Christian Brischke*, Kathrin A. Sachse and Christian R. Welzbacher

Modeling the influence of thermal modification on the electrical conductivity of wood

Abstract: A model has been developed aiming at the description of the effect of thermal modification on the electrical conductivity of wood. The intention was to calculate the moisture content (MC) of thermally modified timber (TMT) through the parameters electrical resistance R, wood temperature T, and CIE $L^*a^*b^*$ color data, which are known to correlate well with the intensity of a heat treatment. Samples of Norway spruce (*Picea abies* Karst.) and beech (*Fagus sylvatica* L.) samples were thermally modified in laboratory scale at 11 different heat treatment intensities and the resistance characteristics of the samples were determined. Within the hygroscopic range, a linear relationship between the resistance characteristics and the mass loss (ML) through the heat treatment was established. Based on this, a model was developed to calculate MC from R, T, and ML. To validate this model, color values of 15 different TMTs from industrial production were determined for estimation of their ML and fed into the model. MC of the 15 arbitrarily heat-treated TMTs was calculated with an accuracy of ±3.5% within the hygroscopic range. The material-specific resistance characteristics based on experimental data led to an accuracy of ±2.5%.

Keywords: electrical resistance, moisture content measurement, moisture meter, moisture monitoring of timber structures, resistance characteristics, thermally modified timber (TMT)

*Corresponding author: Christian Brischke, Faculty of Architecture and Landscape Sciences, Institute of Vocational Sciences in the Building Trade, Herrenhäuser Str. 8, D-30419 Hannover, Germany, e-mail: brischke@ibw.uni-hannover.de
Christian Brischke and Kathrin A. Sachse: Leibniz University Hannover, Hannover, Germany
Christian R. Welzbacher: Heinz-Piest-Institute for Craftsmen Technique (HPI), Hannover, Germany

Introduction

In recent years, thermal cell wall modification has become one of the most established wood modification processes in Europe with still increasing market volume (Welzbacher and Scheiding 2011). Initially, thermally modified timber (TMT) has been produced for outdoor application due to its improved dimensional stability and durability against wood-destroying fungi (Tjeerdsma et al. 1998, 2002; Vernois 2001; Welzbacher 2007). More recently, TMT is also considered for indoor use, for instance, as parquet flooring or furniture (Militz 2008; Jones 2012). Higher durability as well as dimensional stability of TMT is closely related to lower water sorption (Tjeerdsma et al. 1998; Welzbacher 2007; Olek et al. 2013; Ringman et al. 2013). In other words, the hygroscopicity of wood is reduced through thermal modification due to changes of chemical composition and structural changes of the cell wall. In particular, the number of reactive hydroxyl groups and thus the number of sites for binding water molecules is decreased (Krackler et al. 2011). The intensity and the type of heat treatment are essential with this regard (Vernois 2001; Hofmann et al. 2008; Welzbacher et al. 2012; Wetzig et al. 2012). In the hygroscopic range, the equilibrium moisture content (EMC) of TMT can be reduced by more than 50% (Schneider 1966, 1971, 1973; Burmester 1970, 1981; Wang and Cooper 2005; Schnabel et al. 2007; Welzbacher 2007; Akyildiz and Ates 2008).

The knowledge of the actual MC of TMT is important in view of its altered moisture uptake behavior (CEN 2007). For example, in parquet or window joinery, the correct EMC needs to be known before installation or assembling to avoid unacceptable dimensional changes in service. For TMT in outdoor applications, the actual MC plays an important role for determining the risk of decay under certain conditions (Meyer et al. 2012). MC measurements based on electrical resistance (R) are common (Du 1991; Forsén and Tarvainen 2000), because they are rapid and accurate over a wide measuring range and can be performed automatically by means of data logging devices (Brischke et al. 2008). On the contrary, a lot of parameters have an effect on the electrical conductivity (σ) of wood and need to be considered for MC measurements, such as wood species, origin, anatomical direction, T, type and amount of extractives, and the type and position of electrodes (Davidson 1958; Brown et al. 1963; Du 1991; Brischke et al. 2008). Several authors recommended

determining wood species-specific resistance characteristics in addition to a temperature compensation of the measurements (Du et al. 1991; Brischke et al. 2008; Meyer et al. 2012). Beyond that, the impregnation of wood with preservatives as well as chemical and thermal modification have the potential to alter σ (Holleboom and Homan 1998; Smith et al. 2007; Meyer et al. 2012). According to Hearle (1953) and Brown et al. (1963), R is affected by (1) the number or concentration of conducting ions (i.e., the number of charge carriers) and (2) the mobility of the existing charges, which means the ease of charges to move in an electric field. Thermal modification is believed to cause changes of the cell wall nanostructure coming along with changes of accessibility and transportability of ions and an increase of ions dissociated from acetic and formic acid formed during heat treatment (Tjeerdsma et al. 1998; Weiland and Guyonnet 2003; Wikberg and Maunu 2004).

Thus, R measurements on TMT are influenced by many parameters among which the treatment intensity is the most relevant. Therefore, this study aimed on developing a model that generally describes the relationship between thermal modification intensity and σ (and R). The expectation is that the model will allow applying resistance-based MC measurements on an arbitrarily treated piece of wood without the need for a material-specific characteristic.

