# Use of a Resistive Moisture Meter to Estimate the Moisture Content of Untreated and Thermally Modified *Tectona grandis* L.f. Juvenile Wood

Djeison Cesar Batista,* Adriano Ribeiro Mendonça, and Adair José Regazzi

The effects of the TanWood thermal modification process on the resistive properties of *Tectona grandis* juvenile wood were verified, and the best setting for the use of a resistive moisture meter was determined for both untreated and thermally modified wood (TMW). Sixteen treatments were assessed for both untreated and TMW according to three factors: moisture meter scale (four levels), electrode length (two levels), and grain direction (two levels). Moisture content was measured in four steps with equilibrium moisture contents of 6.0%, 8.6%, 12.2%, and 15.6%. For statistical analysis, the oven-drying moisture content was used as the standard. Statistical analysis included the statistics bias, mean absolute difference, mean square error, tests of linear correlation, and comparison of means. The TanWood process of thermal modification significantly changed the resistive properties of *Tectona grandis* juvenile wood once different results were found for untreated and TMW regarding the meter's scale of use and the reliable ranges of moisture content measuring.

*Keywords: Thermal modification; Moisture content; Moisture meter; TanWood process*

*Contact information: Department of Forest and Wood Sciences, Espírito Santo Federal University, Jerônimo Monteiro, Espírito Santo, 29550-000, Brazil; *Corresponding author: djeison.batista@ufes.br*

## INTRODUCTION

Electric moisture meters were first developed in the 1920s and were improved in the 1940s. Currently, they are used worldwide in the wood industry because of their easy operation, low cost of readings, and immediate and reliable results. Additionally, their readings are nondestructive, which is an advantage compared to the oven-drying method. However, the latter is accepted as a standard for calibration and comparison of other methods (James 1988).

The final moisture content of the lumber in a load is one of the most important parameters for quality control of wood before the production of goods. Therefore, precisely measuring the moisture content is fundamental in the wood industry. Many studies about this measurement are carried out because of its great importance (Fridh *et al*. 2014; Dietsch *et al*. 2015; Otten *et al*. 2017; Razafindratsima *et al*. 2017; Casans *et al*. 2018; Gao *et al*. 2018; Konopka *et al*. 2018; Laleicke and Kamke 2018; Li *et al.* 2018; Tham *et al*. 2018).

The need for moisture content control is also true for thermally modified wood (TMW), which is generally used to make secondary machined products such as decks, flooring, window and door frames, cladding, and furniture. Europe has the most developed market for TMW, with a well-established chain of industries, stores, projects, buildings, and end-use consumers. One of the most famous companies in the world achieved production of 179,507 $m^3$ in 2016, an increase of 12.7% compared to 2015, and its production has increased 9.5 times since 2001 (International Thermowood Association 2016). The use of TMW is established in Canada and is spreading to the United States, which is a major world market (Sandberg and Kutnar 2016; Gamache *et al.* 2017).

Because thermal modification significantly changes the chemical characteristics and hygroscopicity of wood (Hill 2006), the electrical properties also change, which can impair the use of moisture meters. For this reason that researchers started to study the effect of this process on the electrical properties of TMW, but there are currently few works available (Brischke and Lampen 2014; Brischke *et al*. 2014; Fernandez-Golfín *et al*. 2014; Scheiding and Stein 2015).

The main goal of this work was to verify the effect of the TanWood thermal modification process on the measuring of the moisture content of *Tectona grandis* wood by the resistive method. The secondary goal was to determine the best setting for the use of a resistive moisture meter for both untreated and thermally modified wood.

## EXPERIMENTAL

### Wood Sampling and Thermal Modification

The *Tectona grandis* L.f. wood was collected from the stock of the company TWBrazil, located in Ponta Grossa, Paraná, Brazil. The firm holds the patent for the TanWood process of thermal modification, which is classified as a closed system (pressurized) and hygrothermal (Hill 2006). It has five phases and lasts around 16 hours, depending on the maximum temperature of the cycle. The process was carried out at the premises of the company, at 160 °C of final cycle temperature, according to a specific proprietary schedule. More information about the process can be found in Batista *et al.* (2015). The products are intended for domestic use such as furniture, flooring, decorative objects, and panels.

The lumber was bought from a company located in Cáceres, Mato Grosso, Brazil, from planted forests, thinned when the trees reached 15 to 18 years old. Three stacks for both untreated wood and TMW were chosen, and then four battens per stack were sampled. The battens were plainsawn and had dimensions of 25 × 70 × 1,070 mm (radial × tangential × longitudinal). They were composed of wood close to the pith mixed with heartwood and sapwood.

### Treatments: Moisture Measuring

The Gann Hydromette HT 65 resistive moisture meter (Gerlingen, Germany) was used with four scales. According to the manufacturer's recommendations in the manual (Gann 2007), the electrodes have to be fixed from 1/4 to 1/3 of the lumber thickness and the potential difference must be measured perpendicularly to the wood grain.

The main operational factors regarding moisture readings with this meter are the scale, electrode length, and the potential difference between the electrodes and the wood grain (simply mentioned as grain direction). The wood temperature is also a significant factor but was not considered in this study because all samples had the same temperature. The combination of the three first factors resulted in the treatments tested for both untreated wood and TMW (Table 1).

The initial hypothesis was that the manufacturer's instructions of use (correspondent to treatment 6, Table 1) would be valid for the untreated wood but not for the TMW. Every sampled batten was trimmed in the middle lengthwise, producing one specimen (free of defects), with dimensions of 25 x 60 x 50 mm (radial x tangential x longitudinal), resulting in 12 specimens for both untreated and TMW. The average initial moisture content was 11.9%, representing the equilibrium condition of the stacks deposited in the company stock.

