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Physical and Mechanical Properties of Poplar Wood Modified by Glucose-Urea-Melamine Resin/Sodium Silicate Compound

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Abstract: In order to improve the performance of soft plantation wood, an environmentally friendly wood modifier was developed. First, using urea and melamine as crosslinking agents, the glucose-urea-melamine resin (MUG) was prepared with glucose under the catalysis of inorganic acid and metal ions. Then MUG, sodium silicate, and distilled water were mixed and stirred at 40 °C to prepare MUG resin/sodium silicate compound modifier ($G_{20}S_{10}$, $G_{10}S_{20}$, the subscript number represents the mass percentage of the component in the solution.). Then plantation poplar wood (*Populus tomentosa*) was impregnated and modified with them. Their physical and mechanical properties were tested and compared with those of the wood treated with sodium silicate of 20% mass fraction (S_{20}). Infrared analysis showed that the amino resin characteristic structure (CO-NH-) existed in MUG, and the absorption peak of the furan ring (C=C) appeared. Compared with S_{20} modified wood, the shrinkage degree of $G_{10}S_{20}$ or $G_{20}S_{10}$ modified wood is reduced, their moisture absorption is decreased, and their dimensional stability is improved. MUG resin/sodium silicate compound modifier can effectively enhance the wood's density, modulus of elasticity, modulus of rupture, and compression strength. SEM analysis showed that there were columnar and granular solid substances attached to the cell wall, cell lumen, intercellular space, and vessel of $G_{20}S_{10}$ modified wood. EDX showed that the number of Si elements on the cell wall was significantly increased compared with the control, indicating that the modifier effectively entered the wood cell wall. The $G_{20}S_{10}$ can greatly improve the wood's physical and mechanical properties through an organic-inorganic compound synergistic effect. It is a green, non-formaldehyde, low cost wood modifier with broad application prospects.

Keywords: poplar; glucose resin; sodium silicate; impregnation modification; wood properties

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1. Introduction

As a natural biomass material, wood is widely used in the construction industry and furniture manufacturing. In order to reduce the logging of naturally-grown forests and protect the ecological environment of forests, plantation trees are widely planted and become the main source of timber supply [1]. Poplar is one of the most widely planted fast-growing tree species in China. The fast-growing wood usually has some undesirable characteristics, such as low density, low durability, and less strength, which limits its applications and development. Wood modification can improve the performance and produce added value of fast-growing poplar [2]. Impregnation treatment is a commonly used modification method for plantation poplar. The main impregnations include low molecular weight prepolymer of urea-formaldehyde resin, phenolic resin, melamine-formaldehyde resin, melamine-urea-formaldehyde resin and other formaldehyde-based resins, and reactive monomers such as furfural, dimethylol dihydroxy ethylene urea, and acetic anhydride [3,4]. The release of small molecule volatiles such as formaldehyde during production and use will endanger human health and environmental safety. Low reactivity (dimethoxyacetaldehyde) [5], strong pungent odor (glutaraldehyde) [6], high cost, poor resin performance, and other issues restrict the application of non-formaldehyde crosslinking agents. It is

the development trend of the wood processing industry to further reduce the emission of harmful substances by developing environmentally-friendly, sustainable, and low-cost wood impregnation resins.

Glucose is a natural product of photosynthesis and a renewable and biodegradable material. Its molecules are rich in active groups such as hydroxyl groups [7]. It has the advantages of low cost and adjustable structure, and can be processed into environmentally friendly polymer products [8,9]. Glucose, urea, phenol, and other cross-linking agents can generate waterborne resins under hydrothermal reaction and inorganic acid and metal ion catalyst conditions [10]. Glucose and other carbohydrates with low molecular weight can be dehydrated under high temperature and strong acid conditions to form the active monomeric substance of 5-hydroxymethyl-2-furaldehyde (HMF) [11]. For glucose, it is first isomerized into fructose, and under the condition of solid acid catalysis, fructose is further dehydrated into HMF [12]. In the presence of a catalyst, HMF reacts with phenol to form resin prepolymer [13], which has a certain degree of water resistance and bonding strength [14,15]. Based on the structural characteristics of HMF, glucose-urea resin and glucose-melamine resin have been tried for synthesis, but most studies are about the performance of the solution, and the mechanism is not discussed [16,17]. Using glucose instead of formaldehyde to prepare formaldehyde-free biomass-based resin products provides a new idea for wood green modification.