Materials and methods

TMT – laboratory-scale production and conditioning

In total, 155 specimens of 25 (tan.)×25 (rad.)×80 (ax.) mm³ were prepared from each European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* Karst.). The specimens were oven-dried at 103°C until constant mass ($m_{0,1}$), weighed to the nearest 0.001 g, and submitted to a laboratory thermal modification process according to the parameters shown in Table 1. Before heat treatment, the specimens were wrapped tightly in aluminum foil to minimize oxidation processes. The mass loss (ML) by thermal modification was determined after weighing the specimens again after the treatment ($m_{0,2}$) according to Eq. (1).

$$ML\% = 100 \times (m_{0,1} - m_{0,2})/m_{0,2} \tag{1}$$

Two holes of 4 mm diameter and with a depth of 17°mm were drilled into each specimen for installation of measuring electrodes. The distance between both holes was 30 mm, which were shifted by 6 mm from the axial direction to avoid crack formation. Specimens were afterwards oven-dried again and weighed. From a total of 15 replicates per batch (treatment intensity), 3 replicates were dedicated to each moisture conditioning regime. For conditioning, specimens were stored in ventilated miniature climate chambers over saturated salt solutions for up to 10 weeks: NaCl, target relative humidity (RH) 75%; KCl, target RH 85%; and K_2SO_4, target RH 97%.

Table 1 Wood species, treatment parameters, ML, and EMC in different climates of TMT for determination of electrical resistance characteristics produced in laboratory scale (SD in brackets).

Wood species	Batch ID	Treatment		ML (%)	% EMC at 20°C/75% RH	% EMC at 20°C/85% RH	% EMC at 20°C/97% RH
		T (°C)	t (h)				
European beech (*F. sylvatica* L.)	B0	–	0.0	0.0 (0.0)	13.2 (0.4)	17.1 (0.3)	29.2 (0.3)
	B1	220	1.0	2.9 (0.9)	8.6 (0.6)	12.7 (1.1)	22.6 (3.0)
	B2	220	2.0	6.5 (1.0)	7.8 (0.3)	10.4 (0.2)	21.4 (0.4)
	B3	220	3.0	10.5 (1.6)	7.2 (0.7)	9.6 (0.4)	16.8 (0.3)
	B4	220	4.0	13.4 (0.9)	6.6 (0.1)	8.7 (0.2)	14.7 (0.1)
	B5	220	6.0	15.7 (1.4)	6.3 (0.2)	8.6 (0.2)	12.7 (0.7)
	B6	180	1.5	1.0 (0.6)	11.5 (0.1)	16.7 (0.2)	26.9 (0.9)
	B7	180	4.0	1.7 (0.6)	10.6 (0.1)	15.0 (0.3)	25.1 (0.7)
	B8	180	8.0	2.5 (0.5)	9.8 (0.1)	13.9 (0.1)	22.5 (0.5)
	B9	180	16.0	3.7 (0.6)	8.5 (0.1)	12.0 (0.2)	20.0 (0.1)
	B10	180	36.0	7.8 (0.8)	7.3 (0.1)	10.1 (0.2)	N.A. (N.A.)
Norway spruce (*P. abies* Karst.)	S0	–	0.0	0.0 (0.0)	12.5 (0.2)	16.4 (0.7)	24.9 (0.9)
	S1	220	1.0	2.9 (0.4)	8.6 (0.4)	12.4 (0.4)	18.9 (1.6)
	S2	220	2.0	4.6 (0.6)	8.2 (0.3)	10.9 (0.6)	16.6 (2.1)
	S3	220	3.0	5.5 (0.6)	7.7 (0.3)	11.2 (0.2)	16.4 (1.0)
	S4	220	4.0	9.4 (0.8)	6.2 (0.2)	9.1 (0.3)	14.7 (0.2)
	S5	220	6.3	10.4 (0.5)	6.3 (0.2)	8.9 (0.2)	13.5 (0.7)
	S6	180	1.5	0.4 (0.1)	10.7 (0.6)	14.9 (0.2)	25.0 (0.6)
	S7	180	4.0	1.1 (0.2)	10.7 (0.2)	14.3 (0.4)	23.9 (0.8)
	S8	180	16.0	2.4 (0.2)	9.8 (0.2)	13.1 (0.4)	22.2 (1.6)
	S9	180	36.0	4.0 (0.4)	9.3 (0.1)	12.1 (0.4)	21.2 (0.9)
	S10	180	72.0	5.5 (0.3)	8.7 (0.1)	11.6 (0.3)	20.6 (1.4)

To establish also MC above fiber saturation (40% and 50%), specimens were vacuum-pressure impregnated with distilled water (4 kPa for 20 min→750 kPa for 30 min), kept submersed for further 24 h, and afterwards dried down to the respective target MC at room temperature (20°C). As soon as the specimens reached their target weight, they were tightly packed into polyethylene bags and stored at 5°C for at least 96 h.

TMT – industrial-scale production and conditioning

To validate the model describing the relationship between MC, R, and modification intensity, a second set of specimens was prepared from industrially heat-treated timber. In total, 15 different TMTs of unknown heat treatment intensity were used, 4 Norway spruce (TMT 1-4, treated in nitrogen atmosphere) and 11 European beech (TMT 5-12, treated in nitrogen atmosphere, and TMT 13-15, treated in water vapor). From each TMT, $n=30$ replicate specimens of $20\times30\times50$ (ax.) mm^3 were prepared (5 per target MC) and provided with two bore holes for installation of electrodes as indicated above. Conditioning of the specimens was done in analogy to the specimens from laboratory production apart from vacuum-pressure impregnation: After 20 min vacuum at 4 kPa, a pressure phase was applied for 15 min at 750 kPa followed by 24 h water submersion. The specimens were dried to the target MC (i.e., 50%).

