Influence of Wood Knots of Chinese Weeping Cypress on Selected Physical Properties

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Abstract: The effects of wood knots of Chinese weeping cypress (Cupressus funebris Endl.) wood on selected physical and color properties were investigated. Thirty samples of live knots, dead knots, and clear wood groups were selected for experiments to determine the physical properties of wood density, wood shrinkage, wood swelling, and wood color. The experimental analysis results showed that the wood density values are in the order: dead knots > live knots > clear wood, with a significant difference in wood density between different groups (p < 0.01). In addition, the values of the air-dry volumetric wood shrinkage, air-dry volumetric wood swelling, oven-dry volumetric wood shrinkage, and oven-dry volumetric wood swelling ratios are in the order: dead knots > live knots > clear wood, being consistent with a variation in wood density. Three groups of wood colors were provided: the color of clear wood is light, the color of live knots is reddish, and the color of live knots is blackish, in relative terms. The chromatic aberration between the three groups can be identified, and the wood color difference resulted from the discrepancy in the lightness index.

Keywords: Cupressus funebris Endl. wood; wood knots; physical properties; wood color properties

1. Introduction

Cupressus L. (common name Cypress) is a genus of evergreen trees belonging to the family Cupressaceae, endemic in the Mediterranean region and includes 20 species distributed in temperate and subtropical regions, such as the southern part of North America, East Asia, the Himalayan region, and the Mediterranean region. Members of the genus Cupressus are mostly tall evergreen conifers with short scale-like leaves when the trees are adult, whereas they are bigger and needle-like when the trees are young, and they have good wood properties, which can be used for the construction of buildings, ships, furniture, and coffins. The branches and leaves of Cupressus trees can provide essential oil, and the genus Cupressus is generally regarded as one of the main tree species that is a commercial Chinese cedarwood oil extraction source. In addition to forest product applications, the use of Cupressus trees as ornamental plants, wind breaks, and hedges has increased all over the world, which mainly includes Cupressus glabra Sudw., Cupressus macrocarpa A.Cunn., Cupressus lusitanica Mill., Cupressus sempervirens Linn., etc. It is possible that Cupressus trees were planted in formal gardens built in proximity to funerary temples and cemeteries in many cultures, including ancient Greece, Rome, and China. This might link the tree to the concept of immortality and solemnity.

China, the main area of natural distribution for Cupressus funebris Endl., known also as Chinese weeping cypress, has four endemic species in the genus Cupressus, one of which is C. funebris [1]. C. funebris is one of the representative evergreen coniferous species in China’s subtropics; it is found in major vegetation restoration forests and is a timber forest species in the upper reaches of the Yangtze River of China, such as in the Sichuan, western Hubei, and Guizhou provinces [2–5]. Some botanists accept Franco’s reclassification of
C. funebris as Chamaecyparis funebris (Endl.) primarily because of its flattened foliage sprays and atypically small ovulate cones [6]. C. funebris wood is moderately hard, with a delicate structure, low wood shrinkage, and high resistance to decay, making it an excellent material for producing durable furniture, handicrafts, and other wood products. Woodwork made of C. funebris is popular with consumers because of its strength, resistance to decay, unique texture, and fragrant smell. Overall, C. funebris wood has been used for shipbuilding, construction, packaging, and woodworking since ancient times [7,8].

Trees spontaneously produce some natural defects during growth, and knots are one of the most common defects [9]; they are also one of the important factors that directly change the timber yield, grade, and price [10–12]. Knots play an important role in the physiological growth process of trees, and external branches are the main source of a tree’s nutritional needs as it grows. The leaves on living branches convert external CO\textsubscript{2} into organic matter and O\textsubscript{2} through photosynthesis, and the organic matter is transported to the tree roots through the sieve tubes of the phloem and then absorbed, contributing to tree growth [13]. Knots arise mainly from decaying parts caused by fungal infections and greatly affect the wood’s appearance, quality, and mechanical properties [14]. Therefore, searching for ways to minimize the occurrence of knots and expand the use of knot-related wood has become an important research topic.

