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Comparison of Wood Moisture Meters Operating on Different Principles of Measurement

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Abstract: This experiment compared commercially available moisture meters (three capacitive metersand one resistance meter) and tested their predictive ability at different moisture conditions on selected beech (*Fagus sylvatica*) and spruce (*Picea abies* (L.) Karst.) wood samples. The measurements were carried out on the samples at specified moisture intervals ranging from 5% to 30% moisture content (MC). The resistance meter showed a close correlation to gravimetric MC values; the influence of the measuring direction for MC below 17% was found when higher MCs in the transverse direction for both species were archieved. The difference was 4.6 times higher for softwood and 1.6 times higher for hardwood. Differences between radial and tangential transverse measuring were not observed. The close correlation coefficient of MC measurements was also found for capacitive methods. The effect of the direction was found for all the tested meters when higher MC values in the longitudinal measurements were found. This effect was especially significant at an MC of wood higher than 20 wt.%. For two capacitive methods, the effect of annual ring deflection only in the spruce samples was found where higher MC values in the tangential direction were observed.

Keywords: wood; gravimetric method; moisture content (MC); capacitive; resistance; moisture meter; spruce; beech

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1. Introduction

In most buildings, the moisture content (MC) of the timber in the structure may increase at some point, which may be caused by water leaching into the wood structure, a technical fault in the technical equipment of the building, or unexpected natural phenomena. From a technological point of view, it is necessary to understand the transportation and sources of moisture acting on the structure [1]. An increase in MC to the hygroscopic limit leads to changes in the mechanical physical properties of the wood associated with swelling and shrinking and increases the risk of wood being affected by mould and wood-boring fungi (MC above 20%) [2]. Usually, the MC of the timber incorporated in the structure is between 8% and 18%; MC exceeding this level can only appear in the event of a failure of the building's technical equipment or failure to comply with design principles [3]. The equilibrium MC of wood depends on the exposure conditions of the timber, and the relative humidity affects its level throughout the year in cycles which maintain the moisture balance of the wood. Changes in the environment and MC of the wood lead to volume changes in the wood up to the saturation limit of the cell walls [4].

In most cases, the design of a timber structure does not include consideration of all critical details of embedded timber elements. The quality and precision of the contractor's workmanship play a very important role in terms of the durability of a structure with timber elements. In view of these facts, the durability of a timber structure could be ensured by long-term monitoring of the embedded timber in the structure using moisture and temperature sensors on selected exposed timber elements [5].

1.1. The Determination of Wood MC

The MC of wood can be determined by destructive or non-destructive methods, which are further divided into direct and indirect measurement methods. The direct measurement method determines the actual water content of the wood. The indirect method determines the water content of the wood using another variable whose value depends on the water content of the wood [5,6]. The basic direct method is the gravimetric method (the oven drying method) which is considered to be the most accurate method for determining the MC of materials according to standardized processes (see EN ISO 12570) [7]. In commercial practice, the woodworking industry demands the immediate determination of the MC of the material with the maximum possible accuracy [8]. Indirect methods based on electrical or dielectric properties have been developed that allow moisture results to be obtained very quickly with sufficient accuracy. Indirect methods are used for in situ moisture measurements. The most common measurement methods (in the case of wood-based materials) available are the capacitance, electrical resistance, microwave field [9], spectrometric, and radiometric methods [5].

1.2. The Resistance Method for Wood MC Determination

The resistance method uses the electrical resistance/conductivity of the wood [10]. Stamm (1927) states that resistance decreases with increasing MC because water has a much higher conductivity than wood [11]. The resistance is measured by applying a voltage between two indented pins (poles of electrodes) of an electric circuit that are in contact with the wood and measuring the current that flows between them [8]. The megohmmeter scale typically indicates the MC of the material directly based on an empirical calibration of resistance versus MC for a particular electrode configuration in a given wood species at a specific temperature [11]. Resistance meters measure the highest moisture across the exposed ends of the pins. Spacing between pins is not critical as the resistance is primarily the surface resistance between the contacts and the wood and is almost independent of the length of the path the current takes through the wood [8].

Accuracy: This method provides acceptable accuracy for measuring wood MC from 6% to the body of the grain saturation. In this range, there is an approximately linear relationship between the logarithm of the MC and the logarithm of the resistance. Below 6% wood MC, the electrical resistance reaches values too high to measure easily [5]; above the fibre saturation point of wood, the accuracy of this method decreases. Vermass (1975) lists several different factors, which can be divided into two categories, that affect the direct current resistance data of wood. The first is the properties of the wood itself, e.g., moisture and its distribution in thecross-section, grain orientation, temperature (resistance of wood decreases with increasing temperature), bulk density, and chemical constituents including major constituents, extractives, and ash content. The second group of variable factors is referred to as experimental variables. These variables include electrode types and configurations, contact pressure, sample shape and size, electrolytic effects at the electrodes, and the magnitude and duration of the applied voltage [12].

