Investigation of the Properties of Color-Changing Powder Water-Based Coating

Xiaoxing Yan 1,2,* and Yijuan Chang 2

1 Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing Forestry University, Nanjing 210037, China
2 College of Furnishings and Industrial Design, Nanjing Forestry University, Nanjing 210037, China; changyijuan@njfu.edu.cn
* Correspondence: yanxiaoxing@nuaa.edu.cn; Tel.: +86-25-8542-7528

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Abstract: The suitable coating process and discoloration effect of the waterborne paint added with color-changing powder on the surface of Chinese fir were investigated using an orthogonal method from three factors of the number of primers, topcoats, and the way of adding color-changing powder. It was found that the number of primers showed the greatest significance on the color difference of paint film, and the method of adding the color-changing powder had the most influence on the gloss of the paint film. Meanwhile, the impact resistance, paint film adhesion, liquid film resistance level, the gloss of coatings, and the composition of waterborne coatings were not affected by the three factors. The results indicated that two primers, two topcoats with color-changing powder, were the most suitable coating technologies for the reversible color waterborne coating to obtain a stable and sustainable discoloration effect. These results will provide a reference for the construction and application of a color-changing coating.

Keywords: waterborne coating; color-changing powder; coating technology; number of primer; number of topcoat

1. Introduction

The surface finishing process can not only protect the surface of the substrate [1–3], but also achieve the purpose of a beautiful color [4]. The temperature-reversible toner is a microencapsulated reversible temperature-sensitive color-changing substance. When the temperature changes, the organic components are electronically transferred to achieve the effect of changing color.

Houska et al. [5] used reactive magnetron sputtering to prepare VO2-based thermochromic coatings, combining four methods to improve coating performance. It is of considerable significance for the design and low-temperature preparation of high-performance and durable thermochromic VO2 coatings for smart windows. Ahangari et al. [6] prepared polyurea formaldehyde microcapsules containing dicyclopentadiene by in situ polymerization and their results showed that the presence of microcapsules could improve the elastic modulus and hardness of the material. Sun et al. [7] studied a phase-change material super-hydrophobic energy storage microcapsule with ZnO/SiO2 as the shell, which could realize functions such as self-cleaning and thermal adjustment. Geng et al. [8] designed and prepared reversible thermochromic microcapsule phase change materials with excellent heat storage release performance and good stability, and applied them to the production of fire service clothing to provide adequate protection against heat. These studies indicated that microcapsule products have been widely used in the construction, clothing, and industrial fields. According to the authors’ literature search, there have been few studies on the color-changing materials of a water-based
coating on the surface of wood, in particular, the color-changing effect of the water-based coating is not clear yet.

Water-based coatings are environmentally friendly materials and have long-term development prospects [9]. However, in practical applications, the poor compatibility of the water component and the resin component [10] in the paint film leads to its inferior performance to oil-based paint in terms of hardness [11], wear resistance [12,13], adhesion [14,15], etc. In our previous work, the author studied the best coating process of coating with color-changing ink [16] and found that in the construction process, it is not easy to add more water-borne coating to the color-changing powder due to the aggregation and agglomeration that occurred. Therefore, based on a water-based color-changing coating film, a better coating process was explored for the reversible color water-based coating by adding the color-changing powder on the surface of the Chinese fir, so that the water-based coating had the best comprehensive performance, providing a technical reference for the color-changing coating.

2. Materials and Methods

2.1. Experimental Materials

Bisphenol A (as the chromogenic agent, \( M_w: 228.29 \text{ g/mol} \), CAS No.: 80-05-7), methyl red (as the leuco agent, \( M_w: 269.5 \text{ g/mol} \), No.: 493-52-7), melamine (coated with methyl red and bisphenol A, \( M_w: 126.12 \text{ g/mol} \), CAS No.: 108-78-1), and tetradecanol (as the solvent, \( M_w: 214.39 \text{ g/mol} \), No.: 112-72-1) were supplied by Huancai Discoloration Technology Co. Ltd. (Shenzhen, China). Sodium dodecyl benzene sulfonate (as emulsifier, \( M_w: 348.48 \text{ g/mol} \), CAS No.: 25155-30-0), 37.0% formaldehyde solution (as the wall material reactant, \( M_w: 30.03 \text{ g/mol} \), CAS No.:50-00-0), anhydrous ethanol (as detergent, \( M_w: 46.07 \text{ g/mol} \), CAS No.: 64-17-5), triethanolamine (as a pH regulator, \( M_w: 149.19 \text{ g/mol} \), CAS No.: 102-71-6), and citric acid monohydrate (as a pH regulator, \( M_w: 210.14 \text{ g/mol} \), CAS No.: 5949-29-1) were provided by Xilong Chemical Co. Ltd. (Guangzhou, China). The waterborne primer and topcoat consisted of a waterborne acrylic copolymer dispersion (the concentration was 90.0%), matting agent (the concentration was 2.0%), additives (the concentration was 2.0%), and water (the concentration was 6.0%). The waterborne wood coatings were supplied by Yihua Lifestyle Technology Co. Ltd. (Shantou, China). The 15.0% NaCl solution and 70.0% medical ethanol were provided by Otopp Biotechnology Co. Ltd. (Hangzhou, China). Detergent was provided by Shanghai Hutchison Whitecat Co. Ltd. (Shanghai, China). Red ink was supplied by Fine Stationary Co. Ltd. (Shanghai, China). The red ink is a dye ink prepared with eosin A, which belongs to the dibenzopyran system and is an orange-red to brown-red powder. Eosin A is widely used in the manufacture of red ink, and the quality of the prepared red ink is stable. Chinese fir boards (100 mm \( \times \) 100 mm \( \times \) 12 mm, Cunninghamia lanceolata (Lamb.) Hook), after polishing by ordinary machinery), were supplied by Yihua Lifestyle Technology Co. Ltd. (Shantou, China).

