# DETERMINATION OF SURFACE MOISTURE CONTENT OF WOOD UTILIZING A COLORIMETRIC TECHNIQUE[1]

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## ABSTRACT

Optical properties of cobalt chloride ($CoCl_2$) hydrate, whose color changes with surrounding humidity, were used to develop a colorimetric technique for determining surface moisture content of wood nondestructively. The colorimetric $CoCl_2$ treated wood technique for determining surface moisture content through color degree change in CIE L*a*b* color space has been experimentally verified.

*Keywords:* Cobalt chloride ($CoCl_2$) hydrate, colorimetric technique, surface moisture content, CIE L*a*b*, spectrophotometer.

## INTRODUCTION

Though the determination of surface moisture content (SMC) is important in the study of stress development and preventing surface checking of wood during drying, methods to measure SMC have not yet been well developed. This paper will introduce a colorimetric technique for determining surface moisture content utilizing the optical properties of $CoCl_2$ hydrate and a color-measuring instrument. Wood surfaces exhibit different color values when exposed under different circumstances. For example, the surface of wet wood is usually relatively dark, while dried surfaces are a lighter color. It is difficult, however, to determine specific moisture content by color change of wood specimens when there is little variation or change with incremental moisture content, especially when below the fiber saturation point. To address this problem, wood specimens were treated with $CoCl_2$ hydrate, a compound whose color depends upon, and changes with, relative humidity (RH) and temperature. $CoCl_2$ hydrate is shown to exhibit a reddish color that then changes to a bluish color, over the high to low humidity range, respectively. In the 1930s Rother developed a wood hygrometer using paper test strips treated with $CoCl_2$. Estimation of moisture content in the range from 6 to 23% in steps of 3% was possible by comparing the color of the test strip with a color scale (cited by Kollmann and

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Côté 1968). The method is cheap and quick. The results, however, are influenced by variation in lighting conditions and the personal element in visual observations. Because of these disadvantages, this optical method could not practically be used to determine moisture content before development of a method and instrument for expressing color numerically. Recently, using optical fiber and color value change of $CoCl_2$ hydrate according to humidity and temperature, fiber optic humidity and temperature sensors have been developed to detect relative humidity and temperature in air (Otsuki and Adachi 1993; Kharaz and Jones 1995; Hypszer and Wierzba 1997; Kawamura et al. 1999; Dybko et al. 1999; Coera et al. 2000). In this study, the surface of wood was treated with $CoCl_2$, and the color changes were measured using a spectrophotometer at various surrounding humidity conditions. The measured color was shown numerically in the CIE L*a*b* color space, which presents all visible color, and was based on the daylight 6500K degree color temperature.

### *Colorimetry*

Colorimetry is the technique of color measurement, and is based on a mechanism of human visual perception. In 1931, an international organization concerned with light and color, the Commission Internationale de l'Eclairage (CIE, International Commission on Illumination), defined CIE XYZ tristimulus values, which are now used throughout the world for color communication. Based on these CIE XYZ tristimulus values, the CIE L*a*b* color space was devised in 1976 to provide more uniform color differences in relationship to visual differences (CIE 1986).

### *CIE XYZ*

To measure the color of a specimen, each of three parameters must be analyzed. The first parameter is the spectral energy distribution of the light source ($S(\lambda)$), the second is the reflectance from the specimen ($R(\lambda)$), and the third is the spectral sensitivity ($x(\lambda)$, $y(\lambda)$, $z(\lambda)$) of the observer (Crisment 1998). The concept for the XYZ tristimulus values is based on the three-component theory of color vision, which states that the eye possesses receptors for three primary colors (red, green, and blue) and that all colors are seen as mixtures of these three primary colors. The values of X, Y, and Z are calculated according to the formulas below:

$$X = K \int_{380}^{780} S(\lambda)R(\lambda)x(\lambda)\, d\lambda,$$

$$Y = K \int_{380}^{780} S(\lambda)R(\lambda)y(\lambda)\, d\lambda,$$

$$Z = K \int_{380}^{780} S(\lambda)R(\lambda)z(\lambda)\, d\lambda \qquad (1)$$

where

$$K = 100 \Big/ \int_{380}^{780} S(\lambda)y(\lambda)\, d\lambda$$

$\lambda$: wavelength (nm)

$S(\lambda)$: relative spectral energy distribution of light source

$R(\lambda)$: spectral reflectance of specimen

$x(\lambda)$, $y(\lambda)$, $z(\lambda)$: spectral sensitivity corresponding to the human eye.

