonding.
2. When the pigment content reached or exceeded 10%, although the hydrophobicity continued to increase (contact angle rising to 109.2°), the mechanical performance declined significantly. For instance, the bending strength decreased by up to 14.8%.
3. Scanning electron microscope (SEM) observations confirmed that pigment agglomeration led to interfacial defects and stress concentration, which became key factors in the deterioration of load-bearing capacity.
4. Fourier transform infrared (FTIR) analysis revealed that the pigment weakened the response of hydrophilic groups such as O–H and C–O bonds in the wood fibers through a physical shielding effect, thereby enhancing the material's hydrophobicity.
5. In summary, 5% represents the performance equilibrium threshold for functional WPC formulation design. In contrast, high pigment loading above 10% is only suitable for applications with extreme hydrophobic requirements, where additional interfacial modification measures should be implemented to compensate for the associated loss in mechanical performance. This study provides both theoretical guidance and practical support for the functional design and performance optimization of WPCs.

## ACKNOWLEDGMENTS

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