Knots are one of the most common wood defects and are specific imperfections in the wood that reduce its strength, which can also be exploited for artistic effects. Knots can be divided into live and dead knots, where live knots, formed from the living part of a branch, are intergrown with the wood, and dead knots, formed from the dead part of a branch, have tracheids that are structurally disjunct from tracheids in the stem [15–17].

Knots are the main influencing factor of wood quality, regarding chemical composition and physical and mechanical properties. Knots have an important influence on the grade of structural lumber via reducing stiffness and strength through local distortion and the deviation of wood fibers from the longitudinal axis of the stem, resulting in weak mechanical areas [18]. Cherry et al. found that knots were significantly different from clear wood for all test types of mechanical properties, within a range of 48% to 196% [19].

Wood density, wood shrinkage, and wood swelling are the most important physical properties that affect processing performance. Yong et al. found that the average width of the annual rings of branch wood was 69% smaller than that of tree trunk wood, and the air-dry wood density of branch wood was 70% greater than that of tree trunk wood [20]. The wood density of knots varies depending on where it is located. Wang et al. found that the closer the knot was to the branch parts, the higher the wood density; the wood density was higher in the upper part of the whole knot and lower in the lower part [21]. Knots reduce the strength of wood, and the effect of knots on strength depends on the proportion of the cross-section of the given piece occupied by the knots and its relative location; as the proportion of knots on the cross-section increases, wood density increases accordingly [22]. In short, knots will increase the wood density of corresponding wood parts. Some studies have found that changes in the orientation of ducts, fibers, and other tissues distorted the grain around the knots, causing the knot grain to be different from normal wood. In contrast, the shrinkage and swelling of wood are anisotropic, resulting in different dry wood shrinkage coefficients between the knots and the surrounding wood in all directions, which can easily cause wood cracking during the drying process [23]. Knots do not shrink as much laterally or in the diameter of the surrounding wood. Studies have shown that knots can influence the wood swelling coefficients in a longitudinal direction, while the influence on wood swelling coefficients in tangential and radial directions is negligible [24]. Knots fall out because the knots and the surrounding clear wood have different wood shrinkage, which can occur during thermal modification processing [25]. The characteristics of the knots, such as volume, affect the wood shrinkage value; studies have shown that wood shrinkage is not different, especially in specimens containing small knots [21].
Knots affect not only the physical properties of wood but also the appearance quality of wood products. It is refereed that checks in knots are the worst defect for a wood’s appearance grade [26]; furthermore, wood color is an important appearance quality characteristic for the appearance grade of wood. Some studies have shown that the color of a wood’s knots is darker than the wood [27,28]; the main causes are that dead knots are separated from the surrounding tissues, and the detached edges varied in color, showing hard black scars with clear boundaries in color from the surrounding area. Further, the color of the live knots underwent gradual changes and deepened [29]. The determination of wood colors after treatment and wood color metrics are increasingly used in wood technology [30–32].

Most studies have focused on forest resource management, wood anatomy, physical and mechanical wood properties, forest genetics and breeding, essential oil properties and extraction, and mechanical properties of wood components of *C. funebris* [7,33–37]. Few studies have been conducted on the effects of knots on physical properties [21,38], and no research specifically on *C. funebris* wood has been reported.

This study had two objectives: the first was to investigate the relationship between different types of knots and the main physical properties of *C. funebris* wood, and the second was to provide certain instructions to realize the commercial application of *C. funebris* wood with knots.

2. Materials and Methods

2.1. Site Sampling

Thirty-three-year-old *Cupressus funebris* Endl. trees from pure forest plantations located in Yongxin Town, Jingyang District, Deyang City, Sichuan Province, China (31°1′–31°19′ N and 104°15′–104°35′ E) were used in this study. This area is a subtropical humid and semi-humid climate zone with little sunshine, abundant rainfall, and four distinct seasons, with an average annual temperature of 16–17 °C. The forest stands were planted in the mid-1980s, during which time no forestry management and cultivation management measures were conducted. A sample site with the same growth conditions on the mountain’s western slope of about 20–30° was selected for harvesting, with a sample area of 0.04 hm² (20 m × 20 m).

