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# The Evaluation of Uncertainty in Wood Moisture Sensor Calibration

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**ABSTRACT**: The objective of this paper is to propose valid procedure for evaluation of measurement uncertainty associated with wood moisture sensor's calibration and for determining contribution of uncertainty component associated with moisture conditioning and drying process due to reference moisture content [MC]. The study represents the uncertainty calculations for the reference instruments, moisture characteristics of wood material in terms of oven drying method and saturated solution of salts and moisture content result from wood moisture sensors. The various preceding experiments and analysis of calibration certificates for several years were conducted to investigate the contribution to the standard uncertainty for environmental uncertainty component, i.e. heterogeneity, density, absorption and desorption of wood specimen, long-term stability and reference standards. Also, the calibration of wood moisture sensor was performed in the reference moisture content from 10 %MC to 20 %MC. Some standard uncertainties were calculated by type B method based on theoretical and experimental data and the other uncertainty was obtained by type A method based on standard deviation of measurement results. The necessity of understanding dominant uncertainty contribution to the standard uncertainty and application of reference formulas to calculate the wood moisture content are discussed. The evaluation procedure of measurement uncertainty is developed in accordance with the principles established in the documents EA-4/02, *Expression of the Uncertainty of Measurement in Calibration* and BIPM2008, *Guide to the Expression of Uncertainty in Measurement*.

**KEY WORDS**: Measurement Uncertainty, Wood Moisture Sensor, Calibration, Moisture Content, Uncertainty component, Moisture Conditioning.

## I.INTRODUCTION

The measurement accuracy and precision of total amount of water in a piece of wood based on reliable instrumentation and method are of importance in various fields of industry such as meteorological analysis and forecasting, many special applications in agriculture, architecture, civil engineering, food [1,2]. The total amount of water in the wood is called its moisture content (MC) and it is usually expressed as a percentage (%MC). The moisture content (MC) is defined as the weight of the water in the wood divided by the weight of the wood [3]. In other word, the amount of water contained in the wood, is usually expressed as a percentage of the weight of the oven-dry wood. Moisture has an essential effect on fungal growth and important factor for the prediction of service life of wooden constructions [4]. Also, the durability and susceptibility to stain, decay and insects of wood are determined by the correlation between wood and water.

In general, an oven drying method is used as the standard method for measuring the moisture of wood, because of the most direct and accurate method for determining the MC. However, portable wood moisture sensors have been more commonly used than oven drying method in manufacturing sites these days owing to quickness, usability, convenience and suitability for use in most commercial situations [4,5]. Therefore, it is essential that the wood moisture sensors should be calibrated within a given period of time and the measurement uncertainty for the results should be evaluated properly according to scientific and authorized method. So far, most of the studies have been done on measurement method and process of the MC such as comparison between dry oven and microwave oven technique, development of control system for wood drying processes and characteristic analysis between resistance and capacitance types of moisture sensors [8-11]. However, the investigations for calibration method and estimation of measurement uncertainty for the wood moisture sensor have been not performed clearly. In particular, environmental factors that affects measurement results such as proper choice of oven drying procedure and reference standard equipment, moisture

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conditioning to create standard wood according to the MC, heterogeneity of standard specimens, moisture desorption and absorption, wood density, data processing technique, and so on have been not considered suitably in measurement uncertainty. In other words, the general evaluation method of measurement uncertainty and uncertainty component limited by specification of the manufacturer has been suggested regardless of environmental measurement condition.

The purpose of this paper is to analyse in more detail the measurement uncertainty as well as propose the evaluation procedure of uncertainty with respect to the actual measurement results of wood moisture sensor and reference wood based on aqueous saturated salt solution and oven drying method. The measurement uncertainties are evaluated for the measurement results at reference MC of approximately 10 %, 15 % and 20 %. The study presented mathematical model, uncertainty components, probability distributions, coverage factors, sensitivity coefficients, effective number of degrees of freedom, expanded uncertainties and methods of type A and B. The evaluation procedure of measurement uncertainty is developed in accordance with the principles established in the documents EA-4/02, *Expression of the Uncertainty of Measurement in Calibration* and BIPM2008, *Guide to the Expression of Uncertainty in Measurement* [6,7].

