Tannin-Sucrose Adhesive Properties: A Comparison of Bayberry and Acacia Tannins

Jiankun Liang,[a,#] Shuang Yin,[b,#] Cheng Li,[a] Linjing Lan,[b] Xin He,[b] Haiyuan Yang,[b] Yuqi Yang,[b] Yu He,[b] Hui Yang,[a,*] and Zhigang Wu [b,*]

Bayberry tannin and acacia tannin were selected as raw materials to prepare tannin-sucrose adhesives, and their properties were investigated. Fourier transform infrared spectroscopy (FT-IR) analysis results indicated that both bayberry tannin and acacia tannin were condensed tannins, composed of polymerized flavonoid monomer units, with their repeating units often closely connected to the A and B rings of carbohydrates, with bayberry tannin containing relatively more trisubstituted benzene structural units. Hot-pressing temperature was found to have a significant impact on the adhesive performance. When the hot-pressing temperature was set at 215 °C, the bayberry tannin-sucrose adhesive exhibited excellent bonding performance, meeting the strength requirements of Class II plywood in GB/T 17657 (2022) (≥0.70 MPa). Thermogravimetric (TG) test results revealed that the cured product of the bayberry tannin-sucrose adhesive had superior thermal stability. Scanning electron microscopy (SEM) observations showed that the cured product of the acacia tannin-sucrose adhesive had cracking and porosity on the cross-section, while the cured product of the bayberry tannin-sucrose adhesive presented a unique complex wrinkled structure on the cross-section, which endowed it with higher toughness and better environmental resistance.

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Keywords: Bayberry tannin; Acacia tannin; Sucrose; Wood adhesive; Bonding performance

*Contact information: a: College of Civil Engineering, Kaili University, Qiandongnan 556011, China; b: College of Forestry, Guizhou University, Guiyang 550025, China; #: These two authors contributed equally to this work; *Corresponding authors: yh7005@126.com; wzhigang9@163.com*

INTRODUCTION

In many industrial production fields today, adhesives have become a key material, especially in the wood processing industry, where their role is of great significance. Although petroleum-based adhesives have long dominated the market, the development of new environmentally friendly adhesives has become an urgent priority due to issues such as raw material shortages, rising costs, and adverse impacts on the natural environment (Liu *et al*. 2019; Mirski *et al*. 2020; Yang and Rosentrater 2020; Xu *et al*. 2022; Deng *et al*. 2025). Tannin, as a natural and renewable resource, has shown great potential in the field of adhesives due to its rich chemical functional groups and good renewability. Therefore, tannin has gradually become a research hotspot (Arias *et al*. 2021; Xiao *et al.* 2022, 2023; Li *et al*. 2023; Oktay *et al*. 2024a).

Tannin is widely found in the plant kingdom, and tannins from different plant sources vary in chemical structure and properties. Both *Myrica rubra* tannin and *Acacia* tannin are typical condensed tannins, with their main components being high molecular weight compounds polymerized from flavonoid units. Tannin molecules contain abundant active functional groups such as phenolic hydroxyl groups and ether bonds, which endow tannins with good reactivity and cross-linking ability. Research has shown that the phenolic hydroxyl groups of tannins can undergo cross-linking reactions with a variety of substances to form a three-dimensional network structure, thereby enhancing the strength and water resistance of adhesives (Gu *et al*. 2023; Liang *et al*. 2024; Oktay *et al*. 2024b; Zhou *et al*. 2025). This characteristic gives tannins a broad application prospect in the field of adhesives, but systematic comparative studies on different types of tannins are still relatively limited at present.