2.2. Physical Tests

Five *C. funebris* trees with normal growth, complete trunks, straightness, and no obvious defects were randomly selected from the sample area, marked with north–south direction, and measured for age. The diameter at breast height (DBH, i.e., diameter at 1.30 m of stem height) was 14.24 ± 0.84 cm and the tree height was 13.11 ± 0.58 m. One log was cut from 1.3 m to 3.3 m (with a length of 2 m), a second from 3.3 to 5.3 m of the trunk height (with a length of 2 m), and a third from 5.3 to 7.3 m of the trunk height (with a length of 2 m). The sets of 30 wood samples with dimensions of 20 mm × 20 mm × 30 mm for each group, including dead knots, live knots, and clear wood (knot-free), were selected from the 10 cut logs and prepared for the different studies (Figure 1). The physical properties of all the samples were tested according to Chinese National Standards GB/T 1928–2009 “General requirements for physical and mechanical tests of wood” [39], GB/T 1929–2009 “Method of sample logs sawing and test specimens selection for physical and mechanical tests of wood” [40], GB/T 1932–2009 “Method for determination of the shrinkage of wood” [41], GB/T 1933–2009 “Method for determination of the density of wood” [42], and GB/T 1934.2–2009 “Method for determination of the swelling of wood” [43]. The only difference between testing the physical properties of knot samples and clear wood samples was that the knot samples were cut from the inside of the tree, and their volume was measured using the drainage method.
where $\rho_w \ (g/cm^3)$ is air-dry wood density when the moisture content is $W$; $M_w \ (g)$ is the air-dry mass of each sample when the moisture content is $W$; $V_w \ (cm^3)$ is air-dry volume of samples when the moisture content is $W$.

$\rho_0 = M_0/V_0$  \hspace{1cm} (2)

where $\rho_0 \ (g/cm^3)$ is oven-dry wood density; $M_0 \ (g)$ is oven-dry mass of each sample; $V_0 \ (cm^3)$ is oven-dry volume of samples.

$P = 2(S_T/X)$  \hspace{1cm} (3)

where $P$ is accuracy index; $S_T$ is the standard error of the mean; $X$ is mean value.

2.3. Surface Color Test

Wood color is closely related to the quality assessment of wood products, which is related to the visual aesthetics of wood products and their decorative properties, thus affecting their economic, collecting, and artistic value. Wood color is a fundamental property of wood, and its chromaticity index is distributed among wood species. There is a great difference in the distribution characteristics of chromatic index among wood species, and even in the same species. Therefore, it is recommended to measure the color variation of wood with knots and its influencing factors to guide the selection and processing of high-value wood products.

A Minolta spectrophotometer model CM-700D (Konica Minolta, Osaka, Japan) was used for color measurement (10° standard observer, D65 standard illumination, color difference format $\Delta E^{*ab}$). We randomly selected an area on the samples for color testing of clear wood; knot areas were tested on dead and live knots samples for color testing. Tangential sections were used for color testing; if there was no knot area in the tangential section of dead and live knotted wood samples, the color test was performed in the radial or transverse section with the knot. The color of live knots, dead knots, and clear wood of *C. funebris* wood was measured using the spectrophotometer and described in the CIE L*a*b* color system. In this system, color was defined as three numerical values known as

![Figure 1. Test specimens from left to right: dead knots, live knots, and clear wood.](image)
the trichromatic coordinates (L*, a*, and b*). The coordinate L* refers to the lightness of a given sample (scored from 0, which represents the black color, to 100, which represents the white one), a* is the coordinate that defines the degree of approximation to the red color when a* takes positive values and green when it takes negative values, and the coordinate b* indicates yellow when it takes positive values and blue when it takes negative values. Each color test was repeated 30 times, and the average was calculated.

2.4. Statistical Analyses

Data were analyzed using Microsoft Excel (version 2013; Microsoft Corp., Redmond, WA, USA) and SPSS (version 19.0; IBM Corp., Armonk, NY, USA), and graphs were generated using Origin (version 9.1; OriginLab Corp., Northampton, MA, USA).