## II. CALCULATIONS OF MOISTURE CONTENT (MC)

To estimate the measurement uncertainty for calibration of wood moisture meter, the measurement was performed with reference wood containing various reference moisture content, approximately 10 % MC, 15 %MC and 20 %MC. The calibration procedure was conducted with comparison calibration between the numerical calculation results of the wood specimen's MC in based on moisture conditioning process and reference formula (1) and calibration results by the wood moisture sensor. The parameters of the formula (1) are determined by weight of wood before and after drying. Proper drying oven process and calculation of the MCplay an important role in wood specimens retaining the reference moisture. The reference MC of the wood specimen to calibrate wood moisture sensor is usually based on the ratio of the weight of the water to the weight of the wood after oven-drying procedure.

$$\%MC = \frac{weight\ of\ wood\ before\ drying - weight\ of\ oven\ dry\ wood}{weight\ of\ oven\ dry\ wood} \quad (1)$$

The drying procedure for determining the MC in wood specimens is carried out in a drying chamber at (103± 2)℃ for 24 hours. Because the oven drying weight is not a natural state for the wood and the wood usually takes up and retains moisture consistently while performing measurement, it may cause a significant error in the results. Therefore, the reference wood should be weighted immediately after being removed from the oven.

## III. INSTRUMENTATION AND MEASUREMENT

Equilibrium moisture content (EMC) for wood-base material and wood is totally dependent on specified temperature and relative humidity condition. Therefore, balance between temperature and relative humidity should be maintained suitably to realize particular equilibrium moisture content (EMC).The calibration of wood moisture sensor was performed to determine various uncertainty components and propose the evaluation procedure of measurement uncertainty.

The calibration procedures of wood moisture sensor were roughly composed of moisture conditioning process for reference wood, measurement by moisture sensor and oven drying treatment. To obtain wood specimen retaining various reference MC, conditioning process due to relative humidity condition was carried out by means of aqueous saturated salt solutions [12, 18]. The moisture conditioning system was initiated with setting up a conditioning chamber which is maintaining constantly temperature and relative humidity stability below± 0.1℃ and ± 0.5 %. In particular, the temperature should be controlled carefully during conditioning process, because temperature variation of ± 0.1℃ can cause the variation of generated relative humidity of approximately ± 0.5%.The fixed humidity environments for the various reference MC was created according to the table 1. The procedure of an aqueous saturated salt solution was based on OIML R92 [13]. The salts used for the preparation of solutions was chemically pure with 99.99 % and

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analytical grade. In particular, various wood-base materials can reach different levels of EMC. Thus, the reference wood specimen prepared in this study was limited to Norway spruce with 100 mm wide and 20 mm thick. The conditioning systems were respectively kept in the state exposed to 50 %R.H., 84 %R.H. and 97%R.H. at 23 ℃using constant temperature and humidity control system and salt solution, KCl and $K_2SO_4$to obtain the wood specimens with various reference values, approximately 10 %MC, 15 %MC and 20 %MC.

The EMC of reference wood usually changes in response to the environmental condition such as dimensional variation and conditioning time [17]. The variation of these environmental parameters has a major effect on the EMC and measurement uncertainty. These wood specimens had been conditioned in the chamber at 23 ℃, room temperature for 60 days to maintain constant equilibrium moisture and uniformly distribute constant moisture. Also, the wood specimens were arranged equally with spacers in the conditioning chamber in a single layer. The conditioning chambers are made of glass and stainless steel to resist any corrosion by aqueous saturated salt solutions. To prevent the effect of moisture deviation caused by leaks in the conditioning chamber, the leak test was conducted with monitoring temperature and humidity in the working space.