1.3. The Capacitive Method for Wood MC Determination

Capacitive moisture meters use changes in the dielectric properties of the wood to determine the MC of the wood as a function of the change in capacitance (or dielectric constant) [13]. Materials, including wood, generally have a dielectric constant ε(F/m) in the range of 2 to 8, which remains (almost) unchanged, while the water contained in the material has a high dielectric constant, i.e., $\varepsilon = 80$. The amount of water creates a variable constant [14]. The dielectric permittivity of dry wood is around 2 for its anhydrous state [15]. The field that forms between the capacitor plates and the material that acts as a dielectric [16] is the measured field. The dielectric constant increases with increasing wood MC, and this effect becomes greater as the frequency of the electric field decreases. The moisture meter does not penetrate the structure of the sample, and the measurement determines the average MC on the surface of the wood (<35 mm) without determining the moisture gradient [5]. Dielectric meters measure the MC of the zone of the wood that is penetrated by the electric field and generally indicate the mean MC of this zone. Generally, dielectric moisture measurement is non-invasive and gauges low MC below the measurement limit of resistance hygrometers with faster and more convenient measurement of large quantities (production lines) [8]. For the measurement, permanent, firm contact with the surface of the measured material, which is free of defects (rot, chips, resins, etc.), must be ensured [17]. Hartley and Marchant (1995) state that dielectric meters are generally not as accurate as resistance moisture meters [8].

Accuracy: An acceptable accuracy for wood MC is provided from 2% up to the fibre saturation point [18]. Forsén and Tarvainen (2000) claim that the capacity range of power-loss-type moisture meters is 0% to 25% MC [17]. The effect of moisture on the dielectric properties of wood can be divided into a range below an MC of 5% (the monomolecular moisture of wood) when the dielectric constant increases slowly and above an MC of 5% when the dielectric constant increases rapidly as a function of MC [19]. The bulk density of wood, material temperature, grain orientation, and alternating current frequency affect the dielectric properties. Unfortunately, the readings depend on the bulk density of the specimen [17]. The dielectric constant increases with increasing wood bulk density and increasing wood temperature, except at a very high MC where the effect becomes erratic [8].

1.4. Objectives of the Paper

The aim of this study was to compare commercially available moisture meters (based on capacitive and resistance principles) in terms of the moisture range of their possible usage, and assess their measurement accuracy. Additionally, the possible dependency of the measurements on the wood parameters of grain direction (longitudinal and transverse) and bulk density (softwood and hardwood) was determined. While the moisture measurement of wood used in structures is mostly accessible transverse to grain orientation, this study assessed the possible influence of the annual rings' deflections (below 45° as the radial plane or above 45° as the tangential plane). This could be very important knowledge because the timbers (both radially and tangentially sawn) do show the variable of the annual rings' deflection throughout the cross-section. Finally, statistical analyses were performed for all the moisture meters.

2. Materials and Methods

2.1. Materials

Two types of wood species were chosen, beech wood (*Fagus sylvatica*) and spruce wood (*Picea abies* (L.) Karst.). Eleven samples of each wood species were prepared from a wood prism; the samples were cut at a distance of 300 mm from the prism edge to fulfil the standard requirement. Samples without visible wood defects (knots and cracks) were selected for testing. The samples were cut to the required dimensions of 80 × 50 × 100 mm. The absolute mean dry bulk density of the samples was 425 kg/m^3 for spruce wood and 650 kg/m^3 for beech wood. To consider the difference in the rings' deflections, the samples were split into two groups: (i) with a deflection in the range of up to 45° as radial plane 'R' and (ii) with a deflection in the range above of 45° as tangential plane 'T'. Figure 1 shows a wood sample for the moisture measurement.

2.2. Methods

2.2.1. Moistening of Wood Test Samples

The samples were placed in a drying oven at 103 ± 2 °C to determine the dry weight of the samples. After reaching a constant weight, the samples were cooled in a desiccator to room temperature, and each sample was weighed to the nearest 0.01 g (dry weight). Based on the determined dry weight, all the samples were then moistened by water spraying to the required initial 5% MC. To ensure a uniform moisture distribution throughout the cross-section, the samples were placed separately in polyethylene film for 72 h. At higher MCs, the time required for moisture stabilisation of equilibrium MC was equivalently increased. The moisture increment interval of the samples was set at 3 wt.% up to a value of 30 wt.% to ensure the wood MC reached the fibre saturation level. Therefore, the MC values of wood samples of 5%, 8%, 11%, 14%, 17%, 20%, 23%, 26% and 30% were chosen for moisture measurement by all the tested meters.

