



# Electrical resistance characteristics of thermally modified wood

Joran van Blokland<sup>1</sup> · Stergios Adamopoulos<sup>1</sup>

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## Abstract

This paper presents electrical resistance characteristics of ThermoWood® Thermo-D Norway spruce for wood moisture content measurements below fibre saturation point. Electrical resistance along the grain of small clear wood specimens was measured at various moisture content levels of ~4–15% for thermally modified and ~5–25% for unmodified spruce. The results show that—similar to unmodified wood—the relationship between wood moisture content and electrical resistance can be well described by a first order polynomial function obtained from simple linear regression. This provides accurate resistance-based predictions of thermally modified wood moisture content. In addition, established temperature corrections derived previously from unmodified wood seem applicable to thermally modified wood.

## 1 Introduction

The amount of moisture present in wood can be determined in-situ by using a pin-style moisture metre with insulated contact pins. Such systems are based on electrical resistance, can record wood moisture content over time, allow precise positioning of measurement points, and are reliable over a wide measurement range (more reliable below fibre saturation point than above) (Brischke et al. 2008; Otten et al. 2017). This technique has recently been used to evaluate in-situ moisture performance of different wood products including thermally modified wood (e.g. Kržišnik et al. 2020). These studies focussed particularly on the amount of moisture in relation to onset of decay. Thermally modified wood has been commercially available in Europe since the early 1990's and was developed to increase the service life of wood in outdoor above-ground situations without the need of toxic chemicals. The most common industrial method in Europe is the ThermoWood® process that uses heat and steam to modify wood at a maximum temperature of 212 °C (Thermo-D). Norway spruce (*Picea abies* [L.] Karst.) and Scots pine (*Pinus sylvestris* L.), two common commercial softwood species with a low natural durability, are mainly used for thermal modification. During treatment,

the cell wall polymers are degraded, especially hemicelluloses, which is regarded as the principal hygroscopic component in wood. After heat treatment, wood–water relations are improved; most importantly, sorption is reduced. This is the main reason why wood becomes less susceptible to decay and to dimensional change. Sorption characteristics decrease with heating time and temperature, but the degree of the effect also depends on wood species and other process conditions, such as initial moisture content and oxygen level. A more extensive review on wood thermal modification with references to original research can be found in van Blokland (2020). Electrical resistance-based wood moisture content measurements require wood species, modification and treatment intensity specific resistance to determine wood moisture content (Brischke and Lampen 2014). Accuracy of determining wood moisture content by electrical resistance is ~5% for native timber and ~10–20% for modified timber below fibre saturation point but decreases above fibre saturation point (Brischke and Lampen 2014). While many researchers determine resistance characteristics, only few present and evaluate calibration curves (Brischke et al. 2014; Otten et al. 2017). In addition, for thermally modified wood, accurate resistance characteristics below fibre saturation point are missing in the literature. This study aims to obtain electrical resistance characteristics of thermally modified (ThermoWood® Thermo-D) Norway spruce (*Picea abies* [L.] Karst.) wood below fibre saturation point, which can be used for accurate in-situ resistance-based wood moisture content measurements. Such measurement data aids

✉ Joran van Blokland  
joran.van.blokland@slu.se

<sup>1</sup> Department of Forest Biomaterials and Technology,  
Swedish University of Agricultural Sciences, Box 7008,  
750 07 Uppsala, Sweden

in explaining the cause of excessive checking in thermally modified wood during weathering (van Blokland 2020).

## 2 Materials and methods

Three side-matched board pairs, i.e. 3 thermally modified and 3 unmodified reference (control) boards, were used to determine resistance characteristics. Boards were taken from a larger batch of 84 side-matched board pairs, which were cut in a 2X-log sawing pattern from 84 logs harvested in central Sweden, and had an annual ring width of  $2.3 \pm 0.4$  mm (mean  $\pm$  standard deviation) and were average in wood density— $453 \pm 3$  kg m<sup>-3</sup>. An overview and details of the specimen preparation can be found in van Blokland (2020). Six small clear wood specimens of  $120 \times 45 \times 20$  mm<sup>3</sup> (length  $\times$  height  $\times$  thickness) were cut along the board's long axis at  $\sim 300$  mm from boards' ends—one specimen from each board. Each specimen was cut in half such that two lengthwise matched specimens of  $60 \times 45 \times 20$  mm<sup>2</sup> remained; one half for weighing and the other half for resistance recording. A set of electrodes with insulated shafts and Teflon washers were screwed in predrilled holes such that electrical resistance was determined over a distance of 30 mm in grain direction (Fig. 1). All air-dry (room conditions, 20 °C/60% relative humidity) specimens were placed in a climate room (KMF 115, Binder GmbH, Tuttlingen, Germany) and electrical resistance [10 log  $\Omega$ ] was measured (Material Moisture Gigamodule, Scantronik Mugrauer, Zorneding, Germany) and logged every 15 min (Thermofox Universal, Scantronik Mugrauer, Zorneding, Germany). The Gigamodule has a measuring range  $< 10$  k $\Omega$  (for moisture content  $> 90\%$ ) and  $> 100$  G $\Omega$  (for moisture content  $< 6\%$ ). Temperature was set to 25 °C and relative humidity to 90%. Specimens' mass and electrical resistance were recorded after 5–7 days when the change in mass was less than 0.1%/24 h and resistance–time curves had reached an asymptote. After that, relative humidity