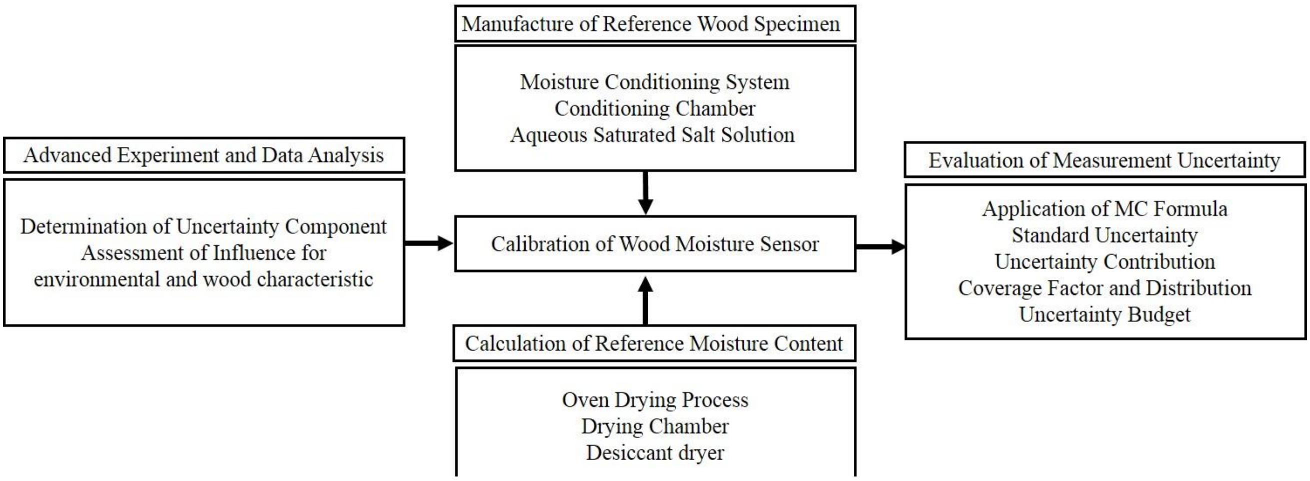


Fig 1. System diagram for calibration setup and evaluation procedure of measurement uncertainty

Heat drying treatment to evaluate the MC of reference wood was conducted as described in “oven-drying method A” of international standards, ASTM D442-15 [14]. The reference specimens were placed in the drying chamber maintained at a temperature (103 ± 2) ℃for 24 hours. The drying chamber and electronic scale to measure weight of the each wood as reference standards were calibrated by comparison with other reference instruments to establish traceability based on international standards, ISO 17025. The effect of electronic scale and drying chamber and their long-term stability was expected to be major uncertainty components in terms of reference instruments.

Table 1.The saturated solution of salts and standard relative humidity value for conditioning reference wood specimen

| Salt solution | Standard relative humidity (%) at 20 ℃ | Standard relative humidity (%) at 25 ℃ |
|---|---|---|
| LiCl | 12.4 | 12.0 |
| $MgCl_2$ | 33.6 | 33.2 |
| NaCl | 75.5 | 75.8 |
| $(NH_4)_2SO_4$ | 80.6 | 80.3 |
| KCl | 84.3 | 84.1 |
| $K_2SO_4$ | 97.2 | 96.9 |

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The measurement was performed for wood moisture sensors under calibration in the reference MC from 10 %MC to 30 %MC at a setting ambient temperature of 23 ℃ in order to analyse major uncertainty components and propose evaluation method of measurement uncertainty. The measurement method was basically followed according to standard calibration procedure of Korea Testing Laboratory (KTL) which assures suitability and traceable results. It is also based on international standards [13-15].

Fig 2. Moisture conditioning and drying process based on aqueous solution and oven drying method

## IV. MEASUREMENT UNCERTAINTY EVALUATION

### Evaluation of standard uncertainty

All the measurement results without evaluation of the measurement uncertainty are incomplete and don't give information enough [16,17]. Thus, the measurement uncertainties due to the each result should be reported at the certain confidence level, by converting uncertainty components into standard uncertainties. Standard uncertainty is the basic elementary unit, which is expressed as a statistical distribution characteristic for each uncertainty component. Combined and Expanded uncertainties are obtained from various standard uncertainties. The metrological performance of the wood moisture sensor's calibration suffers from the influence of environmental conditions.