Silicon compounds are widely used in wood modification. Sodium silicate (also called water glass), a soluble alkali silicate, is non-toxic and low-cost. It can improve the mechanical properties and flame retardancy of wood [18,19]. However, sodium silicate has strong alkalinity and is easy to absorb moisture, which causes the wood to shrink; and it can be easily leached out from the wood [20]. In order to reduce the defects of sodium silicate modified wood, the compounding modification of formaldehyde-based resin and sodium silicate has obvious effects [21]. The compounding effect is primarily due to the mechanism of physical encapsulation of polymerized resin in wood [22].

In this paper, glucose-urea-melamine resin (MUG) was prepared with glucose as the main raw material. Then MUG and sodium silicate were blended to prepare MUG resin/sodium silicate compound modifier. Then the poplar wood was impregnated with this compound modifier, and the properties of the modified wood were tested and analyzed. It is a green wood modification of profound significance.

2. Materials and Methods

2.1. Materials

Ten to twelve-years old plantation poplar (*Populus tomentosa*) wood with a diameter over 30 cm at breast height was obtained from Yixian, Heibei Province, China, and its air-dried density is 0.436 g/cm³. The average tree height is 16 m, with straight trunks and no defects. All samples were cut from the sapwood area of poplar and processed into specified sizes according to national standards. Glucose (C₆H₁₂O₆) was purchased from Xilong Science Co., Ltd., Shantou, China; melamine (C₃H₆N₆) and urea (CH₄N₂O) were obtained from Fuchen Chemical Reagent Company, Tianjin, China; sodium silicate (Na₂SiO₃), itaconic acid (C₅H₆O₄), and boric acid (H₃BO₃) were from Aladdin Reagent Co., Ltd, Shanghai, China; Copper sulfate (CuSO₄) and ammonium chloride (NH₄Cl) were purchased from Sinopharm Chemical Reagent Co., Ltd, Beijing, China. The concentration of self-made sodium hydroxide and hydrochloric acid solution is 20% mass fraction.

2.2. Preparation of MUG Resin/Sodium Silicate Compound Modifier

First, 370 g of glucose, 26 g of melamine, and 260 g of distilled water were added into the reactor and fully stirred to dissolve at 60 °C, an appropriate amount of copper sulfate and ammonium chloride were used to modulate the solution pH value about 3, then 49 g of urea was added, and the temperature was heated up to 100 °C. When the solution color became reddish brown (the color of the solution changes as light blue-colorless and transparent-light yellow-orange-dark red-reddish brown during the whole process), the

pH value was adjusted to 6.5–8.5 using hydrochloric acid and sodium hydroxide, the solution was cooled down to 40 °C, here 2 wt% curing agents (the mass ratio of itaconic acid and boric acid as a curing agent was 1:1) were added and reacted for 1 h. Then the glucose-urea-melamine resin (MUG) was prepared. According to national standard GB/T 14074-200697 [23], its water solubility was tested with a graduated glass tube of 10 mL. When 1 mL resin was fully blended with 9 mL distilled water at 23 °C, the blend solution is still clear without precipitation, the water solubility multiple of the resin is considered to be more than 9. About 1 g resin was heated at 120 °C for 2 h to calculate its solid content as 52.6%. The viscosity of 4.2 m·Pa·s was tested by a rotary viscometer (NDJ-5S, Lichen, China). Each value was tested three times and the average value was taken.

The compound modifier ($G_{20}S_{10}$, $G_{10}S_{20}$) was prepared by blending MUG and sodium silicate at 40 °C for 5 min. The subscript number represents the mass percentage of the component in the solution, i.e., the mass fractions of MUG and sodium silicate in $G_{20}S_{10}$ were 20% and 10%, respectively, the mass fractions of MUG and sodium silicate in $G_{10}S_{20}$ were 10% and 20%, respectively. S_{20} is the sodium silicate aqueous solution of 20% mass fraction.