### *CIE L*a*b**

The tristimulus values XYZ are useful for defining a color, but the results are not easily visualized. Because of this, the CIE also defined CIE L*a*b* color space in 1976 for graphing color. The L*a*b* color space is presently one of the most popular color spaces for measuring object color and is widely used in virtually all fields. The values of L*,a*, and b* are calculated according to the formulas below:

$$L^* = 116(Y/Yn)^{1/3} - 16,$$

$$a^* = 500[(X/Xn)^{1/3} - (Y/Yn)^{1/3}],$$

$$b^* = 200[(Y/Yn)^{1/3} - (Z/Zn)^{1/3}] \qquad (2)$$

where X, Y, Z : Tristimulus valus XYZ of the specimen

Xn, Yn, Zn : Tristimulus values XYZ of a perfect reflection

If X/Xn, Y/Yn, or Z/Zn is less than 0.008856,

$(X/Xn)^{1/3}$ is replaced by $7.787(X/Xn) + 16/116$

$(Y/Yn)^{1/3}$ is replaced by $7.787(Y/Yn) + 16/116$

$(Z/Zn)^{1/3}$ is replaced by $7.787(Z/Zn) + 16/116$

In this color space, L* indicates lightness, and a* and b* are the chromaticity coordinates. a* and b* values indicate color directions: +a* is the red direction, −a* is the green direction, +b* is the yellow direction, and −b* is the blue direction. The center is achromatic. As a* and b* values increase and the color point moves out from the center, the saturation of the color increases.

## MATERIALS AND METHODS

Experiments were carried out with three species, hard maple (*Acer saccharum* Marsh), red oak (*Quercus rubra* L.), and southern pine (*Pinus* spp.). Three different directional, cross, radial, and tangential, sections with the dimension of 15 (length) × 15 (width) × 5 (thickness) mm were prepared and soaked in water. $CoCl_2$ hydrate (from Fisher Scientific Com.) was saturated in water. From this saturated $CoCl_2$ solution, approximately 3 μL was dropped from a dispensing micropipette on the wet surface of specimens (15 × 15 mm) and spread across the surface with the pipette tip. When five specimens each were equilibrated at two different temperatures, 30 and 50°C, and five lower RH conditions, the treated surface spectral reflectance was measured with a portable spectrophotometer (Microflash 200d, DataColor International), and then CIE L*a*b* color values were calculated. The SMC is determined by hygroscopicity of untreated wood and surface color difference ($dE_{mc\text{-}eq}$) between treated wood at any moisture condition and treated wood equilibrated under the specified lowest RH condition. 25%RH was used as the lowest RH condition in these experiments.

$$dE_{mc\text{-}eq} = [(L_{mc}^* - L_{eq}^*)^2 + (a_{mc}^* - a_{eq}^*)^2 + (b_{mc}^* - b_{eq}^*)^2]^{1/2} \qquad (3)$$

where, $L_{mc}^*$, $a_{mc}^*$ and $b_{mc}^*$: L*, a*, and b* values on the surface of treated moist wood equilibrated at any RH.

$L_{eq}^*$, $a_{eq}^*$, and $b_{eq}^*$: L*, a*, and b* values on the surface of treated wood equilibrated at the lowest RH.

When making the regression functions for SMC determined with color value, as a first step, surrounding RH condition on the surface of wood was determined by the $CoCl_2$ treated wood color difference, then SMC of wood is determined by hygroscopicity of untreated wood. Hygroscopicity of three species, hard maple, red oak, and southern pine, was measured with 12 specimens for each species at two temperature conditions, 30 and 50°C.

## RESULTS

### *Hygroscopicity of wood*

As expected, the moisture content (MC) of wood decreased with the decrease of surrounding relative humidity, and moisture content equilibrated at low temperature was higher than MC equilibrated at high temperature for the same RH. The equilibrium moisture contents (EMC) of wood as third-order functions of relative humidity are given in Table 1. These third order functions of sorption curves are well fitted for the relationship between EMC and RH over the whole RH range.