In this study, the twelve uncertainty components for wood moisture sensor's calibration were proposed and their contributions to the standard uncertainties were calculated. The contributions to the standard uncertainty were comprised of experimental standard deviation by repeated measurement, judgment based on result in certificates, long term stability of reference standard, resolution of the sensor under calibration, heterogeneity of standard specimens, moisture desorption and absorption, wood density and measuring depth of sensor needle. Also, all contributions were individual factors independent of each other.

The various uncertainty components could be divided into two categories based on their methods of evaluation. The type A refers to determination of an uncertainty by statistical analysis of a series of observations such as the standard deviation from repeated readings. The type B is evaluation method of uncertainty by means other than the statistical analysis used for type A, for example by reference standards, experience with the behaviour of the instruments and additional information about measurement condition [6,7].Therefore, the evaluation methods of twelve uncertainty components were classified according to type A and type B. The measurement uncertainties in respect of the measurement values at the reference points for MC, approximately 10 %MC, 15 %MC and 20 %MC were reported through uncertainty budgets. The various standard uncertainties were estimated as follows.

**A) Uncertainty due to repeated measurement ($u_{ma}$)**
Uncertainty due to repeated measurement was calculated by standard deviation for three experimental measurement values. The values of uncertainty ($u_{ma}$) can be known from table 4-6 and they are evaluated for each measurement result

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at the reference MC, 10 %MC, 15 %MC and 20 %MC. In the case of 15 %MC, reference point, the standard uncertainty $u_i(y)$ was calculated 0.03 %MC from the standard deviation of repeated measurement values. Also, the contribution to the standard uncertainty $u_i(y)$ was calculated by multiplication between standard uncertainty and sensitivity coefficient.

$$u(x_i) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} = 0.03\ (\%MC)$$

$$u_i(y) = c_i \times u(x_i) = 0.03\ (\%MC) \quad (2)$$

**B) Uncertainty due to reference scale for measurement before drying ($u_{s1}$)**

The standard uncertainty of the reference scale could be classified largely by measurements before drying and after drying.
The standard uncertainty ($u_{s1}$) in terms of measurement before drying was calculated by the evaluation of Type B. The expanded uncertainty and coverage factor ($k$) of reference scale were obtained from calibration certificate. The reference scale presents constant expanded uncertainty in the measuring range (57 ~ 89 g, weight of specimens), for example, $U$=2 mg. The standard uncertainty is calculated 1 mg by the expanded uncertainty and coverage factor ($k$=2) from the calibration certificate. Moisture desorption relevant to the 1 mg, standard uncertainty, was calculated by relation of weight (mg) and MC (%MC) as shown below (3).The expanded uncertainty was divided by coverage factor ($k$) and it was converted into numerical value of MC as in (3). This numerical value was used as one of the standard uncertainties in the calibration of wood moisture sensor.

$$W_1 = \frac{1}{m_2} \times m_{e1} \times 100 \quad (3)$$

Where the moisture desorption ($W_1$) is given Eq (3), $m_2$ and $m_{e1}$are weight(mg) of the wood specimens after drying and standard uncertainty of moisture desorption (mg).

**C) Uncertainty due to reference scale for measurement after drying ($u_{s2}$)**

The standard uncertainty of the reference scale for measurement after drying ($u_{s2}$) was calculated by the evaluation of Type B in the same way as standard uncertainty$u_{s1}$. The expanded uncertainty of reference scale was obtained from the result of calibration certificate. The expanded uncertainty should be divided by coverage factor ($k$) to use as one of the standard uncertainties in the calibration of wood moisture sensor. The standard uncertainty for reference weight of the scalecalculated by coverage factor ($k$) was converted into the standard uncertainty for MCas in (3).

**D)Uncertainty due to long-term stability for reference scale ($u_{ss}$)**

The variation of the calibration values for three years was analysed to estimate long-term stability of reference scale asone of the uncertainty components. The3 g, maximum deviation among the results from annual calibration certificates was determined as an uncertainty component for long-term stability. This uncertainty component was assumed a rectangular distribution. The standard uncertainty due to long-term stability ($u_{ss}$) was calculated 1.73 mg as in (4).We are able to calculate the moisture absorption(%MC) of reference wood by relation of weight (mg) of drying condition and moisture absorption (mg) due to reference MC (%MC) as in (5). Therefore, standard uncertainty by the formula (4) was converted into the averageof the MC(%MC)between calculation values of formula (3) and (5).

$$u_{ss} = \pm \frac{a_{ss}}{\sqrt{3}} \quad (4)$$

where$a_{ss}$ is the maximum variation of the calibration values for three years.