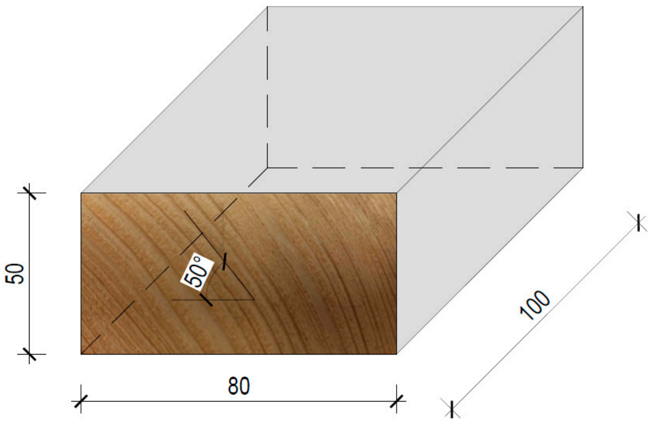

Figure 1. Schema of wood samples for moisture measurement, i.e., a sample with a ring deflection of 50° at a transverse cross-section as a tangentially oriented sample.

2.2.2. Moisture Measurements

After verifying the achieved MC of samples using the gravimetric method, measurements using the selected moisture meters operating with different measurement methods (capacitance and resistance) were carried out. The moisture measurements were carried out at a temperature of 20 ± 2 °C and a relative humidity of 45 ± 5%. The achieved values of MC for every method were rounded to the nearest 0.1 wt.%.

Wood, as an anisotropic material, has different properties depending on the course of the fibres. To consider the wood anisotropy, measurements were made for samples in both the longitudinal direction (i.e., meters attached on both the transverse surfaces) and transverse direction (i.e., meters attached on both the longitudinal surfaces) at 20 °C. The moisture was measured six times for the longitudinal direction and nine times for the transverse direction for each amount of MC of the wood samples. The measurement process fulfilled the requirements of standards EN 13183-2 (2002) [20] for resistance methods and EN 13183-3 (2002) [21] for capacitance methods. All the MC measurements of the test samples were performed in the middle of the width of each tested surface.

2.2.3. Capacitive Moisture Meter

Three capacitive moisture meters, GMI 15 (Greisinger GmbH, Regenstauf, Germany), GMK 100 (Greisinger GmbH, Regenstauf, Germany), and Testo 616 (Testo, Lenzkirch, Germany) were chosen as representatives of the capacitive method.

The GMI 15 is declared by the manufacturer to be an instrument for indicative moisture measurement. The instrument is a specified dimensionless unit (raw data) that is converted to a moisture value according to the manufacturer's enclosed instructions. The recommended measurement range of MC is 0% to 30% by weight. The measurements were carried out according to the manufacturer's recommendations with a set measurement depth of 30 mm.

The GMK 100 considers the wood bulk density, which is given in the range of 50 kg/m^3. The resulting value is displayed on the instrument as a percentage of the absolute wood MC by weight. The manufacturer states a measurement range of 0% to 100% with the accuracy of the measurement decreasing from 0.1% to 1% for moisture values above 19.9%. The instrument enables measurements at depths of 10 mm and 25 mm; for this experiment a measurement depth of 25 mm was chosen. The manufacturer of the moisture meter provides a characteristic table with a specified typical volume weight for the type of wood to be measured, which was entered into the measuring instrument before the moisture measurement. The actual mean dry bulk density of the beech sample was 650 kg/m^3, resulting in MC values being duplicated by setting the bulk density on the instrument for 650 kg/m^3 (650) and 700 kg/m^3 (700). Spruce wood measurements were carried out with the instrument set to a bulk density of 450 kg/m^3.

The Testo 616 measures up to a maximum depth of 50 mm, unlike other capacitive moisture meters. The instrument allows for the choice of material and wood species for the determination of the MC by weight. The range of the measuring device stated by the manufacturer is 0% to 50%; the accuracy of the measurement is not stated. The device enables pre-setting for measuring softwoods (spruce, pine, larch, and others) and hardwoods (beech, oak, maple, and others). An electrode pressure of 1 to 3 kg of the moisture meter on the tested surface material is strictly recommended.

2.2.4. Resistance Moisture Meter

The Testo 606-2 (Testo, Lenzkirch, Germany) resistance moisture meter measures the moisture-dependent electrical resistance using a pair of stop spikes that are driven into the wood structure. Measurements were made on all eleven test samples. The depth of the spikes inserted into the wood was up to 8 mm, which was the maximum length of the spike electrodes used. The instrument contains a sensor for determining the temperature and relative humidity of the environment. The measurement accuracy stated by the manufacturer is 1%. The instrument contains two optional groups of wood species: the first group of wood species (beech, fir, larch, and others) and the second group (oak, pine, maple, and others). The first group was chosen for the experiment with a stated measurement range of 8.8% to 54.8%. The moisture meter contains material curves that allow the MC of the material to be displayed directly in weight percentages relative to the dry weight.