3. Results and Discussion

3.1. Wood Density

The moisture content of the samples was tested. The equilibrium moisture content (EMC) of the dead knot, live knot, and clear wood groups are 14.44%, 14.73%, and 15.08%, respectively. Oven-dry moisture content of the dead knot, live knot, and clear wood groups are 12.25%, 12.41%, and 12.69%, respectively.

Air-dry wood density affects the hardness and strength of wood, and at the same moisture content, it is positively correlated with wood hardness and strength, i.e., the higher the air-dry wood density, the harder and stronger the wood, and vice versa. Furthermore, air-dry wood density is an important factor affecting the final product quality of wood [44]. Whiskers are lines that extend from the top and bottom of the box to the adjacent values.

It can be seen that the box area of clear wood is the largest and the box area of dead knots is the smallest, indicating that the sample data values of clear wood have the largest range of variation and the sample data of dead knots have the smallest range of variation. The mean values of live knots, dead knots, and clear wood are below the median line, indicating that the sample data of all three are clustered at smaller values (Figure 2). Related studies have shown that the wood density is greatest in the branch part of the tree, followed by the knots, and lowest in the trunk. There is an obvious variation in the wood density of trunk [21], for example, in *Pinus taeda*. However, the wood density variation of different parts of the knots has not been reported yet.

In Figure 3, it can be seen that the box area of clear wood is the largest, and the box area of dead knots is the smallest, indicating that the range of variation of sample data for clear wood is the largest among the three groups, and the range of variation of sample data for dead knots is the smallest among the three groups. The mean values of live and dead

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**Figure 2.** Boxplots of air-dry wood density (g/cm³) for the live knots, dead knots, and clear wood. The 95% confidence interval, median, mean values, maximum (Max), and minimum (Min) positioning are shown.

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In Figure 3, it can be seen that the box area of clear wood is the largest, and the box area of dead knots is the smallest, indicating that the range of variation of sample data for clear wood is the largest among the three groups, and the range of variation of sample data for dead knots is the smallest among the three groups. The mean values of live and dead
knots are above the median line, and the mean values of clear wood are below the median line, indicating that the sample data values of live and dead knots are clustered at larger values, contrary to the air-dry wood density of both, while the sample data values of clear wood are clustered at smaller values, consistent with their air-dry wood density.

![Boxplots of oven-dry wood density (g/cm\(^3\)) for the live knots, dead knots, and clear wood.](image1)

**Figure 3.** Boxplots of oven-dry wood density (g/cm\(^3\)) for the live knots, dead knots, and clear wood. The 95% confidence interval, median, mean values, maximum (Max), and minimum (Min) positioning are shown.

The mean values of live and dead knots are above the median line, and the mean values of clear wood are below the median line, indicating that the sample data values of live and dead knots are clustered in larger values and the sample data values of clear wood are clustered in smaller values, which is consistent with the distribution of the oven-dry wood density data of the three groups. The box area of clear wood is the largest among the three groups, and the box area of dead knots is the smallest among the three groups, indicating that the range of variation of sample data for clear wood is the largest among the three groups and the range of variation of sample data for dead knots is the smallest among the three groups (Figure 4).

![Boxplots of basic wood density (g/cm\(^3\)) for the live knots, dead knots, and clear wood.](image2)

**Figure 4.** Boxplots of basic wood density (g/cm\(^3\)) for the live knots, dead knots, and clear wood. The 95% confidence interval, median, mean values, maximum (Max), and minimum (Min) positioning are shown.

Air-dry, oven-dry, and basic wood density are all medium densities, i.e., they are easy to process and can meet the mechanical requirements of the material used. The three-wood
density-changes law for different knots is dead knots > live knots > clear wood. Since knots are the best choice for trees in resisting external changes, and wood density is positively correlated with the resistance of trees, the wood density of knots should be greater than the wood density of clear wood, consistent with the above test results.