In recent years, with the in-depth research on natural polymer materials, sucrose, as a renewable resource, has gradually attracted attention in the field of adhesives. During the thermal treatment process, sucrose undergoes depolymerization reactions to generate 5-hydroxymethylfurfural (5-HMF), which can react with the phenolic hydroxyl groups in tannins to form a stable network structure (Zhao and Umemura 2014, 2015; Zhao *et al*. 2015, 2020; Sakai *et al*. 2023; Wu *et al*. 2025). This reaction mechanism provides a theoretical basis for the development of new tannin-sucrose adhesives. However, research on the effects of hot-pressing process conditions on the properties of tannin-sucrose adhesives and the differences in cross-linking reactions between different types of tannins and sucrose is still not in-depth enough. In the field of wood bonding, the properties of adhesives are directly related to the quality and service life of products. Up to this point, research on the application of tannin-sucrose adhesives in wood bonding mainly has focused on single types of tannins, lacking systematic comparisons of different tannin types. Meanwhile, there has been little research on the relationship between the microstructure and macroscopic properties of adhesives, resulting in an insufficient understanding of the mechanisms for improving adhesive performance.

In summary, a thorough investigation of the performance differences and influencing factors of different tannin-sucrose adhesives is of great theoretical significance and practical application value for the development of high-performance, environmentally friendly wood adhesives. This study used bayberry tannin and acacia tannin to explore the effects of hot-pressing temperature and other process conditions on the bonding performance of tannin-sucrose adhesives. It also reveals the underlying mechanisms for performance improvement from multiple aspects, including chemical structure, thermal stability, and microstructure, with the aim of providing the wood processing industry with a new type of environmentally friendly and efficient adhesive option. Furthermore, the abundant bayberry tannin and acacia tannin in the Guizhou region of China are selected as raw materials, which provided a theoretical and technological foundation for the high-value utilization of the rich forest tannin resources in Guizhou.

EXPERIMENTAL

Materials

Bayberry (*Myrica rubra*) tannin and acacia (*Acacia mangium*) tannin, industrial grade (particle size approximately 150 μm), were obtained from Wuming Tannin Factory in Guangxi, China. Sucrose (99.0 wt%), analytical grade, was purchased from Chengdu Jinshan Chemical Reagent Co., Ltd. Poplar veneer (*Populus* spp., moisture content 8 to 10%), with dimensions of 400 mm × 400 mm and a thickness of 1.5 mm, was sourced from Suqian, Jiangsu, China.

Preparation of Tannin-Sucrose Adhesive and Testing of Bonding Performance

Under ambient temperature conditions, 33.3 g of distilled water was added to a round-bottomed three-neck flask equipped with a mechanical stirrer, thermometer, and condenser. The mixture was heated to 60 °C, and then 20 g of sucrose was added. After the sucrose was completely dissolved, 30 g of tannin was added in batches. The mixture was stirred until it reached a paste-like consistency. Subsequently, sodium dodecylbenzene-sulfonate (0.5% of the total mass of tannin and sucrose) as a dispersant was added, and the mixture was stirred for an additional 5 min. The obtained bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive was named as BTs and ATS, respectively.

Three-layer poplar plywood was fabricated in the laboratory. The adhesive was applied to the veneer with 160 g/m^2 on a single surface. After assembly, the panels were cold-pressed for 10 minutes, followed by hot-pressing. In order to ensure that the adhesive was able to fully cure, based on the previous research (Xiao *et al*. 2022, 2023), two hot-pressing temperatures of 190 and 215 ºC, unit hot-pressing pressure of 1.5 MPa, and hot-pressing time of 1 min/mm were prepared for the experiment. The bonding strength was tested in accordance with the national standard GB/T 17657 (2022). The final strength value was the average of 10 specimens.

Fourier Transform Infrared Spectroscopy (FT-IR) Testing

A Thermo Fisher Scientific Nicolet iS20 spectrometer (USA) was used to record the spectra in the range of 4000 to 400 cm^{-1}, with a resolution of 4 cm^{-1} and 32 scans.

Thermogravimetric (TG) Testing

The solidified adhesive powder was subjected to TG testing using a Netzsch TG 209 F3 thermogravimetric analyzer (Germany). The test was conducted under nitrogen protection, with a heating rate of 10 °C/min and a temperature range of 30 to 800 °C.

Scanning Electron Microscopy (SEM) Testing

After gold-coating the fracture surface of the solidified adhesive layer, observations were made using a ZEISS GeminiSEM 300 scanning electron microscope (Germany).