**Table 1.** Treatments: Untreated and Thermally Modified Wood

| Treatment | Grain Direction | Scale | Electrode Length (mm) | Method of Moisture Content Determination |
|---|---|---|---|---|
| 1 | Parallel | 1 | 10 | Moisture meter |
| 2 | | 2 | | |
| 3 | | 3 | | |
| 4 | | 4 | | |
| 5 | Perpendicular | 1 | | |
| 6 | | 2 | | |
| 7 | | 3 | | |
| 8 | | 4 | | |
| 9 | Parallel | 1 | 17 | |
| 10 | | 2 | | |
| 11 | | 3 | | |
| 12 | | 4 | | |
| 13 | Perpendicular | 1 | | |
| 14 | | 2 | | |
| 15 | | 3 | | |
| 16 | | 4 | | |
| 17 | Not applicable | | | Oven-drying |

The specimens were weighed on a digital balance (4,200 g capacity; 0.01 g accuracy) to determine the initial weight and were then placed in a conditioning chamber of 200 L capacity (Quimis, São Paulo, Brazil) with digital control of temperature and relative humidity (RH%). Four steps of RH% were set (31, 49, 69, and 81%) using a sorption isotherm at 35 °C, resulting in the respective equilibrium moisture contents (EMC): 6.0, 8.6, 12.2 and 15.6%. The moisture conditioning was carried out according to ASTM D 4933 (1999). The EMC was calculated according to the same standard.

For all steps, the specimens were regularly weighed on the same balance until they maintained a constant weight, which indicated they had reached the EMC. The moisture was measured with the meter at the end of every step according to the designed treatments (Table 1). After Step 4, the moisture content of the specimens was measured according to the oven-drying method, as described in ASTM D 4442 (1997). The EMC was used as a measure of the hygroscopicity and calculated for every step, according to Eq. 1,

$$EMC_i = \frac{(A_i - B)}{B} \times 100 \quad (1)$$

where $EMC_i$ is the equilibrium moisture content of wood at step $i$ (%), $A_i$ is the constant weight at the end of step $i$ (g), and $B$ is the oven-dried weight measured at the end of Step 4 (g).

## Statistical Analysis

For the statistical analysis, calibration, and comparison, the results of oven-drying were considered the standard values (James 1988; ASTM D 4442 1997). For all analyses, the significance level was 5%.

*Bias, mean absolute difference and mean squared error*

For the selection of the most accurate treatment the moisture content estimates from the meter treatments 1 to 16 (Table 1) were compared to the oven-drying method (treatment 17) using the statistics bias (B), mean absolute difference (MAD), and mean squared error (MSE), shown in Eq. 2 to 4 respectively,

$$B = \frac{\sum_{i=1}^{n} Y_{ig} - \sum_{i=1}^{n} Y_{ij}}{n} \quad (2)$$

$$MAD = \frac{\sum_{i=1}^{n}\left|Y_{ig} - Y_{ij}\right|}{n} \tag{3}$$

$$MSE = \frac{\sum_{i=1}^{n}\left(Y_{ig} - Y_{ij}\right)^2}{n} \tag{4}$$

where $Y_{ig}$ is the oven-dried moisture content of wood (%) (treatment 17) with i = 1, 2,..., and n = 12, $Y_{ij}$ is the estimate of wood moisture content (%) with the moisture meter (treatments 1 to 16) with j = 1, 2, 3, ..., 16.

Treatments 1 to 16 were ranked from 1 to 16 for the three statistics. The rank 1 was given to the treatment with the smallest result and so on until 16. For B the treatments were ranked according to the absolute value of the result to account for negative results. The choice of the most accurate treatment was based on the smallest sum of ranks for the three statistics (Lima 1986; Mendonça *et al*. 2007; Batista *et al*. 2016).

*Linear correlation (r) test*

In addition to these three statistics, the linear correlation (r) was calculated between the readings with the moisture meter (treatments 1 to 16) and the data of the oven-drying method (treatment 17). The correlations were evaluated with the Student t-test; obtaining significant results ($p < 0.05$) would indicate there was a significant correlation between the readings of the respective treatment (1 to 16) and the oven-drying method (treatment 17).

*Comparison of the means*

The Student t-test for paired data was also used to compare the averages of treatments 1 to 16 (moisture meter) with the average of treatment 17 (oven-drying method). As before, the results were considered significant when $p < 0.05$.

Initially, the calibration of the moisture meter was planned for both untreated wood and TMW. This would be necessary only if all the treatments designed for the moisture meter (1 to 16) differed significantly from the oven-drying treatment (17), which did not happen.

## RESULTS AND DISCUSSION

### Accuracy Statistics for the Analyzed Treatments

After the acclimatization in Step 1, the moisture meter gave negative readings for some specimens. For untreated wood, there were negative readings in all treatments with scale 1 (1, 5, 9, and 13) and in treatment 2 (scale 2). For TMW, this behavior happened only for scale 1 in treatments 1 and 5.

This result indicated the operational capacity of the moisture meter at low moisture contents because the EMC in Step 1 was 6.0%. Although the meter's manual indicated it can provide readings from 4% to 60%, the EMC of the climatic chamber was very close to the lowest limit, which might have caused this operational problem.

Thus, the treatments with negative readings in Step 1 were discarded. This problem did not happen in the other steps. Because these statistics represent the accuracy of the estimates (moisture meter readings), the closer to zero, the better the result is. Negative B denotes overestimation of the average moisture content compared to the oven-drying method, while positive B indicates underestimation.

Table 2 summarizes the analysis of the sum of ranks of the three statistics, both for untreated wood and TMW. The full data are available as supplementary material in the Appendix (Tables A1 to A4). The treatments, which held the three first positions in each step, were indicated, meaning the ones with the lowest sums of ranks or that are most accurate.