Electrical resistance measurements at different temperatures

For measuring R, pairs of polytetrafluorethene-coated stainless steel electrodes (length, 45 mm) were driven centrally into the bore holes. The mass of the specimens with and without electrodes was determined to the nearest 0.001 g. The specimens were tightly packed into polyethylene bags after connecting the electrodes with data logging devices with the help of crocodile clamps. To obtain different T for calibration, the packed specimens were put into precision incubators for conditioning them exactly at 4°C, 20°C, and 36°C. Exposure to a certain T did not exceed 2 h, whereby the T of a reference specimen was recorded with a data logger (Thermofox; Scanntronik, Zorneding, Germany). R was measured by data logging devices type "Materialfox" (Scanntronik). The data loggers were equipped with three ports. The measuring ranged from 2×10^4 to 5×10^8 Ω and a sampling interval of 5 s was chosen. The measuring principle is based on the discharge-time-measurement method. First, a capacitor was charged through a very small ohmic R and then discharged through the material to be measured. Based on the time needed for discharging, R can be calculated. Directly after measuring R, the specimens were weighed again (m_c) to determine gravimetric MC according to Eq. (2).

$$MC\%=100\times(m_c\text{-}m_{0,2})/m_{0,2} \tag{2}$$

Determination of resistance characteristics

Based on the triples – R(10lgΩ), gravimetrically determined MC, and T – an approximation was sought for each material. Therefore, the

method of least square was applied with the help of MS Excel Solver. The exponential function shown in Eq. (3) was used as base function to display the whole MC range considered. The material-specific variables a to i were sought.

$$MC(R; T)=(aT+b)\times Exp((cT+d)R+eT+f)+gR^2+hT+i[\%] \tag{3}$$

In addition, smoothing functions for hygroscopic behavior of wood between 0 and 30% MC were determined based on a linear function according to Skaar (1988) as shown in Eq. (4) using material-specific variables a to c.

$$MC(R; T)=a+bR+cT[\%] \tag{4}$$

CIE L*a*b* color measurements

Color measurements were conducted on planed surfaces at three points per specimen with a colorimeter (Spectro-Guide Sphere Gloss; BYK-Gardner GmbH, Wiesbaden, Germany). The measurements were taken in CIE $L*a*b*$ coordinates. A cumulated color value based on the addition of the lightness $L*$ and the chromatic coordinates of the blue-yellow axis $b*$ ($L*+b*$) was calculated and correlated with ML, as suggested by Brischke et al. (2007).

Results and discussion

ML and EMC

Expectedly, the ML caused by evaporation of wood substances during the heat treatment increased with increasing treatment times and temperatures in agreement with the literature (Tjeerdsma et al. 2002; Paul 2006; Welzbacher et al. 2007). In total, thermal modification intensity covered a range between 0.0 and 15.7% ML for beech and 0.0 and 10.4% for Norway spruce (Table 1), which is approximately the range pursued in industrial TMT production (Welzbacher 2007). The beech specimens showed higher ML compared with spruce specimens modified with same treatment parameters, which can be explained by the higher content of pentosans of beech (as a hardwood), which are less thermally stable than the hexosans in softwoods (Tjeerdsma et al. 2002; Weiland and Guyonnet 2003).

In analogy to ML, the EMC of the TMT is significantly reduced. This is shown for three different climates in Table 1. The reasons for reduced sorption of TMT is still not fully understood but most likely attributed to a decreased number and accessibility of the hydroxyl groups in the cell wall (Tjeerdsma and Militz 2006; Ringman et al. 2013). Accordingly, the lower EMCs will influence the R characteristics of TMT. In extreme, the EMC was reduced by 57% compared with the untreated controls for beech (B5) and

by 46% for spruce (S5) as shown in Table 1. However, the target MC above fiber saturation was unaffected.

Resistance characteristics for the whole MC range

For all thermally modified beech and spruce, resistance characteristics were determined according to the function shown in Eq. (3). Exemplarily, such characteristics are presented in Figure 1a/b for untreated beech wood and beech treated at 220°C for 4 h. The relationship between MC, T, and R was found to be defined based on nine variables a to i. It became apparent that different treatment intensity levels led to different R characteristics. Generally, TMT showed significantly lower R compared with untreated wood, which might be due to acetic and formic acid formed during heat treatment (Tjeerdsma et al. 1998; Weiland and Guyonnet 2003; Wikberg and Maunu 2004). In contrast, a decrease in density as well as the cleavage of hemicellulose side chains may have the opposite effect (Stamm 1964; Vermaas 1984; Du 1991), but obviously these parameters do not superpose the effect of dissociated acids serving as charge carriers in wood. Furthermore, R decreased with increasing T at constant MC, which has been reported earlier by Lin (1967), James (1968), and Du et al. (1991).

The feasibility of this approach has been shown earlier for different native, modified, and preservative-treated timbers (Brischke et al. 2008; Fredriksson 2010; Meyer et al. 2012). The obtained regression suffered from increasing variation with increasing MC. The accuracy of the measurements in the hygroscopic range was found to be sufficient apart from single outliers, whereas the variation increased remarkably above fiber saturation (Figure 2a). This might be explained not only by increasing MC coming along with increasing amount of free water in the cell lumina but also with increasing heterogeneity of moisture distribution in the specimens. On the one hand, capillary water uptake of TMT is considered to be higher compared with untreated wood (Vernois 2001; Metsä-Kortelainen et al. 2006); on the other hand, its sorption is generally decreased; therefore, water transport into and through cell walls hindered or decelerated (Ringman et al. 2013).

Besides increasing error in measurement (Figure 2a), the progression of the regression curves for the different TMTs differed remarkably stronger above fiber saturation as shown for constant T at 20°C in Figure 3a/b. In contrary, the relationship between gravimetric MC and logarithmic R was almost linear below fiber saturation of wood, which is in line with results from Skaar (1988) and Gellerich et al. (2012). For this reason, in the following, the interdependency between thermal modification intensity, R, MC, and T will be analyzed for the hygroscopic range exclusively.