2.2. Preparation of Microcapsules with Color-Changing Powder

The microcapsules were prepared by in situ polymerizations. The 10.0 g of 37.0% formaldehyde solution was put in a beaker, then 10.0 mL of deionized water and 5.0 g of melamine were added to obtain the homogeneous solution. Triethanolamine was added dropwise to adjust the pH to 8.5–9.0. The mixed solution was then placed in a constant temperature water bath at 70 °C and stirred at 700 rpm for 30 min to allow the reaction to proceed to a transparent solution, finally forming a wall material solution, and then cooled to room temperature. The 1.0 g of sodium dodecyl benzene sulfonate was added to 99.0 g of deionized water to completely dissolve in order to obtain a 1.0% aqueous solution of sodium dodecyl benzene sulfonate. The 1.5 g of methyl red, 1.5 g of bisphenol A, and 15.0 g tetradecanol were added to a 1.0% aqueous solution of sodium dodecyl benzene sulfonate, and stirred at 800 rpm for 30 min to obtain a stable core material emulsion. The wall material solution was then added to the core material emulsion and stirred to mix uniformly. The pH of the solution was adjusted to 3.0–4.5 by citric acid monohydrate. The system was reached at 25 °C for 3 h. After filtering with a
vacuum suction filter device and washing with deionized water and absolute ethanol several times, the mixture was put into the oven and dried for 48 h to obtain the microcapsule of color-changing powder (as shown in Figure 1).

Figure 1. Schematic diagram of the preparation of color-changing microcapsules.

2.3. Preparation of Coating

The pre-experimental results showed that when the concentration of the color-changing powder was 5.0%, the comprehensive properties of the waterborne film on the surface of Chinese fir were the best versus other concentrations [17,18]. Based on this result, a 5.0% concentration of color-changing powder microcapsules was added to the water-based paint to carry out the orthogonal experiment of the coating technology (Tables 1 and 2). The Chinese fir boards were placed at room temperature, the relative temperature was 50.0% ± 5.0%, and the humidity was maintained for one week, so that the substrate reached an equilibrium moisture content. Figure 2 shows the coating technology of Sample #1. The 2.0 g primer was coated using the SZQ tetrahedron manufacturing machine (Tianjin Jinghai Science and Technology Testing Machinery Factory, Tianjin, China) to the base material of Chinese fir boards. The primer was dried in air at room temperature for 30 min, transferred to an electric blast drying oven at 35 °C, heated until the mass did not change, and then naturally cooled to room temperature. Afterward, the coating was ground gently with 800 grit sandpaper and wiped by a dry cloth to remove the surface dust. The effect of 800 grit sandpaper on the microcapsules was very small. After the above process was repeated twice, the coating process of the primer was completed. Then, 0.1 g of the color-changing powder was added to 1.9 g of the water-based topcoat, and mixed evenly. The topcoat was applied to the dried primer for two times. Other samples refer to the preparation method of Sample #1. The dry thickness of waterborne wood coatings was about 60 μm.

Table 1. Orthogonal experiment schedule of coating technology.

| Sample | Primer Application Method (Time) | Topcoat Application Method (Time) | Adding Method of Color-Changing Powder |
|--------|---------------------------------|----------------------------------|----------------------------------------|
| #1     | 2                               | 2                                | Topcoat Addition                        |
| #2     | 2                               | 3                                | Primer Addition                         |
| #3     | 3                               | 2                                | Primer Addition                         |
| #4     | 3                               | 3                                | Topcoat Addition                        |
Table 2. Ingredient list of the paint film.

| Sample | Number of Primers | Color-Changing Powder Weight (g) | Primer Weight (g) | Topcoat Weight (g) |
|--------|-------------------|---------------------------------|------------------|-------------------|
| #1, #4 | 2, 3              | 0.1                             | 2.0              | 1.9               |
| #2, #3 | 2, 3              | 0.1                             | 1.9              | 2.0               |
| #5     | 0                 | 0.1                             | 2.0              | 1.9               |
| #6     | 1                 | 0.1                             | 2.0              | 1.9               |
| #7     | 2                 | 0.1                             | 2.0              | 1.9               |
| #8     | 3                 | 0.1                             | 2.0              | 1.9               |
| #9     | 4                 | 0.1                             | 2.0              | 1.9               |
| #10    | 5                 | 0.1                             | 2.0              | 1.9               |

Figure 2. The coating technology of Sample #1.