2.2.5. Statistical Evaluation of the Data

The results of the moisture tests by the described methods were compared statistically with the gravimetric method, which can be considered very accurate. This statistical analysis was performed separately on the test results of one test method, one wood species, one moisture level, and one test direction. The first step of the statistical analysis was the assessment and elimination of outlying test results, which was performed by means of 1.5 multiples of the quartile range. The test results thus adjusted were always subtracted from the results of the gravimetric method. Hence, 154 statistical sets were considered.

Subsequently, a set of statistical tests was performed. First, it was necessary to assess the normality of the data, specifically with the Shapiro–Wilk test. The normality of the differences from the gravimetric method indicates that the test results were only affected by random factors and can be assumed to have been unaffected by systematic influences. Furthermore, the hypothesis was tested using a one-sample *t*-test for the nullity of the mean value of the underlying sets from whose realisations the statistical sets originated. The positive result of both these tests indicates that the results of the observed moisture determination method are not significantly different statistically from the gravimetric method and are therefore influenced only by random factors.

3. Results

3.1. Wood Moisture Measurement

3.1.1. Longitudinal Direction

Figures 2 and 3 show a graphical comparison of the mean differences of the moisture readings from the gravimetric method for each moisture condition, including the sample standard deviations. The lowest differences were obtained with the GMK 100 capacitance moisture meter, in both cases measuring beech samples (hardwood with a set bulk density of 650 kg/m^3) and spruce samples (softwood with a set bulk density of 450 kg/m^3). For this moisture meter, the lowest differences were measured over the entire range of measured moisture conditions, i.e., from 5% to 30%. Conversely, the Testo 616 capacitance moisture meter showed a significant increase in measured moisture values after reaching 26% MC for both tested species of spruce and beech. In the case of the GMI 15 capacitive moisture meter, the limit set by the manufacturer for MC calculated from 'raw' data was exceeded for softwood at an MC of 23 wt.% and for hardwood at an MC of 17 wt.%.

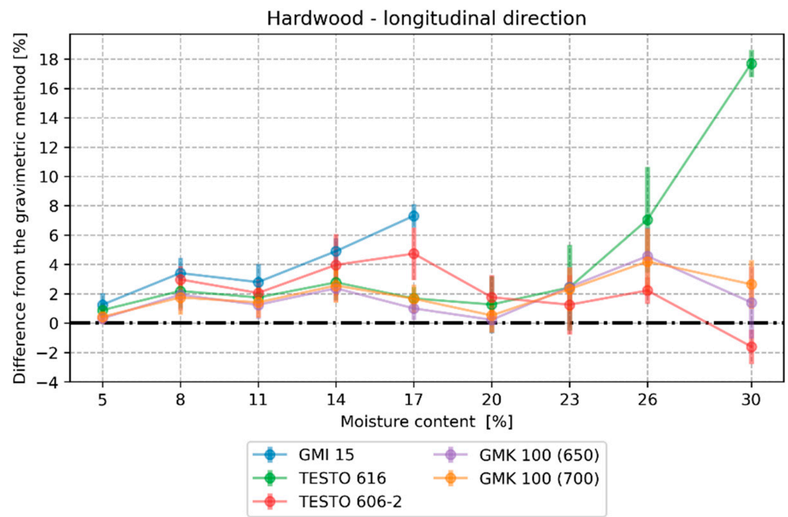

Figure 2. Comparison of average values of differences from the gravimetric method in the longitudinal direction of beech wood using selected moisture meters GMI 15, GMK 100, Testo 616, and Testo 606-2 in different moisture conditions and GMI 100 at different instrument settings of 650 kg/m^3 (650) and 700 kg/m^3 (700).

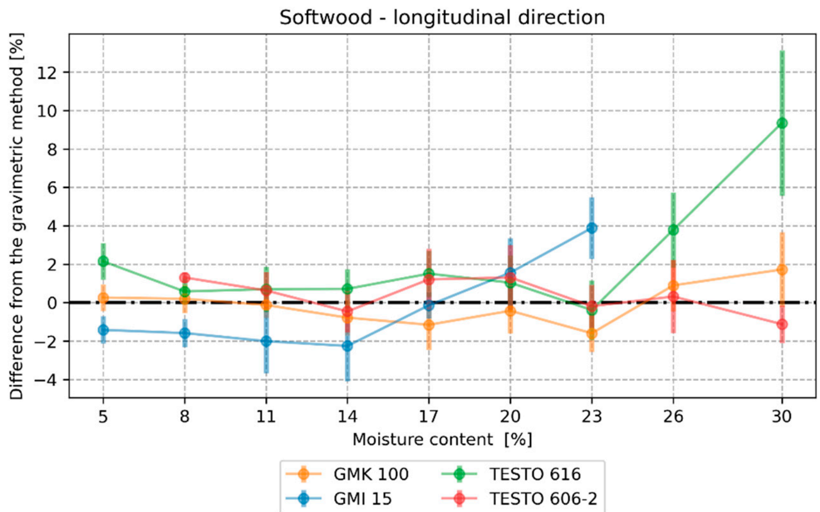

Figure 3. Comparison of average values of differences from the gravimetric method in the longitudinal direction of spruce wood using selected moisture meters GMI 15, GMK 100, Testo 616 and Testo 606-2 in different moisture conditions.