Resistance characteristics for the hygroscopic range

R characteristics were determined for the hygroscopic range between 0 and 30% MC based on Eq. (4) according to Skaar (1988). The relationship between R and MC is shown in Figure 1a′/b′ with the same examples of
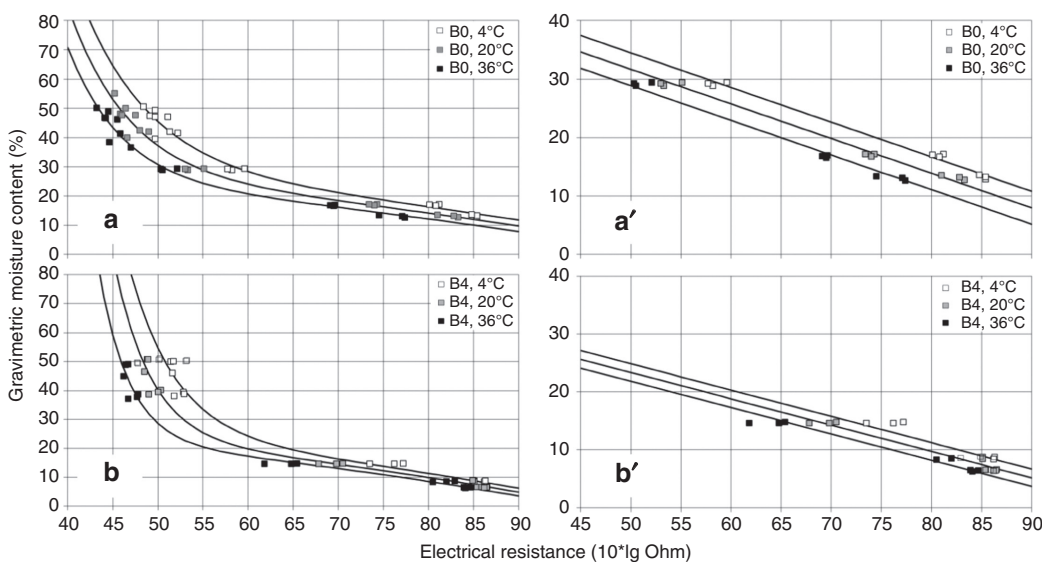
Figure 1 Resistance characteristics for beech at three different temperatures: untreated beech (B0) for the full MC range (a) and in the hygroscopic range (a′) and thermally modified beech (B4) for the full MC range (b) and in the hygroscopic range (b′).
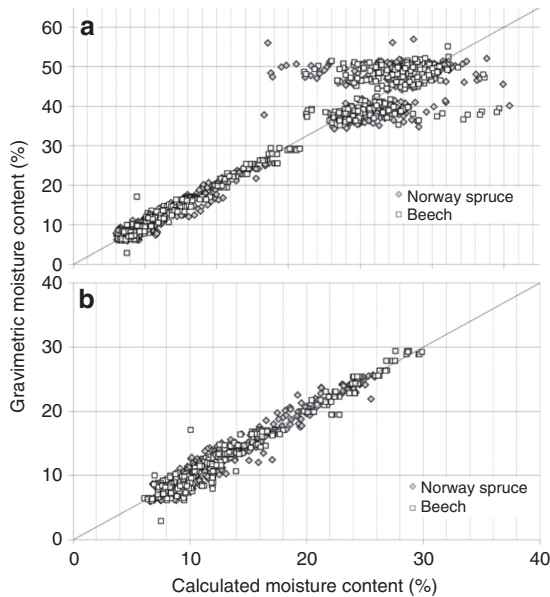
Figure 2 Calculated MC compared with gravimetrically determined MC for all untreated and differently thermally modified samples for the full MC range (a) and the hygroscopic range (b).

Figure 2b revealed only marginal variation of ±2.5%, which coincides with most other studies on unmodified timber (Du 1991; Du et al. 1991; Forsén and Tarvainen 2000; Fredriksson 2010).

In analogy to the examples in Figure 1a′/b′, all linear regression curves have similar gradients and they were shifted toward lower MC as a function of increasing treatment intensity (i.e., increasing ML). Consequently, R decreased with increasing treatment intensity at constant T.

To allow for a more precise description of the relationship between heat treatment intensity and R, the original base function [Eq. (4)] was extended aiming at the consideration of ML as a measure of treatment intensity. Because T solely led to a shift of the characteristics on the ordinate axis and a is a material-specific constant, their gradients depend only from the term $b \cdot R$. Due to the small variation among gradients of the different R characteristics, the parameter b was assumed to be the average gradient d of all characteristics for each wood species. In the case of temperature being $T=0$, the function depends only on R and the material-specific constant a [Eq. (5)].

$$MC(R;\ 0)=a+dR+c0\leftrightarrow MC(R)=a+dR \qquad (5)$$

The ordinate value was thus shifted depending on the respective material-specific constant a and the function $MC(R)$ gave an array of straight lines provided that $T=0$. The respective ordinate intercepts for the different TMT batches can be seen from the arrays of straight lines

untreated beech and beech treated at 220°C for 4 h. Due to a linear correlation, the T parameter shifted the characteristics solely on the ordinate (Figure 1a′/b′). Furthermore, the impact of T on R was significantly reduced compared with the untreated wood, which became apparent through smaller parallel shift of the R characteristics of TMT. The error estimation for both wood species as shown in
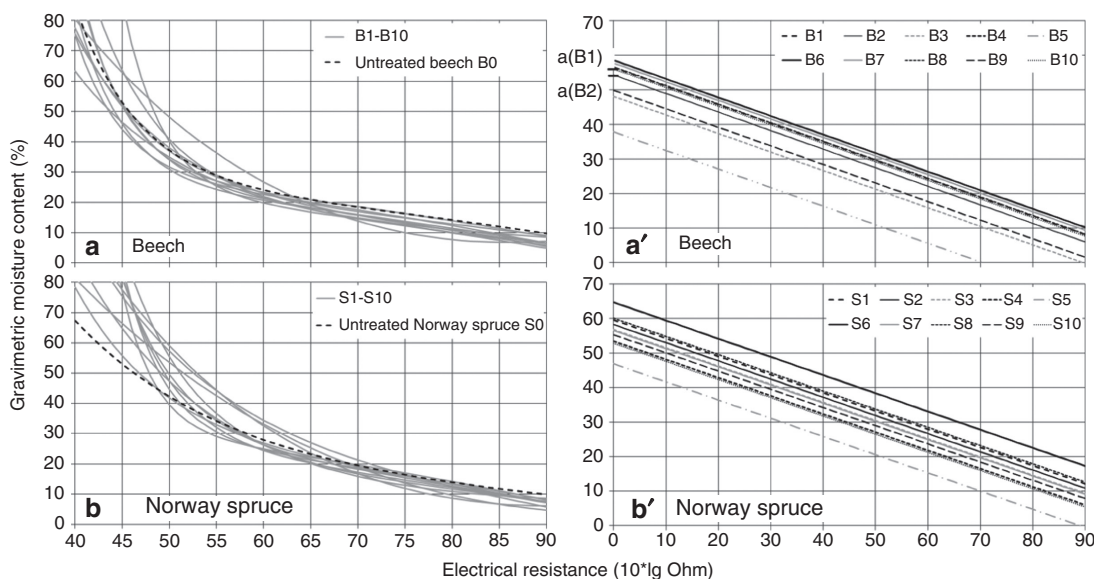