2.4. Testing and Characterization

The morphology of the microcapsules was analyzed using a L2800 biomicroscope (Guangzhou Liss Optical Instrument Co. Ltd., Guangzhou, China) and Quantum 200 environmental scanning electron microscope (SEM, FEI Company, Hillsboro, OR, USA). According to the assessment of surface resistance to cold liquid [19], 15.0% sodium chloride, 70.0% medical alcohol, detergent (25.0% fatty alcohol ethylene oxide and 75.0% water), and red ink were selected to test the liquid resistance of the paint film. The gloss of the coatings was gauged with a 3NH intelligent gloss meter (Shenzhen Xinhua Technology Co. Ltd., Shenzhen, China) according to GB/T 9754-2004 [20]. In winter, the indoor temperature is about 18 °C, while in summer, it is about 35 °C (lower than 40 °C). Therefore, with every two degrees Celsius as a gradient, a SEGT-J portable color difference meter (Guangzhou Biaogeda Laboratory Instrument Co. Ltd., Guangzhou, China) was used to measure the chroma value of the coating from 18 to 40 °C, and the color difference was calculated according to GB/T 3181-2008 [21]. A SEGT-J portable colorimeter was used to directly measure the CIE LAB (International Commission on Illumination Lightness Redness Yellowness) coordinates (D65 and 10° observer) values of the waterborne wood coatings. The coating adhesion was gauged with a QFH-HG600 six-blade cutting tool, 3M brand 600-1PK transparent pressure-sensitive adhesive tape (19 mm wide), and a soft brush (Tianjin Jingke Material Experiment Machine Factory, Tianjin, China) according to ISO 2409-2007 [22]. The film was scratched with a uniform speed and pressure. Then, the sample was rotated 90° and repeatedly cut in the same area to form a 1 mm × 1 mm square pattern. Finally, transparent tape was applied to the scratch area, and then the tape was torn off. A magnifying glass was used to observe whether the paint film was separated from the substrate. Quantum 200 environmental scanning electron microscope (SEM) was used to measure the structure of the coating. A VERTEX 80V infrared spectrometer (Germany Bruker Co., Ltd., Karlsruhe, Germany) was used to analyze the composition of the coating. The impact resistance was gauged with the QCJ-50 paint film impactor (Tianjin Jingke Material Experiment Machine Factory, Tianjin, China) according to GB/T 1732-1993 [23]. A QCJ impactor was used to measure the strength of the coatings. In the impact test, the 1.0 kg ball fell freely from different heights (the maximum height is 50.0 cm). The damage of the coating was observed after the ball fell on the surface of the coating. The impact resistance was the maximum height at which the ball could fall without damaging the coating. The experiments were repeated four times and the error was less than 5.0%.
3. Results and Discussion

3.1. Orthogonal Experiment Analysis

The SEM and microscopic pictures of the color-changing powder are shown in Figure 3. The prepared microcapsules were spherical with a particle size of about 5 μm. Figure 4 shows the SEM images of the coatings of Samples #1–#4 in Table 1. When the color-changing powder was added into the primer, the coating surface was smooth and uniform. When the color-changing powder was added to the topcoat, the particles on the coating surface were obvious.

![Figure 3. Micrograph (A) and SEM (B) of the color-changing powder.](image)

![Figure 4. SEM images of the coatings of Samples #1–#4 (A–D).](image)

The paint films of different coating methods were heated from 18 to 40 °C, and the chroma values of the paint film were recorded. Where “L*” stands for lightness, a large “L*” means the coating surface is bright, while a small “L*” signifies that the coating surface becomes black. The “a*” is red–green, where a positive number is red, and a negative number is green. The “b*” is yellow–blue, where a positive and negative “b*” show that the coating surfaces are yellow and blue, respectively. c represents the color saturation, and H represents the hue. \( \Delta L \) (light difference) = \( L_1^* - L_2^* \), \( \Delta a \) (red–green difference) = \( a_1^* - a_2^* \), \( \Delta b \) (yellow–blue difference) = \( b_1^* - b_2^* \). The \( L_1^*, a_1^*, \) and \( b_1^* \) represent the lightness, red–green, and yellow–blue values at 18 °C, and \( L_2^*, a_2^*, b_2^* \) represent the values at other temperatures. The chroma values are shown in Table 3. The color difference \( (\Delta E_{ab}^*) \) can be calculated according to Equation (1):

\[
\Delta E_{ab}^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}
\]

(1)
Table 3. Effect of the coating process on the chroma value of the waterborne coating with color-changing powder on Chinese fir from 18 to 40 °C.