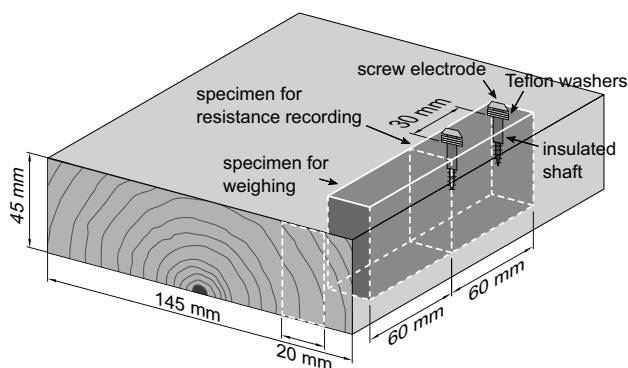


Fig. 1 Preparation of specimens and position of screw electrodes

was set to 95, 90, 60, 30, 10, 30 and 60%, in that order, while temperature was kept constant. At a relative humidity of 90%, temperature was set once to 50 °C and once to 4 °C. Mass and electrical resistance were recorded for each condition as described above. In addition, resistance characteristics were determined on two specimens cut from a randomly chosen board pair taken from the same batch of timber using the procedure described above; one specimen was cut from each board. This data was used for verification. Then, specimens were stored for 1 month in a closed box over a saturated salt solution with potassium sulphate (K<sub>2</sub>SO<sub>4</sub>) to reach  $\sim 97\%$  relative humidity at room temperature. Finally, specimens used for weighing were oven-dried for 24 h and wood moisture content at each condition was calculated from the difference in mass. Temperature correction for all wood species was done according to the manufacturer's recommendation (Scantronik 2014). Moisture content calculated from electrical resistance is denoted as  $M_{\text{calc}}$ , and  $M_{\text{est}}$  is the temperature corrected  $M_{\text{calc}}$ , here referred to as estimated moisture content. Matlab® software (version R2018a) was used for regression analysis and calculation of confidence intervals.

## 3 Results and discussion

Figure 2 shows the experimental data. The relationship between electrical resistance and wood's moisture content is more or less linear below fibre saturation point and this was confirmed by the data shown in Fig. 2a both for control and thermally modified boards. Therefore, simple linear regression was used to establish moisture content–electrical resistance relationships as:

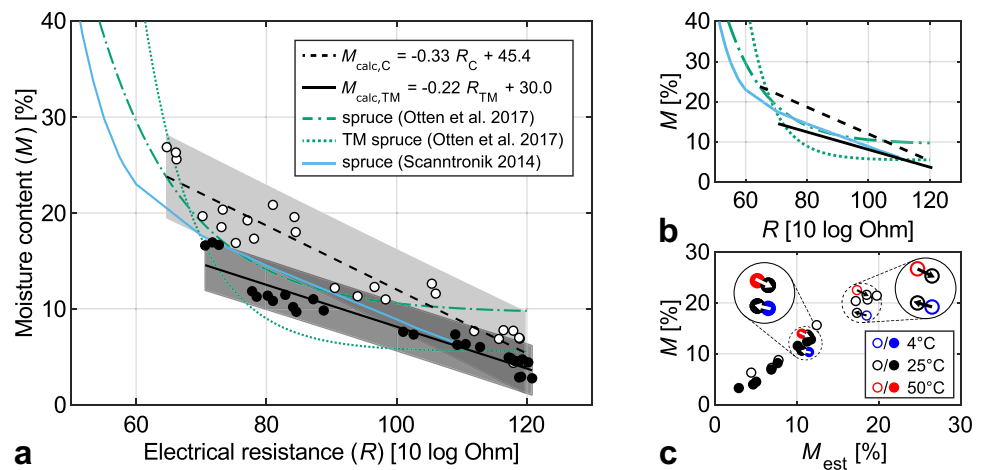
$$M_{\text{calc,C}} = -0.33 \cdot R_{\text{C}} + 45.4[\%] \quad R_{\text{C}} \in [60, 120], \quad (1)$$