Figure 3 Regression curves (resistance characteristics).
Left: Beech (a) and Norway spruce (b) at constant temperature of 20°C. Right: Array of straight lines according to Eq. (5) provided that $T=0$ and using the average gradient of all regression lines d. (a′) Thermally modified beech, $d=-0.536$, ordinate intercept indicated for batches B1(a(B1)) and B2 (a(B2)). (b′) Thermally modified Norway spruce, $d=-0.527$.

shown in Figure 3a′/b′. To describe the interrelationship between the different R characteristics and the ML, a projection rule was sought, which allowed to project, for instance, a(B1) on a(B2) (Figure 3a′). As the material-specific constant a decreased with increasing treatment intensity, a linear relationship was assumed and both parameters were correlated as shown in Figure 4. For both wood species, a satisfying linear correlation was achieved, which can be expressed as follows [Eq. (6)]:

$$a = e \cdot \text{ML} + f \qquad (6)$$

where e and f are material-specific variables.

Consequently, the relationship between MC, R, and ML can be described for $T = 0$ as follows [Eq. (7)]:

$$\text{MC}(R) = a + dR \leftrightarrow \text{MC}(R; \text{ML}) = (e \cdot \text{ML} + f) + dR \qquad (7)$$

To allow consideration of T as another influence parameter, which can also be described as parallel shift of the R characteristics on the ordinate, an additional term was added to Eq. (7). Thus, according to Eq. (8), MC can be described as function of R, T, and ML.

$$\text{MC}(R; T; \text{ML}) = dR + e \cdot \text{ML} + f + gT \qquad (8)$$

where d to g are material-specific variables.

Based on the quadruples according to Eq. (8), the following regressions were derived for beech [Eq. (9)] and Norway spruce [Eq. (10)] based on the method of least squares and led to highly sufficient accuracy of the model as shown by respective error estimation in Figure 5.

$$\text{MC}(R; T; \text{ML}) = -0.49951757R - 0.26144678\text{ML}$$
$$+ 55.3843824 - 0.11374414T \qquad (9)$$

$$\text{MC}(R; T; \text{ML}) = -0.54265832R - 0.37609149\text{ML}$$
$$+ 59.7319416 - 0.11151095T \qquad (10)$$

Figure 5 Calculated MC compared with gravimetrically determined MC in the hygroscopic range for all untreated and differently thermally modified samples based on a function MC (R, T, ML) [Eqs. (9) and (10)].

Correlation between color values and heat treatment intensity

The cumulated color values $L^{\star} + b^{\star}$ correlated well with ML, which can be seen as reliable measure of the heat treatment intensity (Bekhta and Niemz 2003; Brischke et al. 2007; Altgen et al. 2012). The color values decreased with heat treatment intensity; consequently, the wood was darkened as shown for both wood species in Figure 6. Similar correlations were found in former studies with heat-treated Norway spruce, beech, and further 12 wood species (Walter 2010; Welzbacher et al. 2012); thus, the color data seem to be reliable to characterize the thermal modification intensity. Consequently, in the following, the ML of the second set of specimens, which were prepared from industrially heat-treated timber, has been calculated from the regression functions given in Figure 6.