**Table 2.** Most Accurate Treatments According to the Sum of Ranks of the Statistics Bias, Mean Absolute Difference and Means Squared Error

| Step | Equilibrium Moisture Content (%) | Position | Treatment | |
|---|---|---|---|---|
| | | | Untreated Wood | TMW |
| 1 | 6.0 | 1st place | 8 | 3 |
| | | 2nd place | 16 | 9 |
| | | 3rd place | 3, 11, 12, 15 | 4 |
| 2 | 8.6 | 1st place | 15 | 14 |
| | | 2nd place | 11 | 10 |
| | | 3rd place | 3 | 7 |
| 3 | 12.2 | 1st place | 15 | 13 |
| | | 2nd place | 11 | 9 |
| | | 3rd place | 8 | 6 |
| 4 | 15.6 | 1st place | 3, 15 | 14 |
| | | 2nd place | 7, 11 | 7 |
| | | 3rd place | 10 | 9 |

For the untreated wood in Step 1, treatment 8 was the most accurate. For the other steps, treatment 15 was the most accurate but was tied with treatment 3 in Step 4. Treatments 3 and 15 were also tied in third place in Step 1; treatment 3 was also the third in Step 2 but was not among the three best in Step 3. Treatment 11 should also be mentioned even if it was not the first in any of the steps because it was the second in Steps 2 to 4 and the third in Step 1.

For the TMW in Step 1, treatment 3 was the most accurate, but this was not true for any of the other steps. In Steps 2 and 4, treatment 14 was the most accurate and in Step 3 this position was held by treatment 13. Treatments 3, 13, and 14 held neither the second nor the third position in any other step. Treatment 9 should also be mentioned because it was the second place in Steps 1 and 3 and third place in Step 4.

Treatment 6 (manufacturer's recommendations) was not among the first three positions for untreated wood; for TMW it was in third place only in Step 3. Because the manufacturer did not state the criteria for the scale recommendation for *Tectona grandis* wood, it was not possible to identify a reason for the variability of the results. According to the initial hypothesis, it was expected that the manufacturer's recommendations would not be valid for TMW, but would be valid for untreated wood.

The only information in the meter's manual about the scale to be adopted is wood density. Although the manual does not specify what kind of density (basic or apparent, for example) to use, the value informed in the manual for *Tectona grandis* was 0.50 $g\cdot cm^{-3}$, and the averages of apparent density (12.2% moisture content) in this work were 0.588 and 0.472 $g\cdot cm^{-3}$ for untreated wood and TMW specimens, respectively.

However, wood density is not the main factor considered in moisture meter readings (Stamm 1964; James 1988; Galina 1997). This is complemented by the information provided in the manual by Gann (2007), which indicates that the scale 2 should be used for species within a wide range of densities: "Fuma" (0.25 $g\cdot cm^{-3}$), "Jatoba" (0.75 $g\cdot cm^{-3}$), and "Pernambuc" (1.00 $g\cdot cm^{-3}$). Only the common names were presented in the manual. It is supposed that this nonconformity between the manufacturer's recommendations and the results achieved was due to the use of juvenile wood mixed with heartwood and sapwood, which might have interfered in the meter's readings.

When comparing untreated wood and TMW (Table 2), no step had the same treatment as the most accurate for both types. According to our initial hypothesis, this indicates that the resistive properties of wood were significantly changed after thermal modification.

## Linear Correlation Test and Comparison of Means

To determine the most accurate treatment, the results of the sum of ranks of the statistics B, MAD, and MSE in the four steps were analyzed together with the statistics of linear correlation and comparison of means (estimates of the meter [treatments 1 to 16] *vs*. the moisture content of the oven-drying method [treatment 17]). The full statistical results are available as supplementary material in the Appendix (Tables A5 to A8).

*Step 1*

In Step 1, there was no significant correlation between the readings of the moisture meter (treatments 1 to 16) and the results of the oven-drying method (treatment 17) for both untreated wood and TMW. This reinforces the technical difficulty of using the moisture meter in a low moisture content close to its lowest limit (4%). The averages of moisture content were 6.9% and 6.6% for untreated wood and TMW, respectively.

Regarding untreated wood, according to the calculated statistic of the Student t-test (tc), there was no significant (ns) difference between the averages of the treatments 16 (6.2%; tc = $1.45^{ns}$) and 12 (6.7%; tc = $0.32^{ns}$) when compared to the oven-drying treatment (6.9%). However, according to the sums of ranks (Table 2), none of these treatments were the most accurate (treatment 8 was). On the other hand, treatments 16 and 12 held the $2^{nd}$ and $3^{rd}$ positions, respectively.

The result was the same for TMW, where there were no significant differences between the averages of the treatments 16 (6.4%; tc= $0.89^{ns}$), 12 (6.8%; tc= $0.61^{ns}$), and the oven-drying treatment (6.6%). However, the sum of the ranks of the first two treatments was not among the three first positions (Table 2).

The method of combining the sum of ranks of the statistics B, MAD, and MSE with the results of linear correlation and the Student t-test was reliable in determining the best setting to use a resistive moisture meter with *Tectona grandis* wood (Batista *et al*. 2016). However, in Step 1, this method was not reliable. The treatments with the lowest sum of ranks for both untreated wood (treatment 8; tc= 3.98**; r= $0.2268^{ns}$) and TMW (treatment 3; tc= 11,45**; r= $0.2247^{ns}$), had no significant correlation with the oven-drying results and also had significantly different averages when compared to this treatment.

For TMW, the same behavior happened in Steps 3 and 4, indicating the resistive properties of this material are different from those of the untreated wood.

The method was reliable for untreated wood in Steps 2, 3, and 4, where the treatments with the lowest sums of scores had a significant linear correlation and did not differ significantly from the oven-drying results.