From Table 1, it can be seen that all correlations among air-dry wood density, oven-dry wood density, and basic wood density of live knots, dead knots, and clear wood were highly significant ($p < 0.01$), except for the correlation between the basic wood density and the air-dry wood density of dead knots, which was significant ($p < 0.05$). The coefficient of determination of the regression equation between the basic wood density and the oven-dry wood density of dead knots was 0.759 with average regression results. Moreover, the coefficient of the determination of regression equation between the basic wood density and the air-dry wood density of dead knots was 0.184, and the oven-dry wood density and the air-dry wood density of dead knots was 0.273, both with poor regression results.

Table 1. Linear regression equations among wood density at the different studied conditions for dead knots, live knots, and clear wood.

<table>
<thead>
<tr>
<th>Knots Type</th>
<th>Regression Equation of Basic Wood Density (X) and Air-Dry Wood Density (Y)</th>
<th>Regression Equation of Basic Wood Density (X) and Oven-Dry Wood Density (Y)</th>
<th>Regression Equation of Air-Dry Wood Density (X) and Oven-Dry Wood Density (Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live knots</td>
<td>$Y = 0.206 + 0.799X$ $R^2 = 0.557 ** (p &lt; 0.01)$</td>
<td>$Y = 0.046 + 1.025X$ $R^2 = 0.884 ** (p &lt; 0.01)$</td>
<td>$Y = 0.057 + 0.844X$</td>
</tr>
<tr>
<td>Dead knots</td>
<td>$Y = 0.437 + 0.385X$ $R^2 = 0.184 * (p &lt; 0.05)$</td>
<td>$Y = 0.084 + 0.967X$ $R^2 = 0.759 ** (p &lt; 0.01)$</td>
<td>$Y = 0.185 + 0.646X$</td>
</tr>
<tr>
<td>Clear wood</td>
<td>$Y = 0.196 + 0.834X$ $R^2 = 0.672 ** (p &lt; 0.01)$</td>
<td>$Y = 0.003 + 1.098X$ $R^2 = 0.942 ** (p &lt; 0.01)$</td>
<td>$Y = 0.181 + 0.621X$</td>
</tr>
</tbody>
</table>

** indicates that the significance test is significant at the $p = 0.01$ level, * indicates significance test is significant at $p = 0.05$ level.

3.2. Wood Shrinkage and Wood Swelling

Since the growth direction of wood fibers in live and dead knots differs from that of clear wood, the radial, tangential, and longitudinal directions of wood cannot be accurately distinguished, so only the volumetric wood shrinkage and wood swelling ratio of different types of knots were investigated. Air-dry wood shrinkage ratio is the percentage change in volume from the free-drying shrinkage of green or wet wood under no external force to the air-drying state, and oven-dry wood shrinkage ratio is the percentage change in volume from dry-shrinkage of green or wet wood to the oven-dry state. Air-dry wood swelling ratio is the percentage change in volume from the oven-dry state to the air-dry state, and oven-dry wood swelling ratio is the percentage change in volume from the oven-dry state to when water is absorbed to the dimensional stability state.

The data given in Table 2 show the volumetric wood shrinkage and wood swelling ratios of the live knot, dead knot, and clear wood groups. Combined with Figure 5, it can be seen that the volumetric shrinkage and swelling ratio of dead knots are the highest and those of clear wood are the lowest. The reason for the high air-dry and oven-dry wood shrinkage and wood swelling ratio of dead knots may be due to the following:

1. Wood density is shown to affect the various wood shrinkages and wood swellings that occur during wood drying. Wood density is positively correlated with both radial and tangential wood shrinkage, but is also negatively correlated with longitudinal wood shrinkage [45]. The wood density is determined by the proportion of cell wall material. The proportion of tissue is a key anatomical factor in the volume shrinkage of wood [46]. The greater the wood density of the wood, which generally represents a greater number of cell walls, the greater the wood shrinkage and wood swelling ratio, and vice versa. Wood density decreases within the three groups, from the dead
knots to the live knots to clear wood, so the wood shrinkage and wood swelling ratio are consistent with the wood density ranking.

(2) Dead knots contain more extracts, and the chemical composition of the extracts has a greater influence on water absorption and loss, similar to other observations and studies [47]. The coefficients of variation of air-dry and oven-dry wood shrinkage and wood swelling ratios of all three groups were high and belonged to the medium variation.