RESULTS AND DISCUSSION

Structural Analysis of Bayberry Tannin and Acacia Tannin

Figure 1 presents the infrared spectra of bayberry tannin and acacia tannin. A series of characteristic absorption peaks can be clearly observed, which are closely related to the chemical structure of tannins and it also confirm the structural similarity between tannins and phenol, with phenolic hydroxyl groups being the core functional groups (Xiao *et al.* 2022, 2023). Specifically, the absorbance peaks at wavenumbers 1617, 1514, and 1453 cm^{-1} correspond to the stretching vibration modes of the skeletal carbon atoms in the phenolic aromatic ring. These are typical vibrational characteristics of aromatic rings, reflecting the conjugated system and stability of the benzene ring structure. The absorption peaks at 1345 and 1031 cm^{-1} are attributed to the bending vibration of the O-H bond and the stretching vibration of the C-O bond in phenols, respectively. These vibrational modes are directly related to the chemical environment and connectivity of the phenolic hydroxyl groups, providing strong evidence for the presence of phenolic hydroxyl groups in tannins.

The absorbance peaks observed at 1153 and 1103 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of the aromatic ether bond (C-O-C), indicating the presence of ether-linked structural units in the tannin molecules (Zhao *et al*. 2015, 2020). The absorbance peak at 843 cm^{-1} is characteristic of a tri-substituted benzene ring, suggesting the presence of three substituents on the benzene ring. However, the higher intensity of this peak in bayberry tannin indicates certain differences in the benzene ring substitution pattern or molecular structure details between bayberry tannin and acacia tannin, or it may imply that bayberry tannin contains more tri-substituted benzene structural units.

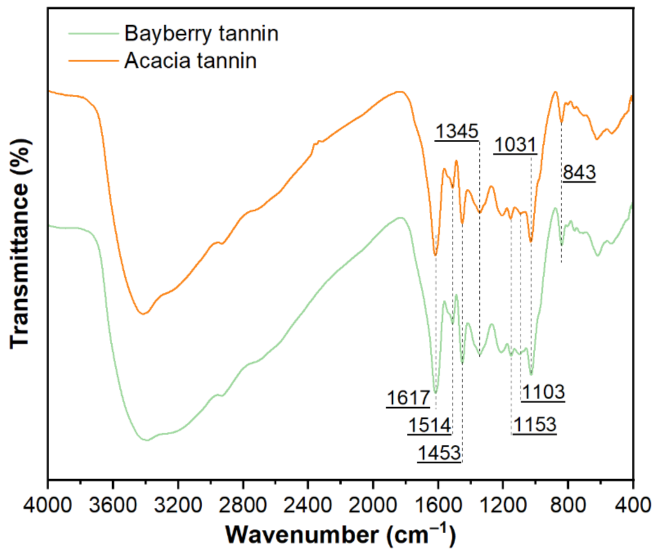

Fig. 1. FT-IR spectra of bayberry tannin and acacia tannin

Overall, the infrared spectra of bayberry tannin and acacia tannin show a high degree of consistency in peak patterns, indicating that both tannins share similar characteristic functional groups in their chemical composition. Both bayberry tannin and acacia tannin are condensed tannins, composed of polymerized flavonoid monomer units, with their repeating units often closely connected to the A and B rings of carbohydrates. The flavonoid units in bayberry tannin are primarily composed of a resorcinol A ring and a biphenyltriol B ring, while those in acacia tannin are mainly constructed from a resorcinol A ring and a catechol B ring (Gu *et al*. 2023; Wu *et al*. 2025). The content of these units is also quite similar in both tannins. From a microscopic perspective of molecular structure, both bayberry tannin and acacia tannin molecules contain a resorcinol A ring. The two phenolic hydroxyl groups on the A ring significantly enhance the electron density of the benzene ring, particularly at the C6 and C8 positions, where the increase in electron density is particularly pronounced. This greatly enhances the nucleophilicity of the aromatic ring. As a result, during chemical reactions, the C6 and C8 positions of the A ring become the primary reactive sites, where various electrophilic reagents often initiate attacks, triggering a series of chemical reactions. There are also some structural differences between bayberry tannin and acacia tannin, which lead to differences in their chemical reactivity (Zhao *et al*. 2020; Gu *et al*. 2023). Bayberry tannin has a relatively low degree of polymerization and a lower average molecular weight, with a significant proportion of branched-chain molecules. These structural characteristics make bayberry tannin exhibit more reactive sites, relatively smaller steric hindrance, and a higher degree of cross-linking when reacting with sucrose.