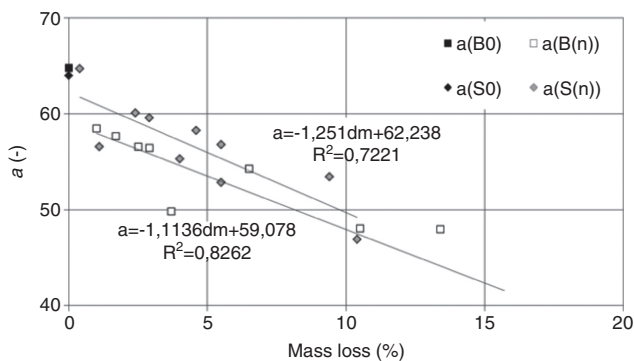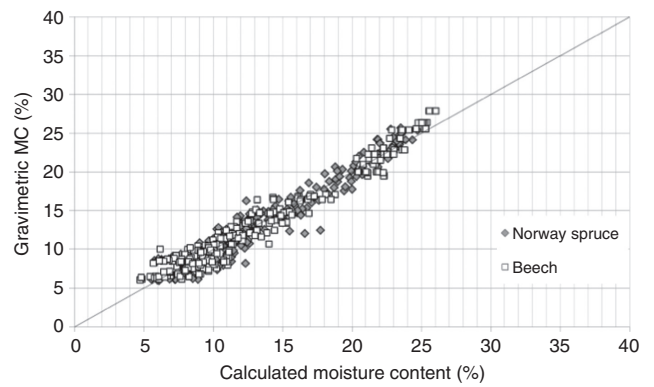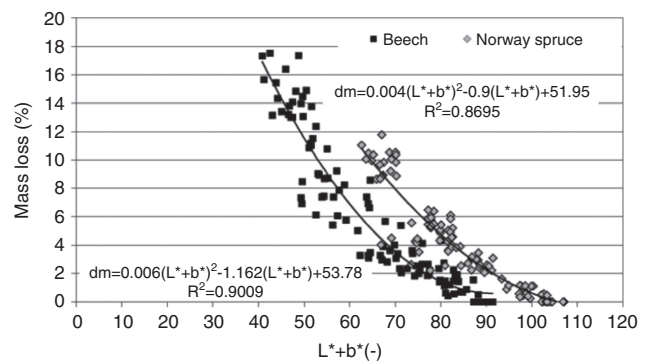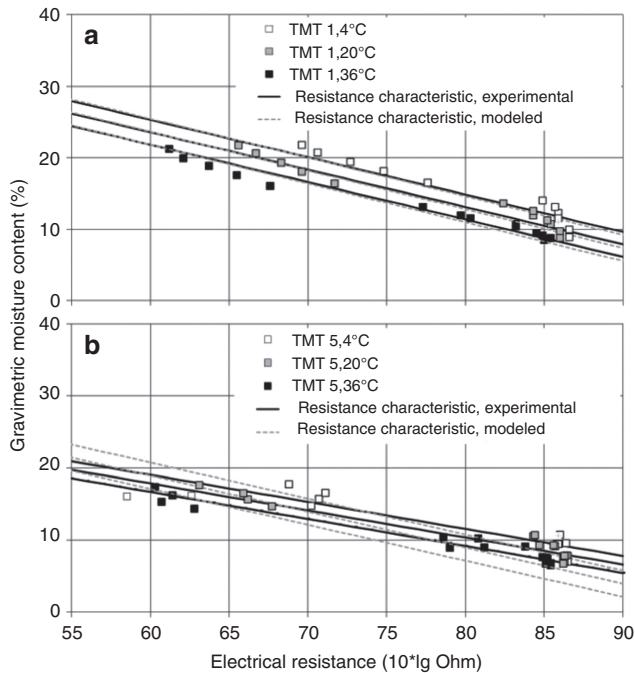**Figure 4** Interrelationship between material-specific constant a and ML of thermally modified beech and Norway spruce.

Figure 6 Relationship between cumulated color values $L^{\star} + b^{\star}$ and ML for all differently thermally modified beech and Norway spruce.

Figure 7 Resistance characteristics based on experimental data according to Skaar (1988) (continuous lines) and based on the developed model (dashed lines) for thermally modified wood in the hygroscopic range at three different temperatures: (a) thermally modified Norway spruce (TMT 1) and (b) thermally modified beech (TMT 5).

Figure 8 Calculated MC compared with gravimetrically determined MC in the hygroscopic range for all untreated and differently thermally modified samples from industrial production.
(a) Resistance characteristics derived from experimental data according to Eq. (4) after Skaar (1988). (b) Resistance characteristics derived from the model [Eqs. (9) and (10)]; ML based on regression function [Eqs. (11) and (12)].
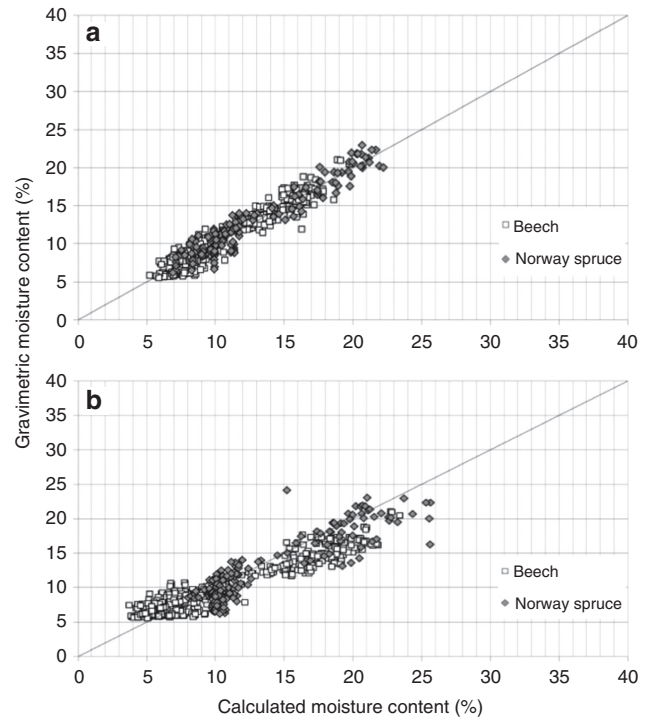
Validation of the model on industrial TMTs

The model that describes the effect of thermal modification on σ was validated by means of 15 different TMTs from industrial production. For each material, a resistance characteristic was determined for the hygroscopic range based on Eq. (4). For comparison, further characteristics were derived from Eq. (9) for beech (TMT 5-15) and Eq. (10) for Norway spruce (TMT 1-4). Then, MLs were calculated based on color values $L^\star+b^\star$ according to the regression curves shown in Figure 6 with Eqs. (11) and (12).

$$ML(L^\star+b^\star)=0.0063(L^\star+b^\star)^2-1.1619(L^\star+b^\star)+53.776 \quad (11)$$

$$ML(L^\star+b^\star)=0.0038(L^\star+b^\star)^2-0.897(L^\star+b^\star)+51.949 \quad (12)$$

A comparison of directly determined R characteristics for industrially produced TMT and characteristics based on the model are exemplarily presented in Figure 7. The model shows significantly better fit with the experimental characteristics for TM-Norway spruce compared with TM-beech. For beech, the gradient of the regression lines was, to some extent, steeper, which led to some inaccuracy of the modeled MC. The directly determined characteristics based on experimental data (Figure 8a) led to similar good

approximation compared with laboratory-scale TMTs (Figure 5). In contrast, the accuracy was lower if MC was modeled based on color, R, and T data (Figure 8b).