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$$W_2 = \frac{m_1}{(-m_2)^2} \times m_{e2} \times 100 \quad (5)$$

Where the moisture absorption ($W_2$) is given Eq (5), $m_1$ and $m_2$are weight (mg) of the wood specimens before and after drying respectively and $m_{e2}$(mg) are standard uncertainty of moisture absorption.

**E) Uncertainty due to drying chamber ($u_{dc}$)**

The standard uncertainty ($u_{dc}$) due to drying chamber was calculated by the evaluation of Type B according to judgment based on result in certificates. The expanded uncertainty of drying chamber used as one of the uncertainty components in the calibration of wood moisture sensor was determined from result of the calibration certificate. The standard uncertainty was obtained by dividing expanded uncertainty with coverage factor($k$). This standard uncertainty concerning temperature was converted into MC from relation of temperature and MC. This uncertainty was assumed a normal distribution and infinite degree of freedom according to the calibration certificate.

**F) Uncertainty due to long-term stability for drying chamber ($u_{cs}$)**

The variation of reference drying chamber's calibration values for three years was analysed to estimate long-term stability as an uncertainty component relevant to reference standards. The maximum deviation among the results from calibration certificate was determined and assumed a rectangular distribution. The standard uncertainty due to long-term stability ($u_{cs}$) was calculated as the same as procedure of section (D).

**G) Uncertainty due to heterogeneity of wood specimens ($u_{wh}$)**

In general, the response characteristics in terms of heterogeneity of wood material might be different according to each measuring location and absorbed MC. Also, the characteristics might be appeared differently by sensor's manufacturers. Therefore, sensing characteristics should be investigated based on the mutual relationship between measuring location and absorbed MC for various sensor's manufacturers.

The experiment in terms of the heterogeneity of wood material was performed in wood specimens with various MC. The measurement results taken at respective nine locations of thirty wood specimens in three conditions of MC, approximately 10 %MC, 15 %MC and 20 %MC,were analysed to evaluate effect these parameters on measuring values of wood moisture sensors as the uncertainty component. Details are shown in Table 2.The maximum deviation induced by measuring locations of the wood specimen increased as the reference MC increased in all occasions. We determined the representative maximum deviation among average values from different manufacturer's sensors for each reference MC to calculate the standard uncertainty. It is desired that the advanced research to obtain experimental databases with regard to response characteristics related to measuring location, sensor's manufacturer and MCshould be conducted. Moreover, the heterogeneity effect should be investigated on the basis of the experimental databases. This uncertainty was assumed a rectangular distribution by the type B evaluation and the standard uncertainty related to the heterogeneity was calculated as in (4).

**Table 2.**The experimental results in terms of heterogeneity of wood specimens

| Manufacturer | Maximum deviation at 10 %MC | Maximum deviation at 15 %MC | Maximum deviation at 20 %MC |
|---|---|---|---|
| A | 1.0 | 1.4 | 1.5 |
| B | 0.7 | 0.9 | 1.5 |
| C | 0.6 | 0.8 | 1.9 |
| Representative maximum deviation | 1.0 | 1.4 | 1.9 |

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**H) Uncertainty due to resolution of wood moisture sensor ($u_{wr}$)**

The uncertainty due to resolution ($u_{wr}$) was calculated by method of type B. It assumed a rectangular distribution as an uncertainty component caused by rounding off of the measuring result. It is considered as half of the display range. Therefore, standard uncertainty due to resolution of wood moisture sensor was estimated as in (6).