### *Determination of surface moisture content. Spectral reflectance*

The surface of treated hard maple at higher RH reflected particularly well the light with longer wavelength (Fig. 1). Similar results were found with red oak and southern pine.

### *CIE L*a*b**

CIE L*a*b* color values were calculated using the reflectance data. Wood treated with

TABLE 1. *Equilibrium moisture content of wood as third order functions of relative humidity.*

| Species | Temp. (°C) | % MC = a·%RH³ − b·%RH² + c·%RH | | | $r^2$ |
|---|---|---|---|---|---|
| | | a × $10^5$ | b × $10^3$ | c × 10 | |
| Hard maple | 30 | 5.19 | 5.95 | 3.64 | 0.99 |
| | 50 | 5.30 | 5.86 | 3.17 | 0.99 |
| Red oak | 30 | 5.76 | 6.68 | 3.80 | 0.99 |
| | 50 | 6.11 | 6.99 | 3.46 | 0.99 |
| Southern pine | 30 | 7.03 | 8.27 | 4.09 | 0.99 |
| | 30 | 7.11 | 8.33 | 3.79 | 0.99 |

$CoCl_2$ exhibits a reddish color at high RH and changes to a green-blue color at low RH. This means that a* and b* values continuously decrease over the high to low RH range. Also, lightness (L*) of the treated wood surface decreases with RH in the hygroscopic range (Fig. 2).

### *Surface moisture content*

Using hygroscopicity of untreated wood, surface moisture content is predicted by $dE_{mc\text{-}eq}$ of wood treated with $CoCl_2$. The linear relationships between surface moisture content and $dE_{mc\text{-}eq}$ on the surface of three directional sections of each species, hard maple, red oak, and southern pine treated with $CoCl_2$ are shown in Fig. 3 and summarized in Table 2.

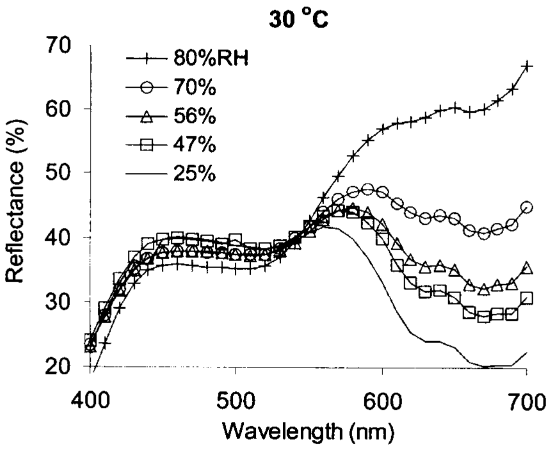

FIG. 1. Spectral reflectance change on the tangential surface of treated hard maple with relative humidity at 30°C.

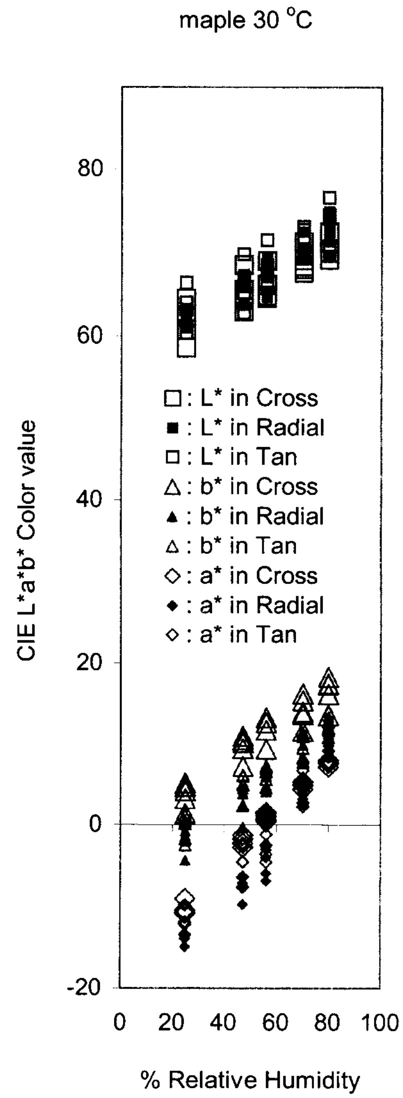

FIG. 2. CIE L*a*b* values of treated hard maple specimens at different relative humidity at 30°C.