*Step 2*

There was a significant linear correlation between the estimates of the moisture meter and the oven-drying results for both untreated wood and TMW in Step 2. For untreated wood, there was no significant difference between the average of the following treatments when compared to the oven-drying treatment (10.1%): 15 (10.3%; tc= $0.47^{ns}$), 11 (10.8%; tc= $1.47^{ns}$), 3 (9.1%; tc= $1.95^{ns}$), 4 (11.2%; tc= $1.96^{ns}$), 7 (9.0%; tc= $2.36^{ns}$), and 8 (11.1%; tc= $1.92^{ns}$). According to Table 2, treatment 15 was the most accurate.

For TMW, there was no significant difference between the averages of treatments

14 (8.2%; tc= 1.11$^{ns}$) and 10 (8.8%; tc= 1.37$^{ns}$) when compared to the oven-drying treatment (8.4%). According to Table 2, treatment 14 was the most accurate.

*Step 3*

In Step 3, there was a significant linear correlation between the estimates of the moisture meter (treatments 1 to 16) and the results of the oven-drying treatment for untreated wood. For TMW, the only treatments where this did not happen were treatments 5 to 8.

For untreated wood, there was no significant difference between the averages of the following treatments when compared to the oven-drying treatment (12.1%): 15 (12.2%; tc= 0.41$^{ns}$), 11 (12.5%. tc= 1.05$^{ns}$), 8 (12.6%; tc= 0.97$^{ns}$), and 4 (12.7%; tc= 1.20$^{ns}$). According to Table 2, treatment 15 was the most accurate.

Among the treatments which had a significant linear correlation for TMW, there was no significant difference between the averages of the treatments 14 (10.1%; tc= 0.67$^{ns}$) and 10 (10.6%; tc= 2.55$^{ns}$) when compared to the oven-drying treatment (9.9%). However, none of these treatments were among the most accurate (Table 2). On the other hand, treatments 4 and 14 had a lower sum of ranks (19) than treatment 10 (23).

*Step 4*

There was a significant linear correlation between the estimates of the moisture meter (treatments 1 to 16) and the oven-drying treatment in Step 4, for both untreated wood and TMW.

For untreated wood, there was no significant difference between the averages of the following treatments when compared to the oven-drying treatment (14.1%): 15 (14.8%; tc= 1.92$^{ns}$), 3 (13.1%; tc= 2.30$^{ns}$), 7 (12.9%; tc= 2.67$^{ns}$), 11 (15.1%; tc= 2.38$^{ns}$), and 8 (15.4%; tc= 2.67$^{ns}$). According to Table 2, treatments 15 and 3 were the most accurate. Comparing them, treatment 15 had lower B (-0.74) and MSE (2.20), which can be used further as tiebreakers.

For TMW, treatment 7 (12.4%; tc= 2.28$^{ns}$) was the only treatment that did not differ significantly from the oven-drying treatment (11.6%). Treatment 7 held the 2$^{nd}$ position regarding the sum of ranks, following treatment 14.

## Final Considerations

Regarding the practical use of the moisture meter, satisfactory results were achieved for untreated wood in Steps 2 to 4 for treatments 15, 11, and 8. Treatments 3, 4, and 7 were satisfactory as well, but only for two of these three steps.

The lowest and highest moisture differences for Steps 2 to 4, on average, were for treatments 15 and 8, respectively. For these steps, the variations ranged from 0.2 to 1.0 percentage points (p.p.), 0.1 to 0.5 p.p. and 0.7 and 1.3 p.p., respectively. This indicates that the moisture meter always overestimates the wood moisture content, and it happens on average up to 1.3 p.p., which is a good estimate when considering the low cost and practicality of its readings.

This result is also important because the meter provides good readings in both grain directions, both electrode lengths, and in scales 3 or 4. For example, treatments 15 and 11 have the same scale (3) and electrode length (17 mm) but represent different grain directions. On the other hand, treatments 15 and 8 have only the grain direction in common (perpendicular). This shows the good quality of the moisture meter due to its capacity of providing reliable readings with different settings (treatments).

Analogously for TMW, only three treatments were satisfactory: 14 and 10 for Steps 2 and 3; and 7 for Step 4.

The lowest and highest moisture differences for Steps 2 and 3, on average, always were for treatments 14 and 10, respectively. For these steps, the variations ranged from 0.2 to 0.4 p.p. and 0.2 to 0.7 p.p., respectively, smaller than those of untreated wood.

For Steps 2 and 3, the factor grain direction had no influence, because treatments 14 and 12 represent perpendicular and parallel orientations, respectively. However, both treatments have the same scale (2) and electrode length (17 mm).

Comparing untreated wood and TMW in Steps 2 and 3, the biggest operational difference was the scale (3 for the former and 2 for the latter). There was a tendency to obtain more accurate results with 17 mm electrodes, and the grain direction had no influence.

As for Step 4, only treatment 7 had satisfactory results for TMW. It was not possible to calculate a range for the error of the estimate, but the moisture content average was 0.8 p.p. higher than the oven-drying method. When comparing the best treatment for untreated wood, there was agreement regarding the grain direction (perpendicular) and scale (3), but not for electrode length (10 mm).

Furthermore, each step indicated that it was not possible to suggest the same setting (treatment) of the moisture meter for both untreated wood and TMW. This indicates that the thermal modification process significantly changed the resistive properties of *Tectona grandis* wood.

Despite this finding, with the experimental and the moisture meter assessed it is not possible to conclude whether the process increased or decreased wood resistivity, and if so, to what extent. According to the literature, the resistivity of *Pinus radiata* increased after thermal modification (Fernandez-Golfín *et al*. 2014).

For this, it would be necessary to use a resistivity meter and to acclimatize both untreated wood and TMW separately in order to achieve the same moisture content. That is because TMW is less hygroscopic and moisture content is the most important factor in wood resistivity, where the higher the moisture content is, the lower the resistivity and *vice versa*.