Bonding Performance

The key to the good bonding performance of the tannin-sucrose adhesive lies in the conversion of sucrose into 5-HMF, which then undergoes cross-linking reactions with tannins. Figure 2 shows the infrared spectral characteristics of sucrose at different temperatures. The absorbance peaks observed at 1129 and 989 cm^{-1} are attributed to the C-O-C stretching vibrations of the glycosidic bonds and the ether bonds in the glucose ring of sucrose molecules, which are key indicators of the sugar ring structure in sucrose molecules. The absorbance peak at 1068 cm^{-1} corresponds to the hydroxymethyl group in sucrose molecules, while the peak at 909 cm^{-1} is assigned to the C-O-C stretching vibration of the pyranose ring in sucrose molecules.

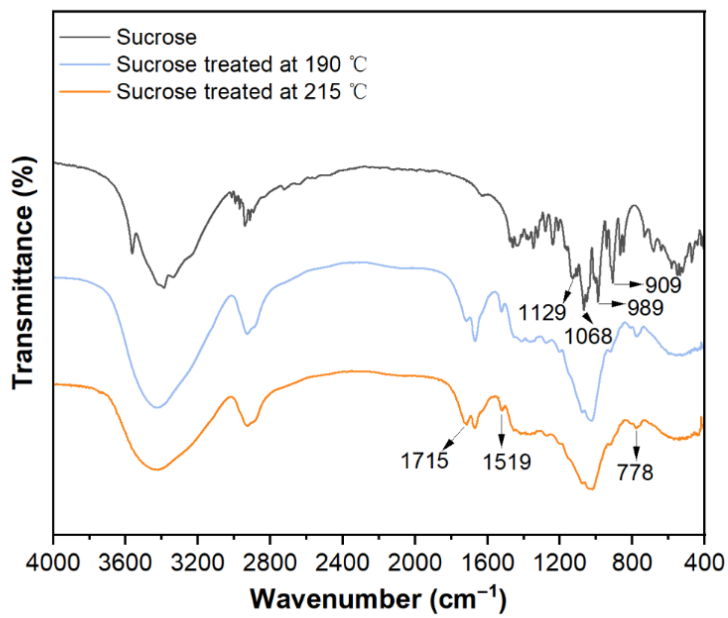

Fig. 2. FT-IR spectra of sucrose at different temperatures

After thermal treatment, the spectra had undergone significant changes: the absorbance peaks at 1129 and 989 cm^{-1} had almost completely disappeared, while new peaks appeared at 1519 and 778 cm^{-1}, which corresponded to the C=C double bond stretching vibrations in the furan ring and the stretching vibrations of unsubstituted CH=CH groups, respectively (Xiao *et al.* 2022, 2023; Wu *et al*. 2025). These changes indicate that during the thermal treatment, the sucrose molecules underwent depolymerization and structural transformation, resulting in the formation of furan compounds. When the treatment temperature was further increased to 215 °C, the absorbance peak at 912.7 cm^{-1} also almost disappeared, indicating that the depolymerization of sucrose was further enhanced and the molecular structure underwent more significant changes. From a chemical reaction mechanism perspective, sucrose is a disaccharide formed by the connection of one molecule of glucose and one molecule of fructose through a 1,2-glycosidic bond. During thermal treatment, the glycosidic bond breaks, and sucrose dissociates into glucose and fructose. Subsequently, glucose molecules undergo isomerization reactions to convert into fructose, and fructose further dehydrates to form 5-hydroxymethylfurfural (5-HMF) (Xiao *et al*. 2022, 2023). The absorbance peak at 1715 cm^{-1} corresponds to the stretching vibration of the aldehyde group, and the appearance of this peak confirms the formation of 5-HMF. Moreover, with increasing thermal treatment temperature, the intensities of the absorption peaks at 1715 and 1519 cm^{-1} gradually increased, indicating that the content of 5-HMF in the product correspondingly increased and the reaction extent deepened. This phenomenon is consistent with reports in the literature (de Oliveira *et al.* 2015), further confirming the transformation pathway of sucrose during thermal treatment.