Conclusions

The need to determine material-specific characteristics is well known for high accuracy of MC measurements (Lin 1967; Du et al. 1991; Brischke et al. 2008; Meyer et al. 2012). Various wood-inherent parameters have an influence on σ and may interact, which leads to scattering results. In the case of TMT, further uncertainties accrue, such as heat treatment intensity, and need to be considered, which is not possible through direct measurements. The indirect determination of the modification levels by means of color values is generating another source of error.

The model developed was found to be feasible in particular for the hygroscopic range, which is traditionally considered for R-based MC measurements. In addition, $L^\star+b^\star$ color values could serve as auxiliary quantity to

determine the heat treatment intensity of a wood piece with unknown heat treatment history. Application of sensors for measuring *R*, *T*, and color data within one device would be advantageous for TMT characterization. The accuracy of modeled *R* characteristics based on color data (±3.5%) was less satisfactory compared with direct measurements of experimental data (±2.5%). A comparison of laboratory- and industrial-scale TMTs is difficult as the parameters concerning the heat-up phase, postconditioning, oxygen content in the chamber, initial MC, and heating medium (nitrogen, steam, oil, and wax) may be very different. Most of all, the models must be wood specific, as the effects of wood species are larger than those of the other parameters. Moreover, further studies should also cover a broader range of MC; therefore, resistometers are needed that allow resistance measuring up to 10^9 Ω.

References

Akyildiz, M.H., Ates, S. (2008) Effect of heat treatment on equilibrium moisture content (EMC) of some wood species in Turkey. Res. J. Agric. Biol. Sci. 4:660–665.

Altgen, M., Welzbacher, C.R., Humar, M., Willems, W., Militz, H. (2012) Bestimmung der Behandlungsqualität von Thermoholz mithilfe von Schnellverfahren. Teil 1: Elektronenspin-Resonanz-Spektroskopie. Holztechnologie 53:44–49.

Bekhta, P., Niemz, P. (2003) Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce. Holzforschung 57:539–546.

Brischke, C., Welzbacher, C.R., Brandt, K., Rapp, A.O. (2007) Quality control of thermally modified timber: interrelationship between heat treatment intensities and CIE *L*a*b** color data on homogenized wood samples. Holzforschung 61:19–22.

Brischke, C., Rapp, A.O., Bayerbach, R. (2008) Measurement system for long-term moisture recording with internal conductively glued electrodes. Build. Environ. 43:1566–1574.

Brown, J. H., Davidson, R. W., Skaar, C. (1963) Mechanism of electrical conduction in wood. For. Prod. J. 13:455–459.

Burmester, A. Formbeständigkeit von Holz gegenüber Feuchtigkeit – Grundlagen und Vergütungsverfahren. BAM-Bericht Nr. 4, Bundesanstalt für Materialforschung, Berlin, 1970.

Burmester, A. (1981) Dimensional stabilisation of wood. Document No. IRG/WP 3171, International Research Group on Wood Preservation, Sarajevo, Yugoslavia.

CEN (2007) CEN/TS 15679: Thermally modified timber – definitions and characteristics. European Committee for Standardisation, Brussels, Belgium.

Davidson, R.W. (1958) The effect of temperature on the electrical resistance of wood. For. Prod. J. 8:160–164.

Du, Q.P. Einfluss holzartenspezifischer Eigenschaften auf die elektrische Leitfähigkeit wichtiger Handelshölzer. Doctoral thesis. University Hamburg, Department Biology, Hamburg, 1991.

Du, Q.P., Geissen, A., Noack, D. (1991) The effect of temperature on the electrical resistance of wood. Holz Roh- Werkst. 49:305–311.

Forsén, H., Tarvainen, V. (2000) Accuracy and functionality of hand held wood moisture meters. VTT Publications 420. VTT Technical Research Centre of Finland, Espoo.

Fredriksson, M. Methods for determination of moisture conditions in wood exposed to high moisture levels. Licentiate thesis. Lund University, Division of Building Materials, Lund, 2010.

Gellerich, A., Bollmus, S., Militz, H., Krause, A. (2012) Influence of moisture conditions on the colonisation of modified wood by sapstaining fungi during outside weathering. In: Proceedings of the 6th European Conference on Wood Modification, Ljubljana, Slovenia, 17–18 September 2012. Eds. Jones, D., Militz, H., Petrič, M., Pohleven, F., Humar M., Pavlič, M. pp. 127–135.

Hearle, J.W.S. (1953) The electrical resistance of textile materials. IV. Theory. J. Text. Inst. Trans. 44:177–198.

Hofmann, T., Rétfalvi, T., Albert, L., Niemz, P. (2008) Investigation of the chemical changes in the structure of wood thermally modified within a nitrogen atmosphere autoclave. Wood Res. 53:85–98.

Holleboom, B., Homan, W. (1998) The effect of wood preservatives on the relation between the electric resistance and moisture content in Scots pine (*Pinus sylvestris* L.) sapwood. Document No. IRG/WP 98-20142, International Research Group on Wood Protection, Maastricht, The Netherlands.

James, W.L. (1968) Effect of temperature on readings of electric moisture meters. For. Prod. J. 18:23–31.

Jones, D. (2012) Life since the European Thematic Network on Wood Modification: the first 10 years. In: Proceedings of the 6th European Conference on Wood Modification, Ljubljana, Slovenia, 17–18 September 2012. Eds. Jones, D., Militz, H., Petrič, M., Pohleven, F., Humar M., Pavlič, M. pp. 29–36.

Krackler, V., Ammann, S., Camathias, U., Niemz, P. (2011) Untersuchungen zum Feuchteverhalten und zur Porosität von thermisch modifiziertem Holz. Bauphysik 33:374–381.

Lin, R.T. (1967) Review of the electrical properties of wood and cellulose. For. Prod. J. 17:54–60.