2.3. Wood Impregnation

Before impregnation, all samples were processed into standard sizes and oven-dried at 103 °C, their oven-dry weight and dimensions were measured. They were impregnated with S_{20} , $G_{10}S_{20}$, and $G_{20}S_{10}$, respectively, through vacuum-pressure method as vacuuming (−0.09 MPa, 0.5 h) → liquid injection → pressurization (1.0 MPa, 24 h) → pressure relief. After being taken out, specimens were first air-dried to about 50% moisture content, then dried at gradually raised 103 °C to be oven-dry, and S_{20} , $G_{10}S_{20}$, and $G_{20}S_{10}$ modified poplar wood were obtained, respectively.

2.4. Physical and Mechanical Properties

Weight percentage gain (WPG) and bulking effect (BE) are used to characterize the size and quality changes of wood before and after impregnation. The WPG and BE were calculated as the following Formulas (1) and (2). The specimen size is $20 \times 20 \times 20 \text{ mm}^3$ (longitudinal × radial × tangential, Abbr. L × R × T). Ten replicates were conducted for each group, and the statistical average value was taken.

$$\text{WPG (\%)} = (m_1 - m_0) / m_0 \times 100 \quad (1)$$

$$\text{BE (\%)} = (v_1 - v_0) / v_0 \times 100 \quad (2)$$

here, m_0 and m_1 are the oven-dry mass (g) of the wood before and after treatment, v_0 and v_1 are the oven-dry volume of the wood before and after treatment.

The specimens were kept in a sealed environment with a relative humidity of 86% at room temperature (regulate the formation with saturated potassium chloride solution and desiccator). The mass of the specimen was recorded when the sample absorbs moisture to a stable state (the mass does not change). The equilibrium moisture content (EMC) of the wood specimen was calculated according to Formula (3). The specimen size is $20 \times 20 \times 20 \text{ mm}^3$ (L × R × T), 10 samples per group, and the statistical average value was taken.

$$\text{EMC (\%)} = (m_3 - m_2) / m_2 \times 100 \quad (3)$$

where, m_2 is the oven-dry mass (g) of the wood, and m_3 is the mass (g) of the wood that absorbs moisture to the equilibrium state.

According to GB/T 1934.2-2009 [24], the size change of the sample from oven dry to moisture absorption equilibrium state at 86% RH was recorded, its tangential change is less than 0.2 mm and its volumetric swelling coefficients (A), and anti-swelling efficiency (ASE) were calculated according to the Formulas (4) and (5), respectively. The specimen

size is $20 \times 20 \times 20 \text{ mm}^3$ ($L \times R \times T$), 10 samples per group, and the statistical average value was taken.

$$A (\%) = (C_1 - C_0) / C_0 \times 100 \quad (4)$$

$$ASE (\%) = (A_0 - A_1) / A_0 \times 100 \quad (5)$$

where, C_0 and C_1 are the size (mm)/volume (mm^3) of the wood before and after moisture absorption, A_0 and A_1 are the size (volume) swelling coefficients (%) of the untreated and treated wood.

According to the standards of GB/T1933-2009 [25], GB/T 1936.1-2009 [26], GB/T 1936.2-2009 [27], and GB/T 1935-2009 [28], the oven-dry density, modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength parallel to grain (CS) of modified wood were measured, respectively. The MOE, MOR (static three-point bending with a span of 240 mm), and CS were measured using a universal testing machine (Model AG-2000A, Shimadzu Corp., Kyoto, Japan). The CS specimen size is $30 \times 20 \times 20 \text{ mm}^3$ ($L \times R \times T$), and the crosshead loading speed is 1 mm/min. The density specimen size was $20 \times 20 \times 20 \text{ mm}^3$ ($L \times R \times T$). The MOR and MOE specimen size was $300 \times 20 \times 20 \text{ mm}^3$ ($L \times R \times T$) and the crosshead loading speed is 5 and 3 mm/min, respectively. Each property has 10 duplicate samples, and its statistical average value is taken.

2.5. Fourier Transform Infrared Spectroscopy (FTIR) Analysis of MUG

The MUG resin was cured in an oven at 120°C for 2 h, and the cured resin was pulverized and sieved with a sprayer to produce 160–200 mesh powder. Glucose and urea powder were taken as the control and FTIR spectrometer (Nicolet 6700, Nicolet, Madison, WI, USA) was used. The scanning range was $4000\text{--}400 \text{ cm}^{-1}$ with a resolution of 4 cm^{-1} and 32 scans.