Given the manufacturer's declared measurement limit (an MC range of 8.8% to 54.8%) for the Testo 606-2 as the resistance method, measurement at an MC level of 5% was carried out. It was confirmed that wood MC at a 5% moisture level in the longitudinal direction for both softwood and hardwood cannot be measured.

3.1.2. Transverse Direction

Figures 4 and 5 show a graphical comparison of the average values of the difference of the measured moisture values of for each of the moisture meters using the gravimetric method for each moisture condition, including the sample standard deviations. The lowest differences for the whole range of moisture conditions from 5% to 30% were achieved using the GMK 100 moisture meter for beech samples (hardwood with a set bulk density of 650 kg/m^3). In the case of the GMI 15 capacitance moisture meter, as opposed to the longitudinal direction, it was possible to use the manufacturer's declared recalculation of the moisture indication over the entire range of moisture conditions up to 30%.

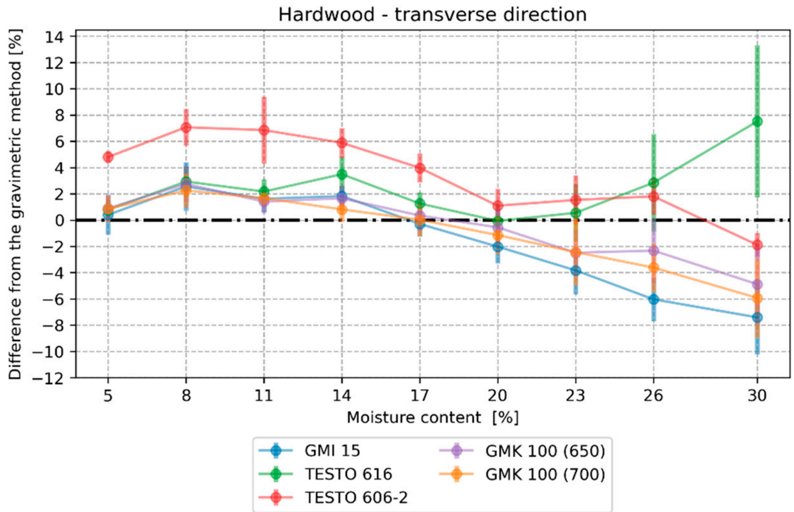

Figure 4. Comparison of average values of differences from the gravimetric method in the transverse direction of beech wood using selected moisture meters GMI 15, GMK 100, Testo 616 and Testo 606-2 at different moisture conditions and GMI 100 at different instrument settings of 650 kg/m^3 (650) and 700 kg/m^3 (700).

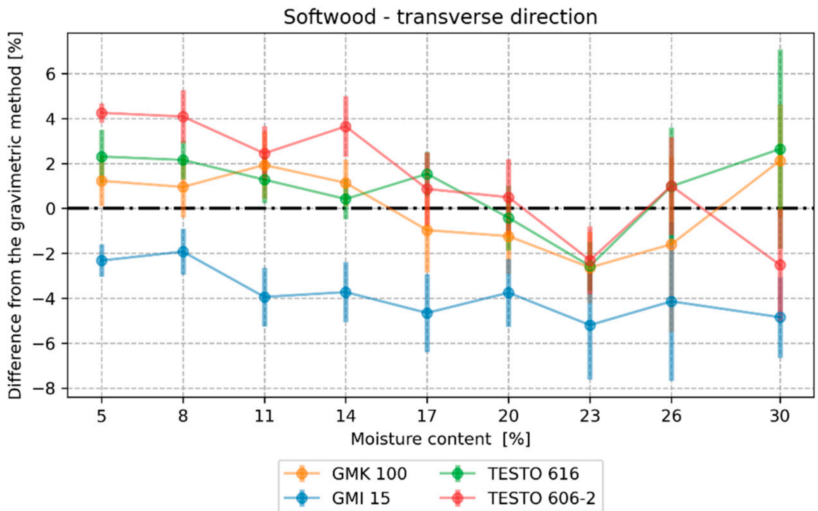

Figure 5. Comparison of average values of differences from the gravimetric method in the longitudinal direction of spruce wood using selected moisture meters GMI 15, GMK 100, Testo 616 and Testo 606-2 in different moisture conditions.

In contrast, the highest differences were obtained using the Testo 606-2 resistance moisture meter for beech, while for spruce the highest differences were found using the GMI 15 moisture meter. With regard to the manufacturer's declared measurement limits (with a range of 8.8% to 54.8%), the measurement showed that when using a Testo 606-2 resistance moisture meter below the manufacturer's specified range, the MCs of the softwood and hardwood at a level of 5 wt.% were measured.