| Sample | Chroma Value | 18 °C | 20 °C | 22 °C | 24 °C | 26 °C | 28 °C | 30 °C | 32 °C | 34 °C | 36 °C | 38 °C | 40 °C |
|--------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|        | $L^*$        | 51.1±1.2 | 51.3±1.2 | 50.9±1.2 | 51.0±1.3 | 50.8±1.2 | 50.9±1.2 | 51.8±1.3 | 77.4±1.9 | 90.5±2.2 | 95.9±2.4 | 97.5±2.4 | 98.1±2.4 |
|        | $a^*$        | 64.0±1.6 | 63.6±1.5 | 63.5±1.5 | 63.8±1.6 | 63.1±1.5 | 62.9±1.5 | 60.3±1.5 | 15.9±0.4 | -6.0±0.1 | -18.8±0.4 | -22.2±0.5 | -23.7±0.5 |
| #1     | $b^*$        | 41.7±1.0 | 42.5±1.0 | 41.5±1.0 | 41.7±1.0 | 41.3±1.0 | 42.5±1.0 | 42.9±1.0 | 69.7±1.7 | 89.0±2.2 | 99.1±2.4 | 103.4±2.5 | 101.7±2.5 |
|        | $c$          | 76.4±1.9 | 76.5±1.8 | 75.8±1.9 | 76.2±1.9 | 75.5±1.8 | 75.9±1.9 | 74.1±1.8 | 71.5±1.7 | 89.2±2.2 | 100.9±2.5 | 105.7±2.6 | 104.4±2.6 |
|        | $H$          | 33.1±0.8 | 33.7±0.8 | 33.1±0.8 | 33.1±0.8 | 33.1±0.8 | 34.0±0.8 | 35.4±0.8 | 77.1±1.9 | 93.8±2.3 | 100.7±2.5 | 102.1±2.5 | 103.1±2.5 |
| #2     | $L^*$        | 53.6±1.3 | 53.7±1.3 | 53.8±1.3 | 53.8±1.3 | 53.7±1.3 | 53.0±1.3 | 54.1±1.3 | 66.0±1.6 | 94.8±2.3 | 95.0±2.3 | 95.0±2.3 | 94.7±2.3 |
|        | $a^*$        | 59.2±1.4 | 59.8±1.5 | 59.2±1.4 | 59.0±1.5 | 58.7±1.4 | 58.3±1.4 | 56.7±1.4 | 35.8±0.9 | -18.9±0.4 | -19.2±0.4 | -19.8±0.5 | -19.1±0.4 |
|        | $b^*$        | 47.5±1.1 | 46.5±1.1 | 47.0±1.1 | 46.9±1.2 | 46.7±1.1 | 46.2±1.1 | 46.9±1.1 | 53.4±1.3 | 88.5±2.2 | 88.3±2.2 | 89.1±2.2 | 88.5±2.2 |
|        | $c$          | 76.0±1.9 | 75.7±1.9 | 75.6±1.8 | 75.4±1.9 | 75.0±1.8 | 74.4±1.8 | 73.6±1.8 | 64.3±1.6 | 90.5±2.2 | 90.4±2.2 | 91.3±2.2 | 90.5±2.2 |
|        | $H$          | 38.7±0.9 | 37.8±0.9 | 38.4±0.9 | 38.4±1.0 | 38.5±0.9 | 38.4±0.9 | 39.5±0.9 | 56.1±1.4 | 102.0±2.5 | 102.2±2.5 | 102.5±2.5 | 102.2±2.5 |
| #3     | $L^*$        | 51.2±1.2 | 51.6±1.3 | 51.6±1.2 | 51.8±1.3 | 51.6±1.2 | 51.8±1.3 | 77.8±1.9 | 97.1±2.4 | 97.8±2.4 | 97.5±2.4 | 98.2±2.4 | 97.3±2.4 |
|        | $a^*$        | 63.0±1.5 | 62.8±1.6 | 63.3±1.5 | 62.9±1.6 | 62.1±1.5 | 61.4±1.5 | 14.7±0.3 | -23.0±0.5 | -23.9±0.6 | -24.0±0.6 | -24.6±0.6 | -24.3±0.6 |
|        | $b^*$        | 47.0±1.1 | 47.8±1.2 | 46.5±1.1 | 47.3±1.2 | 46.8±1.1 | 47.4±1.1 | 76.3±1.9 | 101.5±2.5 | 102.7±2.5 | 101.8±2.5 | 104.0±2.6 | 100.4±2.5 |
|        | $c$          | 78.6±1.9 | 79.0±2.0 | 78.5±1.9 | 78.7±2.0 | 77.8±1.9 | 77.6±1.9 | 77.8±1.9 | 104.1±2.6 | 105.4±2.6 | 104.6±2.6 | 106.9±2.6 | 103.3±2.5 |
|        | $H$          | 36.7±0.9 | 37.2±0.9 | 36.3±0.9 | 36.9±0.9 | 37.0±0.9 | 37.6±0.9 | 79.0±1.9 | 102.7±2.5 | 103.1±2.5 | 103.2±2.5 | 103.3±2.5 | 103.6±2.5 |
| #4     | $L^*$        | 49.9±1.2 | 50.0±1.3 | 50.0±1.2 | 49.8±1.3 | 49.9±1.2 | 49.7±1.2 | 55.2±1.3 | 93.5±2.3 | 96.5±2.4 | 97.2±2.4 | 97.0±2.4 | 97.2±2.4 |
|        | $a^*$        | 62.2±1.5 | 62.5±1.6 | 61.9±1.5 | 61.8±1.5 | 62.0±1.5 | 60.9±1.5 | 53.9±1.3 | -15.8±0.4 | -21.9±0.5 | -23.7±0.5 | -24.0±0.6 | -24.2±0.6 |
|        | $b^*$        | 40.3±1.0 | 40.5±1.0 | 41.5±1.0 | 40.1±1.0 | 40.2±1.0 | 41.0±1.0 | 44.7±1.1 | 100.0±2.5 | 105.1±2.6 | 106.9±2.6 | 106.2±2.6 | 107.1±2.6 |
|        | $c$          | 74.1±1.8 | 74.5±1.8 | 74.6±1.8 | 73.7±1.9 | 73.9±1.8 | 73.4±1.8 | 70.1±1.7 | 101.2±2.5 | 107.4±2.6 | 109.5±2.7 | 108.9±2.7 | 109.8±2.7 |
|        | $H$          | 32.9±0.8 | 32.9±0.8 | 33.8±0.8 | 32.9±0.8 | 32.9±0.8 | 33.9±0.8 | 39.6±0.9 | 98.9±2.4 | 101.7±2.5 | 102.5±2.5 | 102.7±2.5 | 102.7±2.5 |
The results of the color difference from 18 to 40 °C are shown in Figure 5. Figures 6 and 7 are the images of the sample changing with temperature. It can be seen that with the increase in temperature, the coating presented different colors, and the color change effect was good.