Table 2. Volumetric wood shrinkage and wood swelling ratio of different knot types.

<table>
<thead>
<tr>
<th>Properties Type</th>
<th>Knots Type</th>
<th>Number of Samples</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Coefficient of Variation</th>
<th>Accuracy Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-dry volumetric wood shrinkage ratio</td>
<td>Live knots</td>
<td>30</td>
<td>4.33</td>
<td>2.08</td>
<td>0.38</td>
<td>22.14%</td>
<td>18.49%</td>
</tr>
<tr>
<td></td>
<td>Dead knots</td>
<td>30</td>
<td>5.89</td>
<td>1.38</td>
<td>0.25</td>
<td>15.38%</td>
<td>8.36%</td>
</tr>
<tr>
<td></td>
<td>Clear wood</td>
<td>30</td>
<td>4.03</td>
<td>1.25</td>
<td>0.23</td>
<td>16.65%</td>
<td>10.32%</td>
</tr>
<tr>
<td>Oven-dry volumetric wood shrinkage ratio</td>
<td>Live knots</td>
<td>30</td>
<td>9.50</td>
<td>2.90</td>
<td>0.53</td>
<td>18.33%</td>
<td>11.42%</td>
</tr>
<tr>
<td></td>
<td>Dead knots</td>
<td>30</td>
<td>11.22</td>
<td>2.84</td>
<td>0.52</td>
<td>14.24%</td>
<td>9.05%</td>
</tr>
<tr>
<td></td>
<td>Clear wood</td>
<td>30</td>
<td>9.05</td>
<td>1.75</td>
<td>0.32</td>
<td>13.54%</td>
<td>6.64%</td>
</tr>
<tr>
<td>Air-dry volumetric wood swelling ratio</td>
<td>Live knots</td>
<td>30</td>
<td>5.74</td>
<td>2.98</td>
<td>0.54</td>
<td>21.90%</td>
<td>18.58%</td>
</tr>
<tr>
<td></td>
<td>Dead knots</td>
<td>30</td>
<td>6.20</td>
<td>3.46</td>
<td>0.63</td>
<td>19.05%</td>
<td>19.95%</td>
</tr>
<tr>
<td></td>
<td>Clear wood</td>
<td>30</td>
<td>5.68</td>
<td>2.00</td>
<td>0.37</td>
<td>19.97%</td>
<td>12.61%</td>
</tr>
<tr>
<td>Oven-dry volumetric wood swelling ratio</td>
<td>Live knots</td>
<td>30</td>
<td>10.45</td>
<td>3.52</td>
<td>0.64</td>
<td>18.72%</td>
<td>12.42%</td>
</tr>
<tr>
<td></td>
<td>Dead knots</td>
<td>30</td>
<td>12.79</td>
<td>3.70</td>
<td>0.68</td>
<td>14.89%</td>
<td>10.36%</td>
</tr>
<tr>
<td></td>
<td>Clear wood</td>
<td>30</td>
<td>10.18</td>
<td>2.16</td>
<td>0.39</td>
<td>14.53%</td>
<td>7.38%</td>
</tr>
</tbody>
</table>

Figure 5. Histogram of the volumetric wood shrinkage and wood swelling ratios. Mean value (n = 30) and standard deviation of dead knots, live knots, and clear wood.

As shown in Table 3, the differences in the air-dry and oven-dry volumetric wood swelling ratio between live knots and clear wood are not significant. The differences in the air-dry and oven-dry volumetric wood shrinkage ratio between live knots and dead knots are highly significant, the differences in the oven-dry volumetric wood swelling ratio between live knots and dead knots are significant, and the differences in the air-dry volumetric wood swelling ratio between live knots and dead knots are not significant. In addition, the differences between the air-dry volumetric wood shrinkage ratio and the oven-dry volumetric wood swelling ratio between dead knots and clear wood are highly significant, and the air-dry volumetric wood swelling ratio between them is not significant. In general, different knots of *C. funebris* wood have different effects on the air-dry and oven-dry volumetric wood shrinkage and wood swelling ratio; specifically, dead knots have a greater effect on the air-dry and oven-dry volumetric wood shrinkage and wood swelling ratio than live knots.
Table 3. Summary of the results for the significance test of differences between volumetric wood shrinkage and wood swelling ratios of live knots, dead knots, and clear wood.