$$u_{mr} = \pm \frac{a_{mr}}{2\sqrt{3}} \quad (6)$$

**I) Uncertainty due to density of wood specimen ($u_{wd}$)**

A total of 270 wood specimens, which were divided into three groups of thirty depending on the density were prepared to investigate the relation between density of wood specimen and MC. We calculated the specimen's densities before drying in a state of EMC due to deformation of the specimen after drying with the formula (7). The measurements were respectively performed in the nine sections of these specimens with the same conditioning based on aqueous solution in approximately 10 %MC, 15 %MC and 20 %MC. This experiment into consider the effect of wood density on MC as an uncertainty component. We calculate the maximum correction between reference MC of wood specimen and measurement value of the moisture sensor to estimate a standard uncertainty caused by density of the wood specimen. The standard uncertainty was calculated by type B method in a rectangular distribution as in (4).

$$D_{od} = \frac{D_m}{\left(1+\frac{m}{100}\right)} \times (1 - c_3) \quad (7)$$

$$c_3 = 0.009 \times \frac{D_m}{\left(1+\frac{m}{100}\right)} \times \left(\frac{m}{100}\right) \quad (8)$$

Where $D_{od}$ and$D_m$ are specimen's densities before drying and in a state of reference moisture respectively and $c_3$ is specific gravity given by formula (8).

**J) Uncertainty due to insertion depth of wood moisture sensor($u_{sd}$)**

When we penetrate wood moisture sensor in the wood specimen to measure the MC, the variation of insertion depth can have an extremely negative effect on calibration results. Therefore, the experiments with a couple of groups in which the sensors were penetrated fully and half were performed to evaluate the influence relevant to insertion depth of wood moisture sensor. Also, the MC was measured in nine sections of the specimen to minimize the effect of heterogeneity and then the maximum deviations of averages of measurement values between two groups were calculated due to each reference MC of the ten wood specimens. The experimental procedure was applied for three kinds of sensors related to representative manufacturers respectively .The maximum deviations related to the insertion depth were assumed to be a rectangular distribution. The standard uncertainty was estimated by type B method as in (4).

**K) Uncertainty due to desorption of wood specimen ($u_{wd}$)**

The maximum valuesamong the moisture desorption measured in condition of 10 %MC, 15 %MC and 20 %MC respectively were considered as the standard uncertainties related to desorption of the wood specimens. The table 3 shows the experiment results for maximum desorption and absorption due to the reference MC. The deviation of the wood's weight during procedure of the calibration was converted to moisture desorption of the specimen (%MC) using the formula (3). The values of $\boldsymbol{u_{wd}}$ were calculated for each measured weight at the reference MC.

 

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**L) Uncertainty due to absorption of wood specimen ($u_{wa}$)**

The maximum values among the moisture absorption were obtained from the experiment according to the reference MC. The standard uncertainty due to the absorption ($u_{wa}$) was calculated as the same as procedure of the section (K).

**Table 3.**The experimental results for maximum desorption and absorption of wood specimen

| Moisture content | 10 %MC | 15 %MC | 20 %MC |
|---|---|---|---|
| Maximum desorption | 0.02 | 0.18 | 0.28 |
| Maximum absorption | 0.05 | 0.06 | 0.05 |

**Evaluation of combined standard uncertainty ($u_c$)**

The estimation of the combined standard uncertainty ($u_c$) concerning the wood moisture sensor is carried out at different values of the reference MC. The square root of the sum of the $N$ standard uncertainty values $u$ squared, produces the combined uncertainty $u_c$ [6]. The combined standard uncertainty is calculated as in (9) in case of approximately 15 %MC, reference MC.

$$u_c(y) = [\sum_{i=2}^{N} u_i^2(y)]^{\frac{1}{2}} \quad (9)$$

$$= \sqrt{[u_{ma}^2 + u_{s1}^2 + u_{s2}^2 + u_{ss}^2 + u_c^2 + u_{cs}^2 + u_{wh}^2 + u_{wr}^2 + u_{wd}^2 + u_{sd}^2 + u_{wd}^2 + u_{wa}^2]}$$

$$= \sqrt{[0.03^2 + 0.002^2 + 0.002^2 + 0.002^2 + 0.08^2 + 0.03^2 + 0.81^2 + 0.03^2 + 0.98^2 + 0.64^2 + 0.10^2 + 0.03^2]}$$

$$= 1.43 \text{ \%MC}$$

**Evaluation of expanded uncertainty**

The evaluation of uncertainty contributions in terms of the uncertainty components and expaneded uncertainty of wood moisture sensor's calibration based on theoretical conception and experimental results has been suggested in table 1-3 due to reference MC, 10 %MC, 15 %MC and 20 %MC, respectively.The uncertainty budgets (table 4-6) are based on a format that given in the document Expression of the Uncertainty of Measurement in Calibration [6].