Figure 5. The influence of coating technologies on the color difference of waterborne coating from 18 to 40 °C.

Figure 6. Coating images of the orthogonal test: (A–D) the images of Samples #1–#4 at 18 °C; (E–H) the images of Samples #1–#4 at 32 °C.

Figure 7. Image of Sample #1 from 18 to 40 °C.
It can be seen from Figure 5 that the color difference of the Samples #1–#4 paint films between 18–28 °C was 0.2–1.8, and there was no obvious discoloration phenomenon. At 30 °C, only the color difference value of the Samples #3 paint film was larger, while at 32 °C, the Samples #1–#4 paint films had a significant color change effect, the color difference of the paint film did not change much after 32 °C. Therefore, the temperature of 18–32 °C was selected, and the orthogonal analysis was done for the Samples #1–#4 paint films, as shown in Table 4. The last four lines of Tables 4 and 5 are the statistical analysis of the results of the orthogonal experiment on color difference and gloss. The range and variance of the color difference of the number of primers were large, indicating that the method of primer coating had a great influence on the color difference of the paint film, and the number of primer was more significant than other factors. The gloss results (Table 5) showed that the range of the adding method of the color-changing powder was large and significant, indicating that the coating process that had the greatest influence on the gloss of the paint film was the method of adding the color changing powder.

| Sample | Number of Primers | Number of Topcoats | Adding Way of Color Changing Powder | Color Difference |
|--------|-------------------|--------------------|-------------------------------------|------------------|
| #1     | 2                 | 2                  | Topcoat Addition                    | 61.6 ± 1.9       |
| #2     | 2                 | 3                  | Primer Addition                     | 27.1 ± 0.3       |
| #3     | 3                 | 2                  | Primer Addition                     | 111.7 ± 1.4      |
| #4     | 3                 | 3                  | Topcoat Addition                    | 107.5 ± 0.6      |
| Mean 1 | 44.35             | 86.65              | 84.55                               | –                |
| Mean 2 | 109.60            | 67.30              | 69.40                               | –                |
| Range  | 65.25             | 19.35              | 15.15                               | –                |
| Variance | 4257.56            | 374.42              | 229.52                               | –                |

| Sample | Number of Primers | Number of Topcoats | Adding Way of Color Changing Powder | Gloss 60° (%) |
|--------|-------------------|--------------------|-------------------------------------|---------------|
| #1     | 2                 | 2                  | Topcoat Addition                    | 14.2 ± 0.4    |
| #2     | 2                 | 3                  | Primer Addition                     | 69.0 ± 0.4    |
| #3     | 3                 | 2                  | Primer Addition                     | 70.4 ± 1.5    |
| #4     | 3                 | 3                  | Topcoat Addition                    | 15.3 ± 0.1    |
| Mean 1 | 41.60             | 42.30              | 14.75                               | –             |
| Mean 2 | 42.85             | 42.15              | 69.70                               | –             |
| Range  | 1.25              | 0.15               | 54.95                               | –             |
| Variance | 1.56               | 0.02               | 3019.50                             | –             |