3.2. Statistical Evaluation of the Data

Through the quartile range, 381 test results out of a total of 9285 measurements were excluded by means of outliers. The analyses showed that 90.9% of the data sets have a normal probability distribution. However, in order to conclude that the test results of the methods considered are only affected by random factors compared to the gravimetric method, it is also necessary to show that the mean values of the results are not significantly different from zero. The analysis of the results of the mean value tests showed that only 10.4% of the result sets did not deviate systematically from the gravimetric method. This implies that almost 90% of the measurements show statistically significant biases. Table 1 shows the results of the mean value tests in the form of the percentages of unrejected tests for a given measurement method.

Table 1. Test results of mean values in the form of percentages for a given measurement method.

Method of Measurement	(%)
GMI 15 (capacitive)	10.0
GMK 100 (capacitive)	16.7
GMK 100–650 (capacitive)	11.1
GMK 100–700 (capacitive)	5.6
TESTO 606-2 (resistance)	8.8
TESTO 616 (capacitive)	11.1

However, significant biases from the gravimetric method do not necessarily indicate that the measurement methods under consideration are incorrect. As can be seen in Figures 2–5, in most cases the bias is statistically significant, but technically, it is an average bias of a few per cent. Similar biases are reported by the manufacturer of the measuring instruments.

The next step of the statistical analysis was to evaluate the multivariate analysis of variance (ANOVA). The results are presented in Table 2 as *p*-values. The following factors were selected as influencing the resulting deviation from the gravimetric method: measurement method, type of wood species, the direction of measurement, and moisture level.

Table 2. Results of multivariate ANOVA. Factor interactions are marked with an abbr. 'vs'.

Factor	*p*-Value [-]
Method	4.91×10^{-149}
Wood species (softwood/hardwood)	1.17×10^{-240}
Direction (longitudinal/transverse)	6.78×10^{-84}
Moisture level	1.47×10^{-149}
Method vs. Wood species	2.96×10^{-32}
Direction vs. Wood species	2.25×10^{-1}
Method vs. Direction	4.57×10^{-199}
Method vs. Moisture level	6.17×10^{-281}
Moisture level vs. Wood species	7.46×10^{-2}
Moisture level vs. Direction	4.94×10^{-277}

The *p*-value in this test is a measure of the statistical significance of the results. The *p*-value indicates the probability of observing a test statistic as extreme or more extreme than the one calculated, assuming that the null hypothesis is true. In the context of ANOVA, the null hypothesis is that there is no difference between the population means of the groups defined by the factor levels. The *p*-value of each factor and interaction term tests the hypothesis that the factor has no effect on the response variable. If the *p*-value is less than a chosen significance level (0.05), it suggests that there is strong evidence against the null hypothesis and that the factor does have a significant effect on the response variable. The smaller the *p*-value, the stronger the evidence against the null hypothesis, and the more likely it is that the factor has a significant effect. This means that a change in the direction of measurement combined with a change in the type of wood species tested does not significantly affect the results obtained. The same conclusion applies to the change in moisture level and the type of wood species.

4. Discussion

4.1. Comparison of Tested Moisture Meters

As can be seen from the measured values, each of the measuring devices was burdened with a certain error, which was different according to the type of wood and the measured MC level.

The limit of the resistance method is determined by the MC of the wood in the range below 5%, it could not be determined due to high resistance values for measuring [5]. According to EN 13 183-2, the limitation is determined by amoisture range between 7% and 30% [21]. For the tested Testo 606-2 (using the resistance method), at an MC level of 5%, only measurement in the transverse direction for both the softwood and hardwood was possible. However, even in this direction and at this MC level, a complete number of values (max nine values) was not reached for three samples. For softwood samples, only 93% of the measurement was detected, and for hardwood samples, only 85% of the measurement was detected. This instrument showed a close correlation coefficient (when comparing the measured values with the values determined by the gravimetric method), reaching values of 96% to 100%. As can be seen in the following Figure 6, in the whole moisture range from 5% to 30%, the resistance instrument indicates higher values compared to gravimetric values. The same trend was found by Li et al. (2018) when, at an MC of 10% to 20%, only the bound water was present in the wood, and the author observed only a small decrease in resistance, while above 20%, when free water penetrates intercellular spaces in the wood, the decrease in resistance was more significant. Higher MC can lead to an improvement in the electrical contact brought about by the conductivity of water [22].