As shown in Table 1, the hot-pressing temperature had a significant impact on the bonding performance of both bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive. At a hot-pressing temperature of 190 °C, the dry bonding strength of bayberry tannin-sucrose adhesive was 1.50 MPa, while that of acacia tannin-sucrose adhesive was 1.24 MPa. Neither adhesive exhibited water-resistant strength at this temperature. Combined with FT-IR analysis, it can be inferred that the conversion of sucrose to 5-hydroxymethylfurfural (5-HMF) was relatively limited at this temperature, resulting in insufficient cross-linking reactions with tannins and a less dense adhesive network structure.

Table 1. Effect of Hot-Pressing Temperature on the Bonding Performance of Bayberry Tannin-Sucrose Adhesive and Acacia Tannin-Sucrose Adhesive

Adhesive	Bonding strength at hot-pressing temperature of 190 °C			Bonding strength at hot-pressing temperature of 215 °C		
	Dry strength (MPa)	Wet strength in warm water (MPa)	Wet strength in boiling water (MPa)	Dry strength (MPa)	Wet strength in warm water (MPa)	Wet strength in boiling water (MPa)
BTS	1.50(0.08)	0	0	1.81(0.17)	0.90(0.09)	0.62(0.05)
ATS	1.24(0.06)	0	0	1.69(0.15)	0.72(0.08)	0.51(0.07)

When the hot-pressing temperature was increased to 215 °C, the performance of the adhesives underwent a significant and positive transformation. At this temperature, the dry strength of bayberry tannin-sucrose adhesive increased to 1.81 MPa, and that of acacia tannin-sucrose adhesive reached 1.69 MPa. Meanwhile, the water-resistant bonding strength of both adhesives met the Class II plywood strength requirements (≥0.70 MPa) specified in GB/T 17657 (2022), with values of 0.90 and 0.72 MPa, respectively. They also demonstrated certain boiling water-resistant bonding strengths, at 0.62 and 0.51 MPa, respectively. This improvement is attributed to the more complete depolymerization and conversion of sucrose at the higher temperature, resulting in the formation of more 5-HMF. These 5-HMF molecules underwent more extensive cross-linking reactions with tannins, creating a more robust, dense, and stable adhesive network structure, which significantly enhanced the dry strength and water resistance of the adhesives.

From the perspective of the chemical structure of tannins, both bayberry tannin and acacia tannin are rich in active phenolic hydroxyl groups, which can cross-link with 5-HMF to form a three-dimensional network structure. This 3D network structure not only enhances the dry strength of the adhesive but also effectively improves its water resistance. Bayberry tannin, with its relatively low degree of polymerization and higher proportion of branched-chain molecules, has more reactive sites and less steric hindrance when reacting with sucrose. Therefore, it can more efficiently cross-link with 5-HMF, resulting in higher dry strength and superior water resistance.

Thermal Stability Analysis

The maximum decomposition temperature of the cured product of bayberry tannin-sucrose adhesive reached 285 °C, which is significantly higher than that of acacia tannin-sucrose adhesive (205 °C). This phenomenon strongly indicates that the bayberry tannin-sucrose adhesive had superior thermal stability. The flavonoid units of bayberry tannin are constructed based on a resorcinol A ring and a biphenyltriol B ring. This unique structural combination endows it with many favorable characteristics. During the thermal decomposition process, bayberry tannin can form a series of thermodynamically more stable intermediate products. These intermediate products, with their inherent chemical bond strength and structural integrity, can effectively resist heat-induced decomposition reactions, thereby significantly delaying the occurrence of substantial mass loss. As a result, the bayberry tannin-sucrose adhesive can maintain its structural integrity for a longer period when exposed to high-temperature environments, thus significantly enhancing its thermal stability.