From the budgets in various referenceMCs,the contributions for the heterogeneity and density of wood specimen and insertion depth of wood moisture sensor obtained by analysing experimental data were larger than the others relatively. Furthermore, the contributions to the standard uncertainty of these components in a higher MC were more significant compared with them in a lower MC. In other word, these uncertainty components associated with the characteristic of wood material should be considered necessarily because the contribution to standard uncertainty was clearly dominated by the effect of the heterogeneity, density,and insertion depth in all occasions.

The reported expanded uncertaintiesat vaious refernce MCswerestated asthe standard uncertainy multiplied by the coverage factor $k$=2, which for a normal distribution corresponds to a confidence level of approximately 95 %.

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**Table 4.**Uncertainty budget at 10 %MC,reference moisture content

| Symbol | Uncertainty source | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution | Degree of freedom |
|---|---|---|---|---|---|---|
| $u_{ma}$ | Repeated measurement | 0.03 %MC | T | 1 | 0.03 %MC | 2 |
| $u_{s1}$ | Reference scale for measurement before drying | 0.002 %MC. | Normal | 1 | 0.002 %MC. | ∞ |
| $u_{s2}$ | Reference scale for measurement after drying | 0.002 %MC | Normal | 1 | 0.002 %MC | ∞ |
| $u_{ss}$ | Long-term stability for reference scale | 0.002 %MC | Rectangular | 1 | 0.002 %MC | ∞ |
| $u_{dc}$ | Drying chamber calibration certificate | 0.08 %MC | Normal | 1 | 0.08 %MC | ∞ |
| $u_{cs}$ | Long-term stability for drying chamber | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wh}$ | Heterogeneity of wood specimens | 0.58 %MC | Rectangular | 1 | 0.58 %MC | 50 |
| $u_{wr}$ | Resolution of moisture sensor | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wd}$ | Density of wood specimen | 0.87 %MC | Rectangular | 1 | 0.87 %MC | 50 |
| $u_{sd}$ | Insertion depth of moisture sensor | 0.46 %MC | Rectangular | 1 | 0.46 %MC | 50 |
| $u_{wd}$ | Desorption of wood specimen | 0.01 %MC | Rectangular | 1 | 0.01 %MC | 50 |
| $u_{wa}$ | Absorption of wood specimen | 0.03 %MC | Rectangular | 1 | 0.03 %MC | 50 |
| $u_c$ | Combined standard uncertainty | | | | 1.15 %MC | 119 |

**Table 5.**Uncertainty budget at 15 %MC, reference moisture content

| Symbol | Uncertainty source | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution | Degree of freedom |
|---|---|---|---|---|---|---|
| $u_{ma}$ | Repeated measurement | 0.03 %MC | T | 1 | 0.03 %MC | 2 |
| $u_{s1}$ | Reference scale for measurement before drying | 0.002 %MC. | Normal | 1 | 0.002 %MC | ∞ |
| $u_{s2}$ | Reference scale for measurement after drying | 0.002 %MC | Normal | 1 | 0.002 %MC | ∞ |
| $u_{ss}$ | Long-term stability for reference scale | 0.002 %MC | Rectangular | 1 | 0.002 %MC | ∞ |
| $u_{dc}$ | Drying chamber calibration certificate | 0.08 %MC | Normal | 1 | 0.08 %MC | ∞ |
| $u_{cs}$ | Long-term stability for drying chamber | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wh}$ | Heterogeneity of wood specimens | 0.81 %MC | Rectangular | 1 | 0.81 %MC | 50 |
| $u_{wr}$ | Resolution of moisture sensor | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wd}$ | Density of wood specimen | 0.98 %MC | Rectangular | 1 | 0.98 %MC | 50 |
| $u_{sd}$ | Insertion depth of moisture sensor | 0.64 %MC | Rectangular | 1 | 0.64 %MC | 50 |
| $u_{wd}$ | Desorption of wood specimen | 0.10 %MC | Rectangular | 1 | 0.10 %MC | 50 |
| $u_{wa}$ | Absorption of wood specimen | 0.03 %MC | Rectangular | 1 | 0.03 %MC | 50 |
| $u_c$ | Combined standard uncertainty | | | | 1.43%MC | 137 |