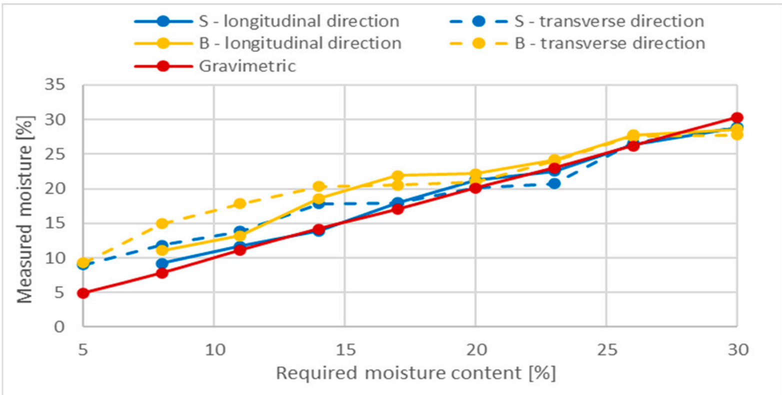

Figure 6. Dependence of the average measured values of MC using the Testo 606-2 moisture meter on the MC of different types of wood (S—spruce, B—beech) and in different directions in the MC range of 5% to 30%.

Further, the achieved results in the range of 5% to 17% of MC showed a difference when higher values were obtained for measuring in transverse directions, whereas from 17% to 30%, no significant differences were found. The effect of the measuring direction has been evaluated by different authors; for instance Hartley [8] states that the electrical resistance of wood is about half as large for a current flowing parallel to the grain as it is for a current flowing perpendicular to the grain. This means up to a 2% higher MC reading for parallel current flow than for perpendicular, contrary to other authors [17,22], who found no difference between the measuring directions that were parallel and perpendicular to the grain.

The capacitive methods (using three different instruments) showed very similar behaviour for MC measurements, as can be seen in Figures 7–9. Very similar results to the gravimetric method were obtained using the Testo 616 and GMK 100 moisture meters in the moisture range of up to 23%. Above 23% MC, significant differences in measured values compared to gravimetric values were found. The increase in measured MC values above 23% (for Testo 616 and GMK 100 in the longitudinal direction) can be attributed to the contribution of contact capacitance. The existence of free water in wood could lead to its infiltration at the wood/electrode interface. Consequently, free water fills the air gap between the electrodes and wood [23], and contributions of interface capacitance increase with increasing MC [17,24]. Both instruments showed a close correlation coefficient when comparing the measured values with the values determined by the gravimetric method, reaching values of 96% to 98% for Testo 616 and 98% to 100% for GMK 100. GMI 15 showed higher differences in counted MC for both of the tested wood species compared to the gravimetric values, and a high correlation coefficient of 94%–100% was reached.

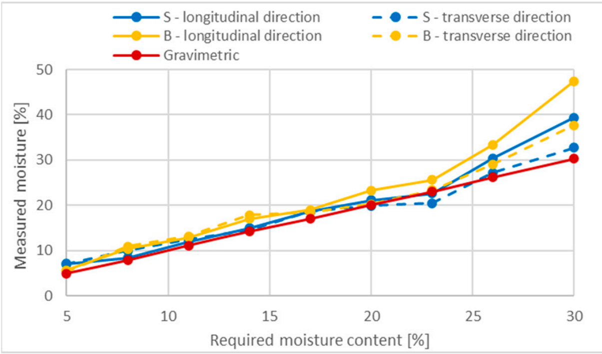

Figure 7. Dependence of the average measured values of MC using the Testo 616 moisture meter on the MC of different types of wood (S—spruce, B—beech) and in different directions in the MC range of 5% to 30%.

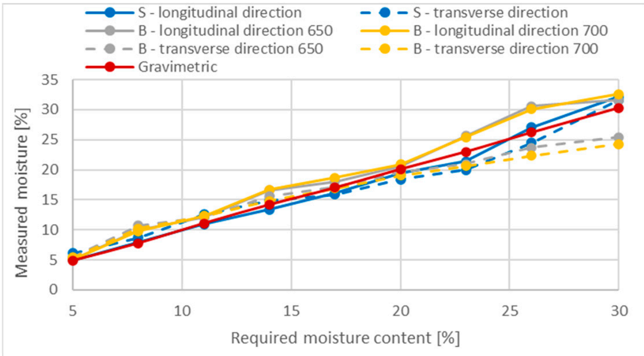

Figure 8. Dependence of the average measured values of MC using the GMK 100 moisture meter on the MC of different types of wood (S—spruce, B—beech) and in different directions in the MC range of 5% to 30%.

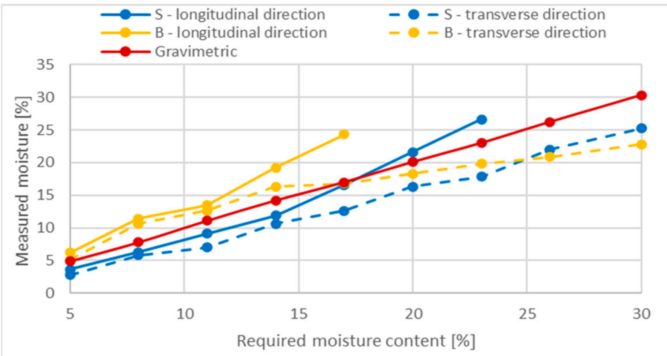

Figure 9. Dependence of the measured values of the GMI 15 moisture meter on the MC of different types of wood (S—spruce, B—beech) and in different directions in the moisture range of 5% to 30%.