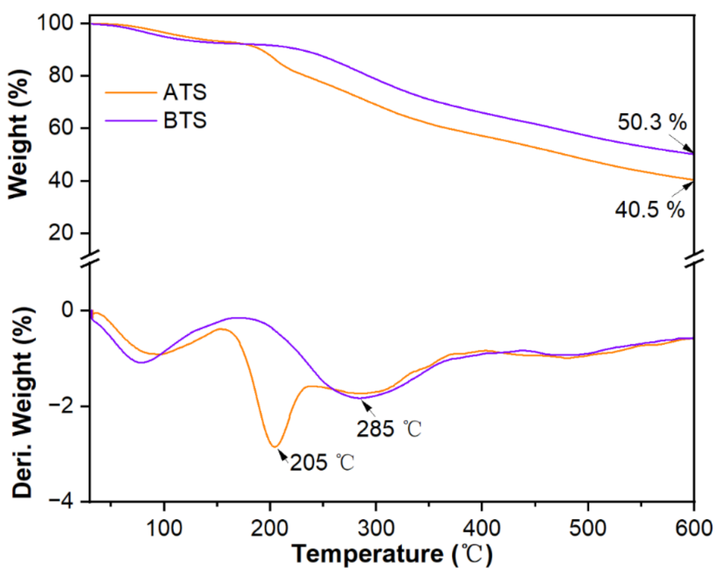

Fig. 3. Thermal stability test results of bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive

At 600 °C, the char yield of the cured product of bayberry tannin-sucrose adhesive reached 50.3%, while that of acacia tannin-sucrose adhesive was only 40.5%. This significant difference in char yield intuitively reflects the superior charring performance of bayberry tannin-sucrose adhesive under high-temperature conditions. Char yield, as a key indicator of the material's ability to retain its carbon skeleton structure at high temperatures, is closely related to the material's chemical composition and structure. Bayberry tannin is rich in active functional groups such as phenolic hydroxyl groups and ether bonds, which play a crucial role in high-temperature environments. During thermal decomposition, phenolic hydroxyl groups can undergo complex reactions such as dehydration and polymerization, recombining with other carbon atoms to form a denser and more stable carbon layer structure. Ether bonds can also promote the cross-linking of the carbon skeleton to some extent, further enhancing its structural stability and integrity (Wu *et al*. 2025). These dense carbon layers act as a robust barrier, effectively resisting further heat intrusion from the outside and reducing continuous mass loss.

In summary, the significant differences in thermal decomposition properties between bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive demonstrate a close intrinsic relationship between the tannin molecular structure and the thermal stability and charring performance of the adhesive.

Scanning Electron Microscopic Analysis

Figure 4 presents the SEM test results of the fracture surfaces of the cured products of bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive. The fracture surface of the acacia tannin-sucrose cured product exhibits a relatively smooth surface morphology. This characteristic may imply that during the curing reaction process, the cross-linking reaction between acacia tannin and sucrose is highly uniform. The molecular chains within the adhesive system can arrange and cross-link in a relatively orderly manner, resulting in a relatively flat fracture surface. However, it is worth noting that beneath this smooth surface, there were evident cracking phenomena and porous structures. The presence of these micro-defects is likely due to localized stress concentration within the adhesive during the curing process (Liang *et al*. 2024). This may be because certain areas in the reaction system did not achieve complete cross-linking, leaving these potential weak points. These micro-defects could have a significant impact on the overall performance of the adhesive. First, in terms of mechanical properties, the presence of pores and cracks reduces the cohesive strength of the adhesive. When subjected to external forces, these defects tend to become stress concentration zones, which can trigger crack propagation and lead to premature adhesive failure. Second, regarding water resistance, these pores and cracks provide pathways for water molecule penetration. Once water molecules infiltrate the interior of the adhesive, they will adsorb and diffuse on the pore surfaces, gradually weakening the interactions between adhesive molecules and the bonding strength between the adhesive and the substrate, ultimately resulting in a significant decrease in the adhesive's bonding strength and water resistance.