A liquid resistance test of the four test solutions of sodium chloride, detergent, ethanol, and red ink on the paint films of different coating technologies was carried out and the temperature was set at 18 and 32 °C. The L*, a*, and b* values of the paint film were measured before and 24 h after the test (Table 6). According to the liquid resistance classification table (Table 7), the Samples #1–#4 coatings had the same liquid resistance to different test solutions (as shown in Table 8), indicating that the coating technology had no influence on the film liquid resistance.
### Table 6. Effect of the coating process on the liquid resistance color value of the waterborne coating with color-changing powder on Chinese fir.

| Sample | Chroma Value | 18 °C | 18 °C after NaCl | 18 °C after Detergent | 18 °C after Ethanol | 18 °C after Red Ink | 32 °C | 32 °C after NaCl | 32 °C after Detergent | 32 °C after Ethanol | 32 °C after Red Ink |
|--------|--------------|-------|------------------|-----------------------|---------------------|---------------------|-------|-----------------|----------------------|---------------------|---------------------|
| #1     | L*           | 51.1 ± 1.2 | 50.9 ± 1.2 | 50.4 ± 1.2 | 50.0 ± 1.2 | 53.5 ± 1.3 | 77.4 ± 1.9 | 85.4 ± 2.1 | 76.3 ± 1.9 | 87.1 ± 2.1 | 64.3 ± 1.6 |
|        | a*          | 64.0 ± 1.6 | 62.2 ± 1.5 | 62.7 ± 1.5 | 63.3 ± 1.5 | 66.4 ± 1.6 | 15.9 ± 0.4 | −10.5 ± 0.2 | 10.6 ± 0.2 | −15.6 ± 0.3 | 35.4 ± 0.8 |
|        | b*          | 41.7 ± 1.0 | 41.5 ± 1.0 | 41.2 ± 1.0 | 41.4 ± 1.0 | 40.9 ± 1.0 | 69.7 ± 1.7 | 78.0 ± 1.9 | 68.1 ± 1.7 | 80.6 ± 2.0 | 51.4 ± 1.2 |
|        | c           | 76.4 ± 1.9 | 74.1 ± 1.8 | 74.6 ± 1.8 | 75.7 ± 1.8 | 77.2 ± 1.9 | 71.5 ± 1.7 | 78.7 ± 1.9 | 69.0 ± 1.7 | 82.1 ± 2.0 | 62.3 ± 1.5 |
|        | H           | 33.1 ± 0.8 | 34.4 ± 0.8 | 33.5 ± 0.8 | 33.1 ± 0.8 | 32.0 ± 0.8 | 77.1 ± 1.9 | 97.6 ± 2.4 | 81.1 ± 2.0 | 101.0 ± 2.5 | 55.3 ± 1.3 |
| #2     | L*           | 53.6 ± 1.3 | 53.5 ± 1.3 | 52.8 ± 1.3 | 53.0 ± 1.3 | 45.2 ± 1.1 | 66.0 ± 1.6 | 81.5 ± 2.0 | 64.8 ± 1.6 | 76.2 ± 1.9 | 53.2 ± 1.3 |
|        | a*          | 59.2 ± 1.4 | 58.9 ± 1.4 | 59.6 ± 1.4 | 58.4 ± 1.4 | 66.1 ± 1.6 | 38.5 ± 0.9 | −2.2 ± 0.1 | 20.1 ± 0.5 | 1.9 ± 0.1 | 61.5 ± 1.5 |
|        | b*          | 47.5 ± 1.1 | 46.3 ± 1.1 | 46.5 ± 1.1 | 46.9 ± 1.1 | 43.7 ± 1.1 | 53.4 ± 1.3 | 71.3 ± 1.7 | 52.7 ± 1.3 | 67.2 ± 1.6 | 46.1 ± 1.1 |