Metsä-Kortelainen, S., Antikainen, T., Viitaniemi, P. (2006) The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170° C, 190° C, 210° C and 230° C. Eur. J. Wood Wood Prod. 64:192–197.

Meyer, L., Brischke, C., Lampen, S.C. (2012) Electric moisture content measurements in the field to examine the performance of wood based materials. In: Proceedings of the 8th Meeting of the Northern-European Network for Wood Science & Engineering (WSE), September 13–14, 2012, Kaunas, Lithuania. Eds. Baltrušaitis, A., Ukvalbergiene, K. pp. 115–121.

Militz, H. (2008) Processes and properties of thermally modified wood manufactured in Europe. Development of commercial wood preservatives: efficacy, environmental, and health issues. American Chemical Society, Washington, DC, 655.

Olek, W., Majka, J., Czajkowski, Ł;. (2013) Sorption isotherms of thermally modified wood. Holzforschung 67:193–191.

Paul, W. Thermische Modifizierung von Spanmaterial und Holzwerkstoffplatten zur Verbesserung ausgewählter Eigenschaften. Doctoral thesis. University Hamburg, Faculty for Mathematics, Informatics and Natural Sciences, Hamburg, 2006.

Schnabel, T., Zimmer, B., Petutschnigg, A.J., Schonberger, S. (2007) An approach to classify thermally modified hardwoods by color. For. Prod. J. 57:105.

Schneider, A. (1966) Der Einfluss von Wärmebehandlungen im Temperaturbereich bis 200°C und von Wasserlagerung bis 100°C auf den spektralen Remissionsgrad verschiedener Hölzer. Holz Roh- Werkst 24:542–547.

Schneider, A. (1971) Untersuchungen über den Einfluss von Wärmebehandlung im Temperaturbereich von 100 bis 200°C auf Elastizitätsmodul, Druckfestigkeit und Bruchschlagarbeit von Kiefern- Splint- und Buchenholz. Holz Roh- Werkst 29:431–440.

Schneider, A. (1973) Zur Konvektionstrocknung von Schnittholz bei extrem hohen Temperaturen. Zweite Mitteilung: Trocknungsschäden, Sorptions-, Farb- und Festigkeitsänderungen von Kiefern- Splint- und Buchenholz bei Trocknungstemperaturen von 110 bis 180°C. Holz Roh- Werkst 31:200–206.

Skaar, C. Wood-water relations. Springer, Berlin, 1988.

Stamm, A.J. Wood and cellulose science. The Ronald Press Company, New York, 1964.

Smith, W.B., Yeo, H.M., Stark, C., Morey, B., Tascioglu, C., Schneider, P., Herdman, D., Freeman, M. (2007) Use of moisture meters with treated wood. Document No. IRG/WP 07-40382, International Research Group on Wood Protection, Jackson Lake, USA.

Tjeerdsma, B.F., Militz, H. (2006) Chemical analysis of heat-treated softwoods. Holz Roh- Werkst. 64:204–211.

Tjeerdsma, B.F., Boonstra, M., Pizzi, A., Tekely, P., Militz, H. (1998) Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Eur. J. Wood Wood Prod. 56:149–153.

Tjeerdsma, B.F., Stevens, M., Militz, H., Van Acker, J. (2002) Effect of process conditions on moisture content and decay resistance of hydro-thermally treated wood. Holzforsch. Holzverwert. 5:94–99.

Vermaas, H.F. (1984) The influence of sample density on the D.C. resistance of wood. Holzforschung 38:109–132.

Vernois, M. (2001) Heat treatment of wood in France – state of the art. Review on heat treatments of wood. In: Proceedings of the special seminar held in Antibes, France, 9 February 2001, Forestry and Forestry Products, France. COST Action E22, EUR 19885. Ed. Rapp, A.O. pp. 35–42.

Walter, N. Farbänderung unterschiedlicher Holzarten unter Hitzeeinwirkung [Color response on various wood species on heat treatments]. Master thesis. Leibniz University Hannover, Faculty of Architecture and Landscape Sciences, Hannover, 2010.

Wang, J.Y., Cooper, P.A. (2005) Effect of oil type, temperature and time on moisture properties of hot oil-treated wood. Eur. J. Wood Wood Prod. 63:417–422.

Weiland, J.J, Guyonnet R. (2003) Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holz Roh- Werkst. 61:216–220.

Welzbacher, C.R. Verhalten von nach neuen thermischen Modifikationsverfahren behandelter Fichte und Kiefer unter besonderer Berücksichtigung der Dauerhaftigkeit gegenüber holzzerstörenden Mikroorganismen. Doctoral thesis. University Hamburg, Faculty for Mathematics, Informatics and Natural Sciences, Hamburg, 2007.

Welzbacher, C.R., Scheiding, W. (2011) Implementation of a quality assurance system for thermally modified timber (TMT) by the Association of Central European TMT-Producers. Document No. IRG/WP 11-40558, International Research Group on Wood Protection, Queenstown, New Zealand.

Welzbacher, C.R., Brischke, C., Rapp, A.O. (2007) Influence of treatment temperature and duration on selected biological, mechanical, physical, and optical properties of thermally modified timber (TMT). Wood Mater. Sci. Eng. 2:66–76.

Welzbacher, C.R., Brischke, Maier, G. (2012) Influence of heat treatment intensity on the structural integrity of 14 timber species. Document No. IRG/WP 12-40586, International Research Group on Wood Protection, Kuala Lumpur, Malaysia.

Wetzig, M., Niemz, P., Sieverts, T., Bergemann, H. (2012) Mechanische und physikalisiche Eigenschaften von mit dem Vakuumpresse-Trocknungsverfahren thermisch behandeltem. Holz. Bauphysik 34:1–10.

Wikberg, H., Maunu, S.L. (2004) Characterisation of thermally modified hard- and softwoods by ^{13}C CPMAS NMR. Carbohydr. Polym. 58:461–466.