and as:

$$M_{\text{calc,TM}} = -0.22 \cdot R_{\text{TM}} + 30.0[\%] \quad R_{\text{TM}} \in [70, 120], \quad (2)$$

for control (C) and thermally modified (TM) boards, respectively. Here,  $R$  is electrical resistance and the given upper and lower limits correspond to moisture content levels of  $\sim 5$ – $25\%$  for control and  $\sim 4$ – $15\%$  for thermally modified boards. These upper limits are in line with previous work that determines the fibre saturation point of unmodified and thermally modified spruce wood (Kržišnik et al. 2020). The slope of Eq. 1 corresponds well with the resistance curve of spruce wood as determined by the German manufacturer (Scantronik 2014), but the  $M_{\text{calc,C}}$  curve is shifted a bit upwards (Fig. 2a, b). Differences between provenances were found earlier, and Norway spruce from Scandinavia appears to experience a higher electrical resistance along the

**Fig. 2** Resistance curves: **a**  $M$ – $R$  relationships for control (non-filled circles) and TM (filled circles) boards including lines from linear regression ( $M_{\text{calc,C}}$  and  $M_{\text{calc,TM}}$ ) and 95% confidence intervals, **b**  $M_{\text{calc,C}}$  and  $M_{\text{calc,TM}}$  compared to the literature (legend in **a**), and **c** verification of  $M$ – $M_{\text{est}}$  relationship for control and TM boards (arrows indicate temperature correction to 25 °C)



grain than spruce from Germany at similar levels of moisture content (Brischke et al. 2008). A larger sampling campaign similar to those used in for example strength grading of timber is necessary to better capture effects of within species variability on moisture content–electrical resistance relationships. The slope for the regression line of thermally modified boards ( $M_{\text{calc,TM}}$ ) is less steep than for control boards, and at similar levels of moisture content the resistance of thermally modified boards is lower than for control boards (Fig. 2a, b). Resistance curves presented earlier by Otten et al. (2017) for unmodified and thermally modified spruce are also shown in Fig. 2a, b. A less pronounced fit was found between those results and the regression lines found in the present work, most likely because Otten’s expressions had to cover the moisture content–electrical resistance relationship below as well as above fibre saturation point and were fitted with one continuous exponential curve. This may have resulted in less accuracy when estimating wood’s moisture content below fibre saturation point.

The calibration was verified and results are shown in Fig. 2c. After the temperature correction, the coefficient of determination and the standard error of the estimate of the relationship between estimated moisture content from resistance recordings and wood moisture content were 0.90 and 1.96 for the control specimen, and 0.93 and 1.04 for the thermally modified specimen, respectively. Figure 2c also shows the effect of the temperature correction on resistance recordings at low and high temperatures (arrows in Fig. 2c indicate temperature correction). In contrast to Brischke and Lampen (2014), a higher accuracy was found for thermally modified wood ( $\pm 2\%$  deviation at 95% confidence interval) compared to unmodified wood ( $\pm 4\%$  deviation at 95% confidence interval). This disagreement was probably caused by the use of different measurement devices (Scantronik Gigamodule versus Scantronik Materialfox) each with a different measurement range (1 k $\Omega$  – 100 G $\Omega$  versus 2 k $\Omega$ –0.5 G $\Omega$ , respectively). Other possible contributing factors are

the different wood species, type of thermal modification method and/or the calibration range (above and below fibre saturation point), which were used in that study.

## 4 Conclusion

The resistance characteristics of thermally modified (ThermoWood® Thermo-D) Norway spruce were determined for a moisture regime below fibre saturation point. Similar to unmodified wood, the relationship between moisture content and electrical resistance was well described by a first order polynomial function obtained from simple linear regression. The results confirm that resistance characteristics depend strongly on the treatment while species variability should also be taken into account. A function with multiple domains and tabulated moisture content–electrical resistance data with interpolation is recommended for resistance-based wood moisture content measurements covering the complete moisture regime, i.e. above and below fibre saturation point. Temperature corrections derived from unmodified wood seem applicable to thermally modified wood, but a follow-up study is recommended.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s00107-022-01813-7>.

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**Data availability** The data is included as supplementary material.

## Declarations

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

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