|        | c           | 76.0 ± 1.9 | 72.7 ± 1.8 | 75.2 ± 1.8 | 73.7 ± 1.8 | 80.8 ± 2.0 | 64.3 ± 1.6 | 71.3 ± 1.7 | 56.1 ± 1.4 | 67.3 ± 1.6 | 76.9 ± 1.9 |
|        | H           | 38.7 ± 0.9 | 38.5 ± 0.9 | 37.5 ± 0.9 | 37.5 ± 0.9 | 29.9 ± 0.7 | 56.1 ± 1.4 | 91.8 ± 2.3 | 69.0 ± 1.7 | 83.2 ± 2.2 | 36.8 ± 0.9 |
| #3     | L*           | 51.2 ± 1.2 | 51.8 ± 1.3 | 51.4 ± 1.2 | 51.4 ± 1.2 | 50.3 ± 1.2 | 97.1 ± 2.4 | 82.7 ± 2.0 | 71.2 ± 1.7 | 66.7 ± 1.6 | 48.2 ± 1.2 |
|        | a*          | 63.0 ± 1.5 | 62.3 ± 1.5 | 63.5 ± 1.5 | 61.9 ± 1.5 | 67.2 ± 1.6 | −23.0 ± 0.5 | −7.8 ± 0.2 | 16.5 ± 0.5 | −5.2 ± 0.1 | 62.1 ± 1.5 |
|        | b*          | 47.0 ± 1.1 | 47.3 ± 1.2 | 47.2 ± 1.1 | 46.5 ± 1.1 | 46.6 ± 1.1 | 101.5 ± 2.5 | 75.1 ± 1.8 | 64.5 ± 1.6 | 63.7 ± 1.5 | 43.3 ± 1.0 |
|        | c           | 78.6 ± 1.9 | 78.3 ± 1.9 | 79.2 ± 1.9 | 76.4 ± 1.9 | 81.8 ± 2.0 | 104.1 ± 2.6 | 75.5 ± 1.8 | 66.6 ± 1.6 | 63.9 ± 1.6 | 75.7 ± 1.8 |
|        | H           | 36.7 ± 0.9 | 37.1 ± 0.9 | 36.6 ± 0.9 | 37.6 ± 0.9 | 34.7 ± 0.8 | 102.7 ± 2.5 | 95.9 ± 2.4 | 75.6 ± 1.8 | 94.6 ± 2.3 | 34.8 ± 0.8 |
| #4     | L*           | 49.9 ± 1.2 | 49.8 ± 1.2 | 50.4 ± 1.2 | 49.6 ± 1.2 | 46.8 ± 1.1 | 95.3 ± 2.3 | 72.2 ± 1.8 | 50.3 ± 1.2 | 46.1 ± 1.1 | 71.8 ± 1.8 |
|        | a*          | 62.2 ± 1.5 | 61.8 ± 1.5 | 61.7 ± 1.5 | 61.4 ± 1.5 | 68.7 ± 1.7 | −15.8 ± 0.4 | 16.4 ± 0.4 | 59.4 ± 1.4 | 45.3 ± 1.1 | 30.6 ± 0.7 |
|        | b*          | 40.3 ± 1.0 | 40.1 ± 1.0 | 40.5 ± 1.0 | 39.5 ± 0.9 | 36.7 ± 0.9 | 100.0 ± 2.5 | 29.0 ± 0.7 | 41.6 ± 1.0 | 47.9 ± 1.2 | 65.4 ± 1.6 |
|        | c           | 74.1 ± 1.8 | 73.7 ± 1.8 | 73.9 ± 1.8 | 72.8 ± 1.8 | 77.9 ± 1.9 | 101.2 ± 2.5 | 33.3 ± 0.8 | 72.5 ± 1.8 | 65.9 ± 1.6 | 72.2 ± 1.8 |
|        | H           | 32.9 ± 0.8 | 32.9 ± 0.8 | 33.2 ± 0.8 | 32.1 ± 0.8 | 28.1 ± 0.7 | 98.9 ± 2.4 | 60.5 ± 1.5 | 35.0 ± 0.8 | 46.5 ± 1.1 | 64.9 ± 1.6 |
The adhesion of the paint film was tested by the method of cross cut. The smaller the damaged area of the paint film, the lower the adhesion grade, and the better the adhesion of the paint film. The damage range of the Samples #1–#4 coatings was 0, the adhesion of the Samples #1–#4 coatings was grade 0, and the adhesion was good, indicating that the coating technology had no effect on the film adhesion. The impact resistance of the Samples #1–#4 coatings was 70.0 N·cm, indicating that the coating technology did not affect the impact resistance of the coatings.