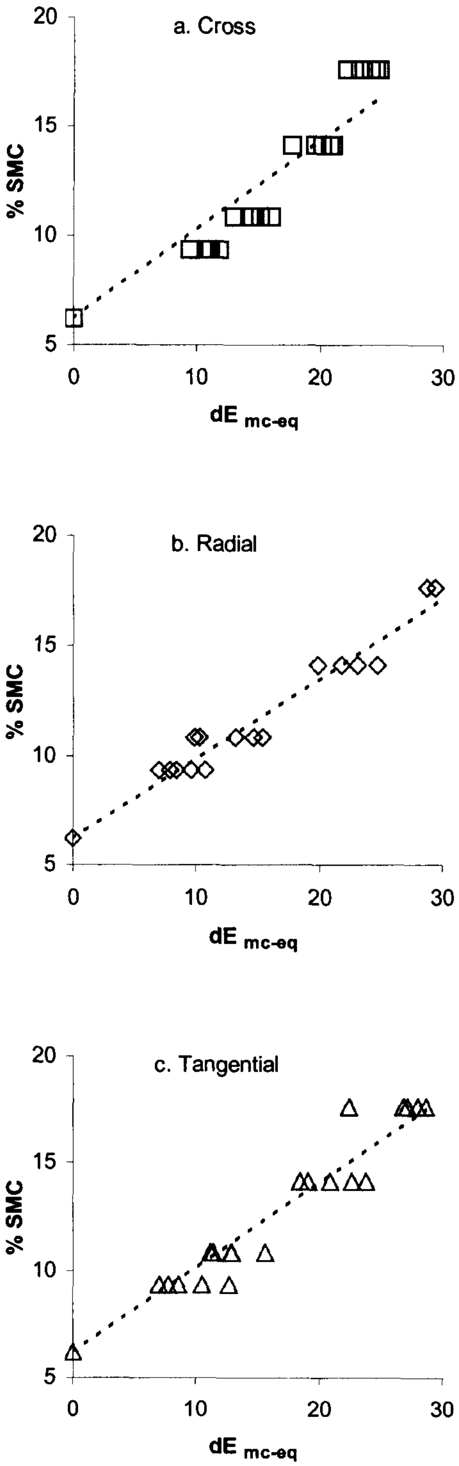

FIG. 3. Relationship between surface moisture content and color difference ($dE_{mc\text{-}eq}$) of a. cross section, b. radial, and c. tangential surfaces of maple at 30°C. Linear regression and $r^2$ values are presented in Table 2.

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### *Resolution of colorimetric method*

The spectrophotometer detector consists of a 128-element diode array. Following the study of Hill et al. (1997), CIE $L^*a^*b^*$ optimal color space is arrayed within the limits $0 < L^* < 100$, $-166 < a^* < 141$, $-132 < b^* < 147$. Since the spectrophotometer might divide the lightness ($L^*$) range 0 to 100, the $a^*$ value range $-166$ to 141, and the $b^*$ value range $-132$ to 147 by the 128 diodes, the spectrophotometer can measure approximately 0.78 of lightness difference ($\Delta L^*$), 2.40 of $a^*$ value difference ($\Delta a^*$), and 2.18 of $b^*$ value difference ($\Delta b^*$), respectively. Because color difference (dE) is defined as $dE = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$, the spectrophotometer can measure 3.33 of dE. Results from this experiment showed that average maximum $dE_{mc\text{-}eq}$ of treated wood between 80%RH and 25%RH was about 30. Therefore, the %RH difference determined by the spectrophotometer can be calculated as (80%RH–25%RH) × (3.33/30) = 6.1%RH. Since EMC of wood at 80%RH is about 18%MC and EMC at 25%RH is about 6%MC, %MC difference determined by the spectrophotometer can be calculated as (18%MC–6%MC) × (3.33/30) = 1.3% MC.

## CONCLUSIONS

The colorimetric $CoCl_2$-treated wood technique, which has been developed for determining surface moisture content through color degree change in CIE $L^*a^*b^*$ space while drying, has been experimentally verified. The good linear relationship between SMC and $dE_{mc\text{-}eq}$ has shown that surface moisture content can be determined by this colorimetric method.