The SEM image of the bayberry tannin-sucrose cured product reveals a completely different microstructural feature. Its fracture surface does not exhibit a single smooth morphology but clearly shows a complex structure composed of both flat and wrinkled regions. The formation of this wrinkled structure may be due to more complex cross-linking reactions between bayberry tannin and sucrose during the curing process (Liu *et al*. 2019; Deng *et al*. 2025). As the adhesive molecular chains cross-link, they undergo a certain degree of displacement and deformation under the influence of internal stresses, resulting in the undulating wrinkled morphology on the fracture surface. This wrinkled structure appears to play a crucial role in enhancing the performance of the adhesive. From a mechanical perspective, the wrinkled structure endows the adhesive with higher toughness. When subjected to external forces, these wrinkled regions can dissipate energy through their own deformation, effectively reducing stress concentration. Compared to acacia tannin-sucrose adhesive, this energy dissipation mechanism allows bayberry tannin-sucrose adhesive to better distribute stress under impact or tensile forces, reducing the risk of crack formation and significantly improving the adhesive's cohesive strength and toughness. In terms of environmental resistance, the high toughness of the adhesive enables it to better accommodate minor deformations at the interface. In practical application environments, bonded structures are often affected by various factors, such as temperature changes, humidity fluctuations, and mechanical vibrations, all of which can cause minor displacements and deformations at the interface. The highly tough bayberry tannin-sucrose adhesive can adapt to these minor changes through its own deformation, preventing crack formation and propagation, and effectively maintaining the integrity of the bonded structure.

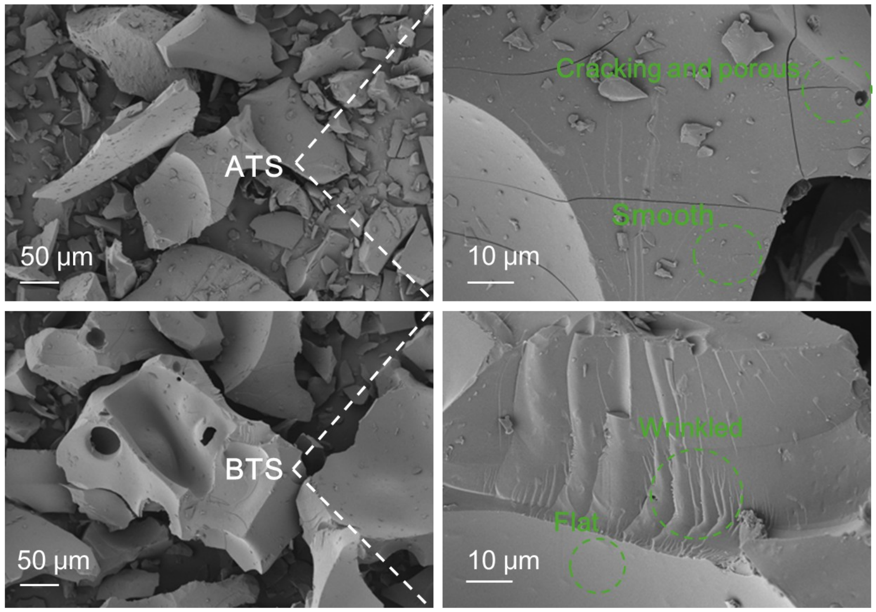

Fig. 4. SEM results of the fracture surfaces of the cured products of bayberry tannin-sucrose adhesive and acacia tannin-sucrose adhesive

CONCLUSIONS

1. Hot-pressing temperature was found to have a significant impact on the adhesive properties. At a higher hot-pressing temperature (215 °C), the conversion efficiency of sucrose to 5-HMF was higher. The bayberry tannin-sucrose adhesive demonstrated superior bonding performance, with higher dry strength and water resistance compared to the acacia tannin-sucrose adhesive, and it met the Class II plywood strength requirements specified in GB/T 17657-2022.
2. The cured product of bayberry tannin-sucrose adhesive exhibited higher thermal stability and charring performance, primarily due to the unique molecular structure of bayberry tannin. In terms of microstructure, the wrinkled structure of the cured bayberry tannin-sucrose adhesive provided advantages in mechanical and environmental resistance properties.
3. The bayberry tannin-sucrose adhesive, with its excellent comprehensive performance, has greater application potential in the field of adhesives and could serve as a high-performance new adhesive. However, further research is still needed to fully assess its practical application value and explore its broader application prospects.

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