According to the results of the above orthogonal test, the most influential factor in coating technology is the number of primers. The most important influence on the gloss of paint film is the method of adding the color-changing powder. The coating technology did not affect the adhesion, impact resistance, and liquid resistance of the coating. According to the comprehensive analysis, the most important performance of the reversible color-sensitive waterborne coating is the color change performance, and the number of primers in the coating process is the most important factor affecting the overall performance of the paint film.

### 3.2. Performance Optimization of Reversible Color Changing Waterborne Coatings

The above results showed that the number of primers in the coating process is the biggest factor affecting the comprehensive performance of the paint film. According to the orthogonal experimental analysis in Table 4, the color difference corresponding to two times of topcoat and color changing powder added in topcoat was 86.65 and 84.55, respectively, while that of three times of topcoat and color changing powder added in primer was 67.30 and 69.40, respectively. The coating performance was better when the color changing powder was added into the topcoat and two times of topcoat were used. Therefore, the number of topcoats was two and the method of adding the color changing powder was fixed in the topcoat. The single factor test was conducted by changing the number of primer coats. The temperature-sensitive reversible color water-based coatings (Samples #5–#10) were prepared for the coating technology optimization test.

As shown in Figure 8, the color difference of coatings Samples #5–#10 from 18 to 30 °C was 0.4–4.0 with no obvious discoloration. The color of coating Samples #7 changed significantly when heated to 32 °C, and the color difference was 61.6. When other paint films were heated to 32 °C, the color difference was between 1.0 and 14.6, and the color change effect was not as good as coating Samples #7. Therefore, it can be preliminarily judged that coating Samples #7 has a good color changing effect. The function of the primer is to seal the catheter hole of the Chinese fir and improve the binding force between the topcoat film and the Chinese fir substrate. It may be that the different primer numbers affect the interface of the primer, thus changing the coating performance. The appropriate number of primers can ensure the uniform application of the topcoat, and make the topcoat performance have the best effect [25,26]. It can be seen from Table 9 that the gloss of the coating in the same coating
technology increased as the angle of incidence of light increased. Under the same intensity of incident light, the gloss of the paint film of different coating technologies did not change much.

![Color difference vs. temperature](image)

**Figure 8.** Effect of coating technologies on the color difference between 18 and 40 °C of waterborne color-changing coating.

**Table 9.** Effect of coating technologies on the gloss of the reversible color-changing coating.

| Sample | 20° Gloss (%) | 60° Gloss (%) | 85° Gloss (%) |
|--------|---------------|---------------|---------------|
| #5     | 2.7 ± 0       | 12.9 ± 0      | 32.2 ± 0      |
| #6     | 3.4 ± 0       | 16.3 ± 0.4    | 39.5 ± 0.6    |
| #7     | 2.8 ± 0       | 14.2 ± 0.4    | 31.0 ± 0.9    |
| #8     | 2.8 ± 0       | 17.6 ± 0.6    | 43.2 ± 0.9    |
| #9     | 3.9 ± 0       | 16.2 ± 0.2    | 40.8 ± 1.3    |
| #10    | 4.1 ± 0       | 17.7 ± 0.6    | 40.2 ± 1.4    |

The adhesion level, impact resistance, and liquid resistance level of Samples #5–#10 were the same as Samples #1–#4 (Table 10). Therefore, the coating technology did not affect the adhesion, impact resistance, and liquid resistance of the coating. SEM images of water-based color-changing coatings in the different coating technologies are shown in Figure 9. The coatings in the different coating technologies showed partial agglomeration, and the particles were obvious. There was no obvious difference in the microstructure.

**Table 10.** Effect of coating technologies on adhesion level, impact resistance, and liquid resistance level of the reversible color-changing coating.

| Sample | Adhesion (Level) | Impact Resistance (N·cm) | NaCl (Level) | Detergent (Level) | Ethanol (Level) | Red Ink (Level) |
|--------|------------------|--------------------------|--------------|-------------------|-----------------|----------------|
| #5     | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
| #6     | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
| #7     | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
| #8     | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
| #9     | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
| #10    | 0 ± 0            | 70.0 ± 0                 | 1 ± 0        | 1 ± 0             | 1 ± 0           | 3 ± 0           |
The performance of the color-changing powder water-based coating was compared with that of the traditional water-based coating and water-based coating with thermochromic ink [27], as shown in Table 11. The adhesion of these three coatings could reach the 0 level. The impact resistance and color difference of the color-changing powder water-based coating were better than the traditional water-based coating and water-based coating with thermochromic ink. The liquid resistance had little change. The gloss of the color-changing powder water-based coating was lower than that of the traditional water-based coating and water-based coating with thermochromic ink.

| Sample Adhesion (Level) | Impact Resistance (N·cm) | NaCl (Level) | Detergent (Level) | Ethanol (Level) | Red Ink (Level) | Gloss 60° (%) | Color Difference |
|-------------------------|---------------------------|--------------|------------------|----------------|----------------|--------------|-----------------|
| Traditional Water-Based Coating | 0 | 40.0 | 1 | 1 | 1 | 1 | 43.1 | 0.8 |
| Water-Based Coating with Thermochromic Ink Color-Changing Powder Water-Based Coating | 0 | 50.0 | 1 | 1 | 1 | 3 | 55.6 | 21.4 |
| Traditional Water-Based Coating | 0 | 70.0 | 1 | 1 | 1 | 3 | 14.2 | 61.6 |

4. Conclusions

The coatings with two primers, two topcoats, and with color-changing powder had a better color changing effect. Under the same intensity of incident light, there was no obvious change in the gloss using the different coating technologies. The coating technology had no influence on the adhesion, impact resistance, and liquid resistance of the paint film. Different coating technologies did not show different coating microstructure as well as coating composition. The color-changing effect is stable and sustainable, and it is an optimized combination of coating technology. Compared with previous work [27], the gloss of the color-changing powder water-based coating was lower and the impact resistance was greater than that of the traditional water-based coating and water-based coating with thermochromic ink. The adhesion level and the liquid resistance of the color-changing
powder water-based coating to sodium chloride, ethanol, detergent, and red ink was the same as the water-based coating with thermochromic ink. The thermochromic performance of the color-changing powder water-based coating was better than that of the traditional water-based coating and water-based coating with thermochromic ink. The results will provide a technical reference for a color-changing coating on wood materials.

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