## CONCLUSIONS

1. The TanWood process of thermal modification significantly changed the resistive properties of *Tectona grandis* wood.
2. The use of the assessed moisture meter is not recommended for readings close to 6.9% and 6.6% (oven-drying) for untreated wood and TMW, respectively.
3. Reliable moisture content readings with the moisture meter were achieved in the ranges of 10.3 to 14.8% and 8.2 to 12.4% (oven-drying) for untreated wood and TMW, respectively. Above these ranges, the moisture meter is expected to work properly up to the fiber saturation point, but this statement requires further validation.
4. In the moisture content ranges presented above, the use of the moisture meter is recommended for untreated wood with the following settings: scale 3, 17 mm electrodes, and direction perpendicular to the grain.
5. For TMW in the moisture content range from 8.2 to 10.1%, the use of the moisture meter is recommended with the following settings: scale 2, 17 mm electrodes, and direction perpendicular to the grain. Above this range and up to 12.4% it is recommended to use the following settings: scale 3, 10 mm electrodes, and direction perpendicular to the grain.

6. The manufacturer's settings recommendations for untreated wood were not correct regarding the scale, where more reliable results were achieved with scale 3 instead of scale 2. This was probably because juvenile wood (from planted forests) was assessed, instead of mature wood from natural forests.

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## APPENDIX

**Table A1.** Step 1 (6.0% EMC) – Average Moisture Content (AMC) and the Statistics Bias (B), Mean Squared Error (MSE), and Mean Absolute Difference (MAD)

| Treat-ment | Untreated Wood | | | | | | | | Thermally Modified Wood | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks |
| 1 | 1.6 | - | - | - | - | - | - | - | 0.7 | - | - | - | - | - | - | - |
| 2 | 2.6 | - | - | - | - | - | - | - | 1.8 | 1.92 | 4 | 4.26 | 3 | 6.11 | 13 | 20 |
| 3 | 3.6 | 3.21 | 8 | 3.84 | 1 | 3.21 | 8 | 17 | 3.3 | 1.54 | 2 | 3.13 | 2 | 1.91 | 5 | 9 |
| 4 | 5.2 | 1.66 | 4 | 6.51 | 3 | 6.00 | 11 | 18 | 4.8 | 0.22 | 1 | 0.74 | 1 | 6.12 | 14 | 16 |
| 5 | 1.3 | - | - | - | - | - | - | - | 0.9 | - | - | - | - | - | - | - |
| 6 | 2.3 | 4.60 | 11 | 5.44 | 2 | 1.93 | 5 | 18 | 1.9 | 6.11 | 13 | 37.64 | 13 | 1.92 | 6 | 32 |
| 7 | 3.8 | 3.04 | 7 | 10.51 | 4 | 3.04 | 7 | 18 | 3.5 | 3.15 | 5 | 10.54 | 5 | 3.15 | 7 | 17 |
| 8 | 5.3 | 1.51 | 3 | 13.35 | 5 | 1.53 | 3 | 11 | 5.1 | 3.33 | 7 | 12.04 | 7 | 4.91 | 11 | 25 |
| 9 | 1.8 | - | - | - | - | - | - | - | 1.7 | 3.26 | 6 | 11.18 | 6 | 1.55 | 3 | 15 |
| 10 | 3.4 | 3.46 | 9 | 27.86 | 9 | 5.53 | 10 | 28 | 3.4 | 3.61 | 8 | 13.52 | 8 | 3.26 | 8 | 24 |
| 11 | 5.0 | 1.85 | 5 | 36.45 | 11 | 1.32 | 1 | 17 | 5.1 | 6.12 | 14 | 37.85 | 14 | 0.81 | 2 | 30 |
| 12 | 6.7 | 0.16 | 1 | 34.53 | 10 | 2.34 | 6 | 17 | 6.8 | 4.69 | 9 | 22.56 | 9 | 1.59 | 4 | 22 |
| 13 | 1.8 | - | - | - | - | - | - | - | 1.4 | 4.91 | 11 | 24.50 | 11 | 5.25 | 12 | 34 |
| 14 | 2.9 | 3.97 | 10 | 13.50 | 6 | 5.16 | 9 | 25 | 3.0 | 5.25 | 12 | 27.89 | 12 | 3.61 | 9 | 33 |
| 15 | 4.5 | 2.34 | 6 | 22.11 | 7 | 1.90 | 4 | 17 | 4.7 | 1.86 | 3 | 4.38 | 4 | 4.69 | 10 | 17 |
| 16 | 6.2 | 0.66 | 2 | 24.40 | 8 | 1.38 | 2 | 12 | 6.4 | 4.81 | 10 | 23.81 | 10 | 0.76 | 1 | 21 |
| 17 | 6.9 | Not applicable | | | | | | | 6.6 | Not applicable | | | | | | |

**Table A2.** Step 2 (8.5% EMC)– Average Moisture Content (AMC) and the Statistics Bias (B), Mean Squared Error (MSE), and Mean Absolute Difference (MAD)