<table>
<thead>
<tr>
<th>Properties Type</th>
<th>Live Knots and Clear Wood</th>
<th>Live Knots and Dead Knots</th>
<th>Dead Knots and Clear Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-dry volumetric wood shrinkage ratio</td>
<td>−0.695</td>
<td>−4.102 **</td>
<td>4.602 **</td>
</tr>
<tr>
<td>Oven-dry volumetric wood shrinkage ratio</td>
<td>−0.581</td>
<td>−2.702 **</td>
<td>2.698 **</td>
</tr>
<tr>
<td>Air-dry volumetric wood swelling ratio</td>
<td>−0.059</td>
<td>−0.362</td>
<td>0.36</td>
</tr>
<tr>
<td>Oven-dry volumetric wood swelling ratio</td>
<td>−0.487</td>
<td>−2.660 *</td>
<td>2.701 **</td>
</tr>
</tbody>
</table>

** indicates that the significance test is significant at the $p = 0.01$ level. * indicates significance test is significant at $p = 0.05$ level.

From Figure 5, it is clear that the change rules of the air-dry and oven-dry volumetric wood shrinkage ratio and air-dry and oven-dry volumetric wood swelling ratio are consistent among the live knots, dead knots, and clear wood: air-dry volumetric wood shrinkage < air-dry volumetric wood swelling < oven-dry volumetric wood shrinkage < oven-dry volumetric wood swelling.

3.3. Wood Color Parameters

The test results of the color parameters of different knot types of *C. funebris* wood are shown in Table 4.

Table 4. Wood color parameters of different knot types.

<table>
<thead>
<tr>
<th>Type of Wood</th>
<th>Number of Samples</th>
<th>Wood Color Parameters</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Coefficient of Variation</th>
<th>Accuracy Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live knots</td>
<td>30</td>
<td>L*</td>
<td>55.29</td>
<td>7.76</td>
<td>1.74</td>
<td>14.03%</td>
<td>6.15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a*</td>
<td>10.30</td>
<td>1.24</td>
<td>0.28</td>
<td>12.02%</td>
<td>5.27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b*</td>
<td>21.58</td>
<td>1.69</td>
<td>0.38</td>
<td>7.83%</td>
<td>3.43%</td>
</tr>
<tr>
<td>Dead knots</td>
<td>30</td>
<td>L*</td>
<td>49.17</td>
<td>6.70</td>
<td>1.34</td>
<td>13.63%</td>
<td>5.34%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a*</td>
<td>9.60</td>
<td>1.19</td>
<td>0.24</td>
<td>12.40%</td>
<td>4.86%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b*</td>
<td>18.10</td>
<td>2.90</td>
<td>0.58</td>
<td>16.04%</td>
<td>6.29%</td>
</tr>
<tr>
<td>Clear wood</td>
<td>30</td>
<td>L*</td>
<td>73.83</td>
<td>5.52</td>
<td>1.23</td>
<td>7.47%</td>
<td>3.27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a*</td>
<td>7.70</td>
<td>0.75</td>
<td>0.17</td>
<td>9.74%</td>
<td>4.27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b*</td>
<td>24.99</td>
<td>3.20</td>
<td>0.72</td>
<td>12.80%</td>
<td>5.61%</td>
</tr>
</tbody>
</table>

As can be seen from Figures 1 and 6, the lightness of dead knots is the smallest and the lightness of clear wood is the largest, indicating that the visible light reflection of dead knots is the smallest among the three groups and its color is more biased toward black, and vice versa for clear wood. The $a^*$ values of live knots, dead knots, and clear wood are all positive. The $a^*$ value of clear wood is the smallest and the $a^*$ value of live knots is the largest, indicating that they are all biased towards red. Clear wood has the weakest reflection of red light, but live knots have the strongest reflection of red light.