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**Table 6.**Uncertainty budget at 20 %MC,reference moisture content

| Symbol | Uncertainty component | Standard uncertainty | Distribution | Sensitivity coefficient | Uncertainty contribution | Degree of freedom |
|---|---|---|---|---|---|---|
| $u_{ma}$ | Repeated measurement | 0.04 %MC | T | 1 | 0.04 %MC | 2 |
| $u_{s1}$ | Reference scale for measurement before drying | 0.002 %MC | Normal | 1 | 0.002 %MC | ∞ |
| $u_{s2}$ | Reference scale for measurement after drying | 0.002 %MC | Normal | 1 | 0.002 %MC | ∞ |
| $u_{ss}$ | Long-term stability for reference scale | 0.002 %MC | Rectangular | 1 | 0.002 %MC | ∞ |
| $u_{dc}$ | Drying chamber calibration certificate | 0.08 %MC | Normal | 1 | 0.08 %MC | ∞ |
| $u_{cs}$ | Long-term stability for drying chamber | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wh}$ | Heterogeneity of wood specimens | 1.10 %MC | Rectangular | 1 | 1.10 %MC | 50 |
| $u_{wr}$ | Resolution of moisture sensor | 0.03 %MC | Rectangular | 1 | 0.03 %MC | ∞ |
| $u_{wd}$ | Density of wood specimen | 1.27 %MC | Rectangular | 1 | 1.27 %MC | 50 |
| $u_{sd}$ | Insertion depth of moisture sensor | 1.21 %MC | Rectangular | 1 | 1.21 %MC | 50 |
| $u_{wd}$ | Desorption of wood specimen | 0.16 %MC | Rectangular | 1 | 0.16 %MC | 50 |
| $u_{wa}$ | Absorption of wood specimen | 0.03 %MC | Rectangular | 1 | 0.03 %MC | 50 |
| $u_c$ | Combined standard uncertainty | | | | 2.08 % R.H. | 150 |

## V. DISCUSSION AND CONCLUSION

In this study, we proposed and discussed an evaluation procedure of measurement uncertainty for the calibration of wood moisture sensor using experimental and numerical analysis. The reference MC in standard wood specimens was determined by aqueous saturated salt solution and oven drying method. Actual calibration for the wood moisture sensor and preceding experiments were conducted to estimate the measurement uncertainty. The measurement uncertainty based on approximately 95 % confidence level with a coverage factor of $k$ = 2 was estimated at 10 %MC, 15 %MC and 20 %MC, reference MC. The total twelve uncertainty components were suggested and their contributions were evaluated respectively. The effect of repeated measurement, material characteristics and certificate of the reference standards, environmental and measurement condition was investigated and the contribution for their effects was taken into account and calculated respectively to obtain the combined standard uncertainty. The preceding experiments to analyse the influence of wood characteristic for heterogeneity, density and long-term stability and insertion depth of wood moisture sensor on the calibration of wood moisture sensor and the measurement uncertainty had been performed due to the range of reference MC.

The contribution for heterogeneity and density of the standard wood and insertion depth of the wood moisture sensor had a mainly effect on the expanded uncertainty for calibration of wood moisture sensor. In particular, the contribution to the standard uncertainty of these components was more significant in the high MC. It is expected that measurement condition such as heterogeneity, density and insertion depth had directly effect on the deviation characteristic of calibration results. Thus, it is necessary that essential understanding and contribution for the uncertainty component based on experimental data due to the range of reference MC should be required prior to beginning the calibration to obtain the reliable measurement result as well as to reduce uncertainty. Furthermore, the contribution to the standard uncertainty for the other standard wood except for the spruce and hence the measurement uncertainty has not yet addressed and should be the subject of further study.

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