| Treat-ment | Untreated Wood | | | | | | | | Thermally Modified Wood | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of rank s | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks |
| 1 | 4.9 | 5.17 | 15 | 28.41 | 15 | 5.17 | 15 | 45 | 5.3 | 3.12 | 11 | 10.41 | 11 | 3.12 | 11 | 33 |
| 2 | 7.0 | 3.10 | 11 | 11.85 | 11 | 3.10 | 11 | 33 | 7.4 | 1.02 | 3 | 1.85 | 5 | 1.16 | 4 | 12 |
| 3 | 9.1 | 1.00 | 3 | 3.89 | 4 | 1.52 | 3 | 10 | 9.5 | -1.13 | 6 | 2.26 | 6 | 1.16 | 5 | 17 |
| 4 | 11.2 | -1.11 | 5 | 4.74 | 7 | 1.98 | 7 | 19 | 11.7 | -3.30 | 14 | 12.12 | 14 | 3.30 | 14 | 42 |
| 5 | 4.9 | 5.25 | 16 | 29.06 | 16 | 5.25 | 16 | 48 | 5.2 | 3.21 | 13 | 10.74 | 12 | 3.21 | 13 | 38 |
| 6 | 6.9 | 3.17 | 12 | 11.97 | 12 | 3.17 | 12 | 36 | 7.3 | 1.11 | 5 | 1.83 | 4 | 1.19 | 6 | 15 |
| 7 | 9.0 | 1.12 | 6 | 3.70 | 3 | 1.41 | 2 | 11 | 9.4 | -1.03 | 4 | 1.79 | 3 | 1.05 | 3 | 10 |
| 8 | 11.1 | -1.02 | 4 | 4.10 | 5 | 1.84 | 6 | 15 | 11.6 | -3.19 | 12 | 11.14 | 13 | 3.19 | 12 | 37 |
| 9 | 6.3 | 3.78 | 13 | 15.84 | 13 | 3.78 | 13 | 39 | 6.5 | 1.90 | 7 | 4.15 | 7 | 1.90 | 7 | 21 |
| 10 | 8.6 | 1.55 | 7 | 4.39 | 6 | 1.63 | 5 | 18 | 8.8 | -0.34 | 2 | 0.80 | 2 | 0.68 | 1 | 5 |
| 11 | 10.8 | -0.70 | 2 | 2.96 | 2 | 1.54 | 4 | 8 | 11.0 | -2.63 | 10 | 7.76 | 10 | 2.63 | 10 | 30 |
| 12 | 13.1 | -2.98 | 10 | 11.84 | 10 | 3.02 | 10 | 30 | 13.3 | -4.93 | 16 | 25.41 | 16 | 4.93 | 16 | 48 |
| 13 | 5.9 | 4.21 | 14 | 18.98 | 14 | 4.21 | 14 | 42 | 5.9 | 2.47 | 9 | 6.59 | 9 | 2.47 | 9 | 27 |
| 14 | 8.1 | 2.04 | 8 | 5.71 | 8 | 2.04 | 8 | 24 | 8.2 | 0.26 | 1 | 0.66 | 1 | 0.70 | 2 | 4 |
| 15 | 10.3 | -0.20 | 1 | 2.01 | 1 | 1.25 | 1 | 3 | 10.4 | -1.98 | 8 | 4.65 | 8 | 1.98 | 8 | 24 |
| 16 | 12.5 | -2.42 | 9 | 8.29 | 9 | 2.53 | 9 | 27 | 12.6 | -4.23 | 15 | 18.77 | 15 | 4.23 | 15 | 45 |
| 17 | 10.1 | Not applicable | | | | | | | 8.4 | Not applicable | | | | | | |

**Table A3.** Step 3 (12.5% EMC) – Average Moisture Content (AMC) and the Statistics Bias (B), Mean Squared Error (MSE), and Mean Absolute Difference (MAD)

| Treat-ment | Untreated wood | | | | | | | | Thermally Modified Wood | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks |
| 1 | 6.1 | 5.99 | 15 | 37.37 | 15 | 5.99 | 15 | 45 | 6.6 | 3.33 | 12 | 3.36 | 6 | 1.63 | 6 | 24 |
| 2 | 8.3 | 3.80 | 11 | 16.39 | 11 | 3.80 | 11 | 33 | 8.9 | 1.09 | 4 | 13.53 | 13 | 3.53 | 13 | 30 |
| 3 | 10.5 | 1.56 | 5 | 4.97 | 5 | 1.64 | 5 | 15 | 11.0 | -1.10 | 5 | 2.16 | 5 | 1.17 | 4 | 14 |
| 4 | 12.7 | -0.60 | 4 | 3.17 | 4 | 1.61 | 4 | 12 | 13.5 | -3.53 | 13 | 3.74 | 7 | 1.78 | 7 | 27 |
| 5 | 5.9 | 6.14 | 16 | 38.98 | 16 | 6.14 | 16 | 48 | 6.1 | 3.84 | 14 | 5.48 | 8 | 2.23 | 8 | 30 |
| 6 | 8.1 | 3.92 | 12 | 17.23 | 12 | 3.92 | 12 | 36 | 8.3 | 1.63 | 6 | 1.18 | 3 | 0.86 | 3 | 12 |
| 7 | 10.3 | 1.75 | 6 | 5.29 | 6 | 1.75 | 6 | 18 | 10.5 | -0.59 | 2 | 10.64 | 11 | 3.13 | 11 | 24 |
| 8 | 12.6 | -0.49 | 3 | 3.02 | 3 | 1.56 | 3 | 9 | 12.8 | -2.84 | 10 | 32.71 | 16 | 5.63 | 16 | 42 |
| 9 | 7.7 | 4.34 | 13 | 20.18 | 13 | 4.34 | 13 | 39 | 8.2 | 1.78 | 7 | 1.11 | 2 | 0.79 | 2 | 11 |
| 10 | 10.1 | 1.96 | 7 | 5.59 | 7 | 1.96 | 7 | 21 | 10.6 | -0.64 | 3 | 9.09 | 10 | 2.84 | 10 | 23 |
| 11 | 12.5 | -0.46 | 2 | 2.36 | 2 | 1.36 | 2 | 6 | 13.1 | -3.13 | 11 | 1.89 | 4 | 1.23 | 5 | 20 |
| 12 | 15.0 | -2.92 | 10 | 11.21 | 10 | 2.95 | 10 | 30 | 15.6 | -5.63 | 16 | 15.32 | 14 | 3.84 | 14 | 44 |
| 13 | 7.5 | 4.60 | 14 | 22.22 | 14 | 4.60 | 14 | 42 | 7.7 | 2.23 | 8 | 0.63 | 1 | 0.62 | 1 | 10 |
| 14 | 9.8 | 2.23 | 8 | 6.38 | 8 | 2.23 | 8 | 24 | 10.1 | -0.16 | 1 | 7.44 | 9 | 2.58 | 9 | 19 |
| 15 | 12.2 | -0.16 | 1 | 1.78 | 1 | 1.16 | 1 | 3 | 12.5 | -2.58 | 9 | 25.60 | 15 | 4.94 | 15 | 39 |
| 16 | 14.7 | -2.59 | 9 | 8.90 | 9 | 2.62 | 9 | 27 | 14.9 | -4.94 | 15 | 11.64 | 12 | 3.33 | 12 | 39 |
| 17 | 12.1 | Not applicable | | | | | | | 9.9 | Not applicable | | | | | | |