2.6. Micromorphology Characteristic

Use a slide-away microtome to cut the middle slice of the $5 \times 5 \times 3 \text{ mm}^3$ ($L \times R \times T$) sample, fix it on the metal stage with conductive glue, spray gold, observe the modifier distribution in the wood with a scanning electron microscope (S4800, Hitachi, Tokyo, Japan), and observe the changes and distribution of Si before and after the treatment by the built-in energy spectrometer (EDX).

3. Results and Discussion

3.1. Infrared Spectroscopy (FTIR) Analysis of Resin

Figure 1a,b presents the infrared spectrum of the resin. $3600\text{--}3100 \text{ cm}^{-1}$ is the coupling vibration peak of -NH and -OH [29]; the absorption peaks of 2926 cm^{-1} , 2937 cm^{-1} , and 2885 cm^{-1} are attributed to the stretching vibration of $-\text{CH}_2-$ [30,31], 1667 cm^{-1} is the stretching vibration peak of the urea amide carbonyl group; 1630 cm^{-1} is the characteristic peak of amide absorption band II, reflecting the in-plane bending vibration of the N-H bond of urea CO-NH_2 [32]; 1552 cm^{-1} is the coupling of the in-plane bending vibration of the N-H bond in CO-NH- and the stretching vibration of the C-N bond [32,33]; 1421 cm^{-1} is the CH bending vibration in $-\text{N-CH}_2-$ and $-\text{CH}_2\text{-O-}$ [33]; 1120 cm^{-1} . The absorption peak at 1029 cm^{-1} is attributed to the asymmetric stretching vibration of $-\text{C-O}$ [31]. The two peaks that appeared at 1561 cm^{-1} and 775 cm^{-1} can be attributed to conjugate $\text{C}=\text{C}$ bond and skeletal vibration of 2,5-disubstituted furan rings, respectively [34,35]. Comparing the spectrum of urea, glucose, and MUG, it can be seen that the flexural vibration of the amide carbonyl group and the N-H bond at 1667 cm^{-1} at 1630 cm^{-1} of urea weakened, and the characteristic peak CO-NH- of MUG appeared at 1552 cm^{-1} and 1421 cm^{-1} . It indicates the formation of secondary amino groups and the cross-linking reaction between urea and glucose.

Figure 1. Schematic illustration of: (a,b) Infrared spectrum image of resin, (c) the reaction process of glucose isomerization-dehydration to form 5-HMF, (d) synthetic mechanism of linear glucose-urea-melamine (MUG) resin, (e) color change during resin synthesis.

Glucose can be acidified and hydrolyzed to form 5-HMF at high temperatures [11,36]. As shown in Figure 1c, it is first isomerized to fructose, and then further dehydrated to form 5-HMF, which contains aldehyde groups, hydroxymethyl, and furan rings, and is chemically active. As shown in the red mark in Figure 1d, 5-HMF can polymerize with urea to form secondary amino groups. Correspondingly, Figure 1e shows the color change of the resin reaction. It is a complicated process. After the resin crosslinking reaction, the molecular weight increases and the color becomes darker. In addition, there are many more potential brown substances originating from caramelization and Maillard-reactions.

3.2. Physical Properties of Wood

WPG is an index to evaluate the ability of modifiers to penetrate wood. From Table 1, the WPG of S₂₀, G₁₀S₂₀, and G₂₀S₁₀ treated wood are 25.63, 43.23, and 55.79%, respectively. Among them, G₁₀S₂₀ and G₂₀S₁₀ have the same solid content, but the WPG of G₂₀S₁₀ treated wood increases by 29% compared with G₁₀S₂₀, indicating that the higher the MUG resin content in the GS modifier, the better the penetration of the modifier to wood. The bulking effect (BE) represents the swelling effect of the modifier on the wood cell wall. The modifier enters the non-crystalline area of the wood cell wall, increases the distance between the microfibrils and the fibrils in the cell wall, and expands the volume of the wood [37].

Table 1. Weight percent gain, bulking effect, and oven-dry density of the modified wood.

Groups	WPG (%)	BE (%)	Oven-Dry Density (g·cm ^{−3})
Control	–	–	0.385 ± 0.01
S ₂₀	25.63 ± 0.29	−14.90 ± 0.65	0.529 ± 0.01
G ₁₀ S ₂₀	43.23 ± 1.22	−0.55 ± 2.37	0.522 ± 0.10
G ₂₀ S ₁₀	55.79 ± 2.89	7.84 ± 0.69	0.515 ± 0.10

Note: The values in the table are the average ± standard deviation, the same below.