Because this colorimetric technique has the advantage of freedom from electromagnetic interference and offers the prospect of remote monitoring of surface moisture content, a

TABLE 2. *Linear relationships between surface moisture content and $dE_{mc\text{-}eq}$ on the three different directional sections of hard maple, red oak, and southern pine treated with $CoCl_2$.*

| Temp. (°C) | Species | Section | %SMC = a·$dE_{mc\text{-}eq}$ + b<br>a | b | $r^2$ |
|---|---|---|---|---|---|
| 30 | Hard maple | Cross | 0.410 | 6.2 | 0.91 |
| | | Radial | 0.366 | 6.2 | 0.98 |
| | | Tangential | 0.395 | 6.2 | 0.95 |
| | Red oak | Cross | 0.399 | 6.2 | 0.87 |
| | | Radial | 0.338 | 6.2 | 0.97 |
| | | Tangential | 0.353 | 6.2 | 0.97 |
| | Southern pine | Cross | 0.300 | 6.2 | 0.77 |
| | | Radial | 0.275 | 6.2 | 0.96 |
| | | Tangential | 0.275 | 6.2 | 0.96 |
| 50 | Hard maple | Cross | 0.513 | 5.1 | 0.93 |
| | | Radial | 0.479 | 5.1 | 0.97 |
| | | Tangential | 0.482 | 5.1 | 0.96 |
| | Red oak | Cross | 0.471 | 5.2 | 0.89 |
| | | Radial | 0.446 | 5.2 | 0.96 |
| | | Tangential | 0.428 | 5.2 | 0.97 |
| | Southern pine | Cross | 0.322 | 5.4 | 0.72 |
| | | Radial | 0.312 | 5.4 | 0.83 |
| | | Tangential | 0.366 | 5.4 | 0.93 |

number of useful applications of this technique might be possible. Examples include surface moisture content sensing of wood and other hygroscopic particle and powder materials in bulk storage, and humidity monitoring through industrial drying systems to optimize use of energy.

Also, because the color value measured by this technique is representative as a standard color value for determining the surface MC of wood, if there is good color space conversion from CIE L*a*b* to other color spaces, especially the RGB that is used in image capture devices (scanners and digital camera), surface moisture content and geometrical information can be simultaneously determined in pixel units. This might encourage better analysis in studies on various hygroscopic materials' physical properties related to moisture.

## REFERENCES

CHRISMENT, A. 1998. Color and colorimetry. Ed. 3C. Conseil, Paris. 30 pp.

CIE. 1986. Colorimetry. CIE Publication No 15.2. 2nd Ed. Commission Internationale de l'Eclairage, Vienna, Austria. 74 pp.

COERA, F. P., A. GASTON, AND J. SEVILLA. 2000. Relative humidity sensor based on side-polished fiber optic. Proc. 17th IEEE Instrumentation and Measurement Technology Conference, Baltimore, MD. 1:17–22.

DYBKO, A., W. WROBLEWSKI, E. ROZNIECKA, J. MACIEJEWSKI, AND Z. BRZOZKA. 1999. Comparison of two thermochromic solutions for fiber optic temperature probes. Sensors and Actuators A (Physical) A76:203–207.

HILL, B., T. ROGER, AND F. W. VORHAGEN. 1997. Comparative analysis of the quantization of color spaces on the basis of the CIE LAB color-difference formula. ACM Trans. Graphics 16(2):109–154.

HYPSZER, R., AND H. J. WIERZBA. Fiber optic technique for relative humidity sensors. 1997. Proc. SPIE—Int. Society for Optical Engineering 3054:145–150.

KAWAMURA, M., T. TAKEUCHI, H. FAUD, AND S. SATO. 1999. Feb. Humidity and temperature sensing using an optical fiber and a corner cube prism. Jap. J. Appl. Physics, Part 1. 38(2A):849–850.

KHARAZ, A., AND B. E. JONES. 1995. A distributed optical-fiber sensing system for multipoint humidity measurement. Sensors and Actuators A (Physical) A46–47:491–493.

KOLLMANN, F. F. P., AND W. A. CÔTÉ. 1968. Principles of wood science and technology. Vol. I. Solid Wood. Springer-Verlag, New York, NY. 592 pp.

OTSUKI, S., AND K. ADACHI. 1993. Humidity dependence of visible absorption spectrum of gelatin film coating cobalt chloride. J. Appl. Polymer Sci. 48(9):1557–1564.