**Table A4.** Step 4 (15.8% EMC) – Average Moisture Content (AMC) and the Statistics Bias (B), Mean Squared Error (MSE), and Mean Absolute Difference (MAD)

| Treat-ment | Untreated Wood | | | | | | | | Thermally Modified Wood | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks | AMC (%) | B | B ranking | MSE | MSE ranking | MAD | MAD ranking | Sum of ranks |
| 1 | 8.2 | 5.93 | 15 | 36.50 | 15 | 5.93 | 15 | 45 | 8.0 | 3.64 | 10 | 13.78 | 10 | 3.64 | 10 | 30 |
| 2 | 10.6 | 3.50 | 10 | 13.96 | 10 | 3.50 | 10 | 30 | 10.4 | 1.23 | 5 | 2.23 | 4 | 1.32 | 4 | 13 |
| 3 | 13.1 | 1.02 | 2 | 3.23 | 2 | 1.26 | 1 | 5 | 12.8 | -1.21 | 4 | 2.38 | 5 | 1.35 | 5 | 14 |
| 4 | 15.6 | -1.50 | 6 | 5.03 | 8 | 1.96 | 8 | 22 | 15.3 | -3.68 | 11 | 14.73 | 12 | 3.68 | 11 | 34 |
| 5 | 8.1 | 6.02 | 16 | 37.42 | 16 | 6.02 | 16 | 48 | 7.5 | 4.07 | 13 | 17.33 | 13 | 4.07 | 13 | 39 |
| 6 | 10.5 | 3.58 | 11 | 14.32 | 11 | 3.58 | 11 | 33 | 9.9 | 1.71 | 8 | 3.91 | 8 | 1.71 | 8 | 24 |
| 7 | 12.9 | 1.16 | 4 | 3.45 | 4 | 1.30 | 2 | 10 | 12.4 | -0.76 | 1 | 1.78 | 2 | 1.20 | 2 | 5 |
| 8 | 15.4 | -1.32 | 5 | 4.42 | 6 | 1.89 | 7 | 18 | 14.7 | -3.11 | 9 | 11.13 | 9 | 3.11 | 9 | 27 |
| 9 | 9.8 | 4.25 | 13 | 19.38 | 13 | 4.25 | 13 | 39 | 10.5 | 1.09 | 3 | 1.93 | 3 | 1.27 | 3 | 9 |
| 10 | 12.5 | 1.61 | 7 | 4.28 | 5 | 1.70 | 5 | 17 | 13.2 | -1.61 | 6 | 3.48 | 7 | 1.61 | 6 | 19 |
| 11 | 15.1 | -1.06 | 3 | 3.31 | 3 | 1.59 | 4 | 10 | 16.0 | -4.35 | 14 | 20.04 | 14 | 4.35 | 14 | 42 |
| 12 | 17.8 | -3.76 | 12 | 16.88 | 12 | 3.76 | 12 | 36 | 18.7 | -7.12 | 16 | 52.11 | 16 | 7.12 | 16 | 48 |
| 13 | 9.6 | 4.49 | 14 | 21.13 | 14 | 4.49 | 14 | 42 | 10.0 | 1.62 | 7 | 3.11 | 6 | 1.62 | 7 | 20 |
| 14 | 12.2 | 1.87 | 8 | 4.82 | 7 | 1.87 | 6 | 21 | 12.6 | -1.01 | 2 | 1.62 | 1 | 1.06 | 1 | 4 |
| 15 | 14.8 | -0.74 | 1 | 2.20 | 1 | 1.34 | 3 | 5 | 15.3 | -3.71 | 12 | 14.50 | 11 | 3.71 | 12 | 35 |
| 16 | 17.5 | -3.45 | 9 | 13.94 | 9 | 3.45 | 9 | 27 | 18.0 | -6.44 | 15 | 42,43 | 15 | 6.44 | 15 | 45 |
| 17 | 14.1 | Not applicable | | | | | | | 11.6 | Not applicable | | | | | | |

**Table A5.** Step 1: Statistics of Linear Correlation and Comparison of Means

| Treatment | Untreated Wood | | Thermally Modified Wood | |
|---|---|---|---|---|
| | r | tc | r | tc |
| 1 | † | | | |
| 2 | † | | 0.4008 ns | 19.09 ** |
| 3 | 0.1550 ns | 6.06 ** | 0.2247 ns | 11.45 ** |
| 4 | 0.1290 ns | 2.85 ** | 0.2467 ns | 6.37 ** |
| 5 | † | | | |
| 6 | 0.2358 ns | 15.41 ** | 0.2703 ns | 20.77 ** |
| 7 | 0.1959 ns | 8.92 ** | 0.2741 ns | 13.20 ** |
| 8 | 0.2268 ns | 3.98 ** | 0.2577 ns | 5.88 ** |
| 9 | † | | 0.3729 ns | 25.16 ** |
| 10 | 0.1300 ns | 9.35 ** | 0.3686 ns | 14.36 ** |
| 11 | 0.1437 ns | 4.30 ** | 0.3524 ns | 6.08 ** |
| 12 | 0.1371 ns | 0.32 ns | 0.3087 ns | 0.61 ns |
| 13 | † | | 0.4220 ns | 30.00 ** |
| 14 | 0.0669 ns | 10.45 ** | 0.3921 ns | 16.77 ** |
| 15 | 0.0772 ns | 5.41 ** | 0.4130 ns | 8.25 ** |
| 16 | 0.0887 ns | 1.45 ns | 0.4785 ns | 0.89 ns |

ns: not significant (p>0.05); *: significant at 5%; **: significant at 1%. †: no analysis because the meter presented negative readings.