The BE of S₂₀, G₁₀S₂₀, and G₂₀S₁₀ treated wood are −14.90, −0.55, and 7.84%, respectively. The mass percentage of S₂₀ is small (20%), but the shrinkage of the treated wood is 14.9%. It shows that pure sodium silicate solution treatment will cause serious shrinkage of wood, which is caused by its alkaline dissolution on wood hemicellulose and other components [38]. G₁₀S₂₀ treatment wood shrinks slightly, while G₂₀S₁₀ has a significant swelling effect on wood cell walls, indicating that MUG resin can effectively inhibit wood shrinkage caused by inorganic sodium silicate, but as the content of MUG resin increases, the cell wall is swollen. The filling and fixing effect of the modifier will cause the volumetric expansion of the treated wood, and the bulking rate of the modified wood increases with increasing MUG resin content. Density is an important index to evaluate wood mechanical properties. From Table 1, the oven-dry density of S₂₀, G₁₀S₂₀, and G₂₀S₁₀ treated specimens are 0.529, 0.522, 0.515 g·cm^{−3}, respectively, all higher than the untreated wood. The highest density of S₂₀ treated wood is caused by its severe shrinkage and smaller volume.

3.3. Hygroscopicity and Dimensional Stability of Wood

As shown in Figure 2. The EMC of S₂₀ and G₁₀S₂₀ treated wood is 34.2% and 19.8%, which are 96.5% and 13.7% higher than that of the control, respectively. This is due to the strong hygroscopicity of inorganic sodium silicate, which makes the modified specimen easy to absorb moisture. The EMC of G₁₀S₂₀ and G₂₀S₁₀ treated wood is 42.1% and 65.7% lower than that of S₂₀ treated wood, respectively, indicating that MUG resin can seal the hygroscopic groups of sodium silicate and wood to a certain extent and reduce its hygroscopicity. The EMC of the G₂₀S₁₀ treated wood is 11.7%, which is 32.7% lower than that of the control, indicating that as the MUG resin content increases to a certain extent, the moisture absorption problem of the treated wood can be effectively solved.

Figure 2. Equilibrium moisture content of the modified wood.

As shown in Figure 3. The swelling rates are all in order as $S_{20} > G_{10}S_{20} > W > G_{20}S_{10}$, and all is volume > tangential > radial, which is consistent with the heterogeneous nature of the structure of wood itself. Table 2 shows that the ASE size of modified wood is $G_{20}S_{10} > G_{10}S_{20} > S_{20}$, and the dimensional stability of $G_{20}S_{10}$ is significantly improved compared with the control. The more MUG resin in the compound modifier, the higher the dimensional stability of the modified wood. In summary, the volume ASE of $G_{20}S_{10}$ treated wood reached 60.01%. Compared with the studies of Yinlun et al., it was found that the improvement effect of $G_{20}S_{10}$ on the dimensional stability of poplar was similar to that of formaldehyde-melamine-urea (MUF) resin [39].

Figure 3. Swelling rate of the modified wood.

Table 2. Anti-swelling efficiency (%) of the modified wood.

Group	Radial	Tangential	Volume
S ₂₀	−241.11 ± 32.26	−232.05 ± 12.14	−221.71 ± 12.33
G ₁₀ S ₂₀	−66.40 ± 18.07	−12.33 ± 6.29	−14.45 ± 1.37
G ₂₀ S ₁₀	30.85 ± 4.10	43.30 ± 18.86	60.01 ± 3.37

3.4. Mechanical Properties of Wood

From Table 3, the MOE, MOR, and CS of modified wood are all significantly higher than that of the control. The $G_{10}S_{20}$ treated wood has the highest MOE, MOR, and CS, which increases by 72.2, 50.8, and 113.6%, respectively, compared with the control. Their MOE and CS are in order as $S_{20} < G_{20}S_{10} < G_{10}S_{20}$, and their MOR is in order as $G_{20}S_{10} < S_{20} < G_{10}S_{20}$. Compared with S_{20} , the $G_{20}S_{10}$ has slightly lower MOR, because inorganic silicon is a rigid

substance. The more inorganic silicon in S_{20} modifier contributes more to the bending strength and mechanical support effect of wood. Compound modifier ($G_{10}S_{20}$) has the same effect as the common melamine-urea-formaldehyde (MUF) resin on the reinforcement of wood [40]. In particular, the MOE of $G_{10}S_{20}$ treated wood has been significantly improved.