The $b^*$ values of live knots, dead knots, and clear wood are all positive. The $b^*$ value of clear wood is the largest, and the $b^*$ value of dead knots is the smallest, indicating that the wood color of all three groups is more biased toward yellow; clear wood has the strongest reflection of yellow light, but dead knots have the weakest reflection of yellow light. The chromatic aberration between the three groups was 19.341, 29.642, and 10.301, respectively, which is identifiable in [48]. The magnitude of variation of the wood color parameter $L^*$ among different groups is significantly larger than that of $b^*$ and $a^*$, indicating that the chromatic aberration among the three groups is mainly due to lightness ($L^*$).
strongest reflection of yellow light, but dead knots have the highest wood shrinkage, wood swelling, and wood color of the sample, a* value refers to the redness of the sample and the b* value gives the yellowness of the sample).

Pearson’s correlation analysis was performed to define the relationship between the color parameters of different knot types in *C. funebris* wood (see Figure 7). This analysis is classified into correlation categories: very weak \((r < 0.2)\), weak \((0.2 \leq r < 0.4)\), moderate \((0.4 \leq r < 0.6)\), strong \((0.6 \leq r < 0.8)\), and very strong \((r \geq 0.8)\) [49]. As can be seen from Figure 7, the correlation coefficients between \(L^*\) and \(a^*\) and \(L^*\) and \(b^*\) are \(r = -0.622\) and \(r = 0.616\), respectively, indicating that \(L^*\) is strongly correlated with both \(a^*\) and \(b^*\), and combined with the results of the paired \(t\)-test, \(L^*\) is significantly negatively correlated with \(a^*\) and significantly positively correlated with \(b^*\) at the 0.01 level. The correlation coefficient between \(a^*\) and \(b^*\) is \(r = -0.354\), which indicates that \(a^*\) is weakly correlated with \(b^*\), and combined with the results of the paired \(t\)-test results, \(a^*\) and \(b^*\) are significantly negatively correlated at the 0.01 level.

![Figure 6. Wood color parameter histogram of mean value and standard deviation of different knot types.](image)

**Figure 6.** Wood color parameter histogram of mean value and standard deviation of different knot types (\(L^*\) value refers to the lightness of the sample, \(a^*\) value refers to the redness of the sample, and the \(b^*\) value gives the yellowness of the sample).

![Figure 7. Correlation heat map of wood color parameters of dead knots, live knots, and clear wood.](image)

**Figure 7.** Correlation heat map of wood color parameters of dead knots, live knots, and clear wood (\(L^*\) value refers to the lightness of the sample, \(a^*\) value refers to the redness of the sample and the \(b^*\) value gives the yellowness of the sample).

## 4. Conclusions

In this study, the main differences in physical properties, including wood density, wood shrinkage, wood swelling, and wood color of *C. funebris* wood were investigated, and the main conclusions obtained are as follows.

The air-dry, oven-dry, and basic wood density differed among dead knots, live knots, and clear wood. Overall, the descending order of wood density is dead knots, live knots, and clear wood. The changing order of air-dry and oven-dry volumetric wood shrinkage and wood swelling among dead knots, live knots, and clear woods group is consistent with the changing order of wood density among them: dead knots > live knots > clear wood.
The decreasing order of lightness and yellow–blue color chromaticity is from clear wood to live knots to dead knots, and the decreasing order of red–green color chromaticity is from live knots to dead knots to clear wood. The color of clear wood is bright, the color of live knots is reddish, and the color of dead knots is blackish, in relative terms. The chromatic aberration between the three groups is recognizable, and the difference in color results from the difference in L* values.

Therefore, when wood with knots is used in products, the wood density of knots has less influence on the wood from the physical aspect of wood; wood with knots and clear wood may be applied without distinction, in terms of wood density. However, the wood shrinkage and wood swelling of dead knots and live knots have more influence on wood compared to clear wood. If wood is used as a joint material for buckets, boats, etc., wood with knots should be selected to increase the tightness between the materials when wet.

In short, in terms of wood shrinkage and wood swelling, the effect of knots should be fully considered.

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Conflicts of Interest: The authors declare no conflict of interest.

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