**Table A6.** Step 2: Statistics of Linear Correlation and Comparison of Means

| Treatment | Untreated Wood | | Thermally Modified Wood | |
|---|---|---|---|---|
| | r | tc | r | tc |
| 1 | 0.6117 * | 13.11 ** | 0.6250 * | 12.92 ** |
| 2 | 0.5983 * | 6.88 ** | 0.6135 * | 3.73 ** |
| 3 | 0.5967 * | 1.95 ns | 0.6154 * | 3.74 ** |
| 4 | 0.5964 * | 1.96 ns | 0.6231 * | 9.87 ** |
| 5 | 0.5816 * | 14.25 ** | 0.5950 * | 15.94 ** |
| 6 | 0.5831 * | 7.55 ** | 0.6214 * | 4.74 ** |
| 7 | 0.5920 * | 2.36 ns | 0.6072 * | 3.95 ** |
| 8 | 0.5888 * | 1.92 ns | 0.6083 * | 10.83 ** |
| 9 | 0.5013 * | 9.96 ** | 0.6431 * | 8.54 ** |
| 10 | 0.5089 * | 3.65 ** | 0.6404 * | 1.37 ns |
| 11 | 0.5066 * | 1.47 ns | 0.6557 * | 9.34 ** |
| 12 | 0.5159 * | 5.76 ** | 0.6556 * | 15.81 ** |
| 13 | 0.5152 * | 12.44 ** | 0.6698 * | 12.04 ** |
| 14 | 0.5308 * | 5.45 ** | 0.6673 * | 1.11 ns |
| 15 | 0.5236 * | 0.47 ns | 0.6678 * | 7.57 ** |
| 16 | 0.5116 * | 5.18 ** | 0.6730 * | 14.59 ** |

ns: not significant (p>0.05); *: significant at 5%; **: significant at 1%.

**Table A7.** Step 3: Statistics of Linear Correlation and Comparison of Means

| Treatment | Untreated Wood | | Thermally Modified Wood | |
|---|---|---|---|---|
| | r | tc | r | Tc |
| 1 | 0.6548* | 16.07 ** | 0.6167* | 15.15 ** |
| 2 | 0.6563* | 8.93 ** | 0.6206* | 4.32 ** |
| 3 | 0.6519* | 3.26 ** | 0.6335* | 3.74 ** |
| 4 | 0.6392* | 1.20 ns | 0.6235* | 11.16 ** |
| 5 | 0.6534* | 17.73 ** | 0.4661 ns | 16.97 ** |
| 6 | 0.6424* | 9.55 ** | 0.4849 ns | 6.48 ** |
| 7 | 0.6609* | 3.91 ** | 0.4777 ns | 2.15 ns |
| 8 | 0.6479* | 0.97 ns | 0.4761 ns | 9.37 ** |
| 9 | 0.6404* | 12.31 ** | 0.6082* | 7.90 ** |
| 10 | 0.6369* | 4.94 ** | 0.6116* | 2.55 ns |
| 11 | 0.6386* | 1.05 ns | 0.6098* | 11.10 ** |
| 12 | 0.6373* | 5.92 ** | 0.6102* | 18.05 ** |
| 13 | 0.6500* | 14.52 ** | 0.6513* | 10.56 ** |
| 14 | 0.6449* | 6.23 ** | 0.6639* | 0.67 ns |
| 15 | 0.6412* | 0.41 ns | 0.6444* | 9.82 ** |
| 16 | 0.6479* | 5.79 ** | 0.6189* | 15.11 ** |

ns: not significant ($p>0.05$); *: significant at 5%; **: significant at 1%.

**Table A8.** Step 4: Statistics of Linear Correlation and Comparison of Means

| Treatment | Untreated Wood | | Thermally Modified Wood | |
|---|---|---|---|---|
| | r | tc | r | tc |
| 1 | 0.8556* | 17.14** | 0.6881* | 16.17 ** |
| 2 | 0.8551* | 8.85** | 0.6808* | 4.81** |
| 3 | 0.8578* | 2.30 ns | 0.6844* | 4.14** |
| 4 | 0.8524* | 2.99** | 0.6654* | 11.19** |
| 5 | 0.7738* | 18.72** | 0.4976* | 15.45** |
| 6 | 0.7788* | 9.71** | 0.4632* | 5.74** |
| 7 | 0.7989* | 2.67 ns | 0.4416* | 2.28 ns |
| 8 | 0.7680* | 2.67 ns | 0.4527* | 8.45** |
| 9 | 0.8027* | 12.21** | 0.6140* | 4.25** |
| 10 | 0.8012* | 4.14** | 0.6146* | 5.71** |
| 11 | 0.7994* | 2.38 ns | 0.6056* | 13.47** |
| 12 | 0.7973* | 7.54** | 0.6121* | 20.04** |
| 13 | 0.7877* | 15.11** | 0.7164* | 7.69** |
| 14 | 0.7926* | 5.43** | 0.7165* | 4.36** |
| 15 | 0.7911* | 1.92 ns | 0.7066* | 14.00** |
| 16 | 0.7922* | 8.04** | 0.7108* | 21.65** |

ns: not significant ($p>0.05$); *: significant at 5%; **: significant at 1%.