Table 3. Mechanical properties of the modified wood.

Group	MOE (GPa)	MOR (MPa)	CS (MPa)
Control	10.57 ± 0.61	92.17 ± 4.12	58.02 ± 4.79
S_{20}	16.20 ± 0.55	131.87 ± 2.98	119.17 ± 8.98
$G_{10}S_{20}$	18.21 ± 0.91	139.33 ± 2.51	123.94 ± 2.18
$G_{20}S_{10}$	18.02 ± 0.22	121.52 ± 2.05	122.20 ± 4.54

The compound of sodium silicate and MUG resin can further improve the bending resistance of wood. The reason may be [18,41]: The inorganic sodium silicate deposited on the cell lumen and cell wall can increase the resistance of the wood to external loads; MUG resin reacts with the active groups on the cell wall and wraps around the cell wall, inhibiting the free sliding of the microfibrils; the modifier inflates the cell wall micropores to reduce the moisture content of the cell wall and weaken the plasticizing effect of water on microfibrils.

3.5. Microstructure Analysis

The porous hierarchical structure of wood helps it to absorb modified substances and improve the performance of wood. The internal structure changes before and after wood modification were observed by SEM and EDX, and the distribution and combination of MUG resin and sodium silicate in wood were explored to further analyze the modification mechanism. It can be seen from Figure 4 that the wood fiber cells, ray cells, and duct tissues of the control are all in a hollow state, and the energy spectrum scan shows that a small amount of Si is distributed in the cell wall of the control (Figure 4A,a). Some cell walls, cell lumens, intercellular space, and vessels of the $G_{20}S_{10}$ treated wood are attached or filled with columnar and granular solid substances (the red arrows in Figure 4B,C); compared with the control, the Si elements in the cell walls and vessels of the $G_{20}S_{10}$ treated wood increased significantly (Figure 4a,b). It shows that the compound modifier ($G_{20}S_{10}$) can effectively enter the characteristic pores of poplar wood cell walls. Through resin curing, the modifier can crosslink with the cell wall substances, wrap around the microfibrils, and deposit and fill in the wood voids. It effectively increases the ability of wood to resist external forces and reduce the moisture absorption sites and moving channels. The filling of wood pores and crosslinking with cell wall substances by resin are the main factors to improve the physical and mechanical properties of wood.

Figure 4. Cont.

Figure 4. SEM-EDX image of the modified wood (**A**—cross section the untreated wood; **B**—cross section of $G_{20}S_{10}$ treated wood; **C**—longitudinal section of $G_{20}S_{10}$ treated wood; **a**, **b**, **c**—are the scanning distribution diagrams of silicon in **A**, **B**, and **C**, respectively).

4. Conclusions

In this study, MUG resin was prepared with glucose as main raw material, and then compounded with Na_2SiO_3 solution to prepare MUG resin/sodium silicate compound modifier. The compound modifier ($G_{20}S_{10}$) has the advantages of strong rigidity and high hardness of inorganic silicon, and the good compatibility of MUG resin and wood. It can fully penetrate into the wood tissue and exert the synergistic effect of organic–inorganic compound to improve wood properties.

(1) Infrared analysis shows that there was a prepolymer structure in MUG resin; MUG resin has good ability to penetrate wood, and will bulk wood cell wall, and reduce the shrinkage and moisture absorption of the Na_2SiO_3 modified wood.

(2) The EMC of the $G_{20}S_{10}$ treated wood was 32.7% lower than that of the control, and its ASE was 60.01%. The $G_{10}S_{20}$ treated wood has the highest strength, and its MOE, MOR, and CS increase by 72.2, 50.8, and 113.6%, respectively, compared with the control.

(3) SEM-EDX analysis shows that the modifier ($G_{20}S_{10}$) can effectively enter the inherent pores of poplar wood. It penetrates or adheres to the cell wall and undergoes polycondensation to form a wood-resin-inorganic consolidation and filling system.

The MUG resin/sodium silicate compound modifier is an ecological, low cost wood modifier. It has broad application prospects and is worthy of in-depth research for promotion and application.

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