4.2. The Effect of Wood Anisotropy

Regarding the wood anisotropy, including the effects of the measuring direction (longitudinal and transverse) and density of the wood (beech and spruce), Figure 10 shows a graphical comparison of the mean percentage differences of measured MCs compared to gravimetric values from all the selected moisture levels.

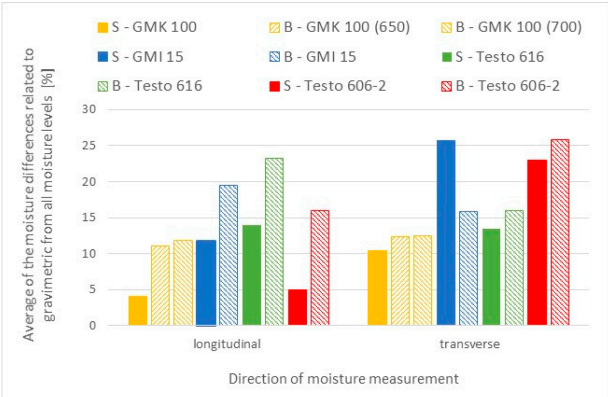

Figure 10. Comparison of the mean percentage differences in measured MC values compared to gravimetric values for all the selected moisture levels from 5% to 30%.

Taking into account the measuring direction, for all the tested meters, the transverse direction values show higher differences compared to gravimetric MC for softwood and hardwood (except for measurements by the GMI 15 and Testo 616 capacitive meters for hardwood).

For the capacitive method, the difference for GMK 100 was 2.5 times higher in transverse for softwood and 1.1 times higher for hardwood. The Testo 616 capacitive meter did not show any significant differences. Regarding the capacitance, the difference in MC values could be attributed to variation in the dielectric properties between the longitudinal and transverse direction in the wood, as can be proven, for example, by Kabir et al. and Norimoto [25,26], who found the dielectric constant and dielectric loss factor higher for wood when parallel to the grain (by 20% to 50%) than perpendicular to the grain. Forsén [17] found no effect of the measuring direction in wood on the MC measured with capacitance meters. The possible influence of the grain orientation for the capacitance method is stated by James [27], where at moisture levels below about 15% the effect of grain direction is negligible. A reading of MC above 20% perpendicular to the grain may occasionally be as much as 2% lower than MC parallel to the grain. Lower values in transverse measuring than in the longitudinal direction were found for all the tested capacitance meters, as shown in Figures 7–9. This behaviour was more dominant for moisture levels above 20 wt.%.

Conversely, the highest difference was reached for the resistance device for spruce samples where the orientation of the grain (parallel and perpendicular) showed 4.6 times higher differences in the transverse measurement for softwood and 1.6 times higher values for hardwood.

In comparing the effect of wood density, the MC values obtained for hardwood showed significantly higher differences compared to gravimetric MC than those for softwood in both measured directions (except for capacitance GMI 15 for the transverse direction), as can be seen in Figure 10. These differences were higher for longitudinal directions (GMK 100 and Testo 606-2 values were nearly 3 times higher; GMI 15 and Testo 616 values were 1.7 times higher), whereas for the transverse direction, the difference between softwood and hardwood MC values were ca. 1.2 times higher for hardwood (except for GMI 15). For capacitance measurement, it is known that meters are calibrated for the average specific gravity, and error in the readings is directly proportional to the difference between the tested density and the value used for calibration [17]. Skaar [10] claimed that the dielectric constant, as anticipated, increases with wood density at constant MC. Forsén and Tarvanainen (2002) demonstrated the strong effect of density on the meter readings experimentally in [17] For the resistance method, Forsén and Tarvanainen (2002) reported no significant influence of densities (<450 kg·m^{-3}; 450–550 kg·m^{-3}, and >550 kg·m^{-3}) on the MC values measured for Nordic pine wood in [17].

4.3. The Effect of Annual Rings' Deflection in Transverse Measuring

The tested samples were divided into two groups including annual ring deflection at the transverse cross-section (radial for 0–45°, tangential for 45–90°). The effect was only observed for spruce samples using the GMK 100 (the mean difference between the two groups of samples reached 12.8%) and GMI 15 (the mean difference was 10.6%) capacitance meters; for the Testo 616 capacitance meter, no significant differences were found, as shown in Figures 11 and 12. For this meter, the increase was found in the range of 2.9%. Norimoto (1972) only found a slight decrease in the dielectric constant and dielectric loss factor for a decrease in the grain angle of 0–90° for the R-T plane of wood (in the transverse direction) in Hoonoki wood. This means that only a slight difference could occur for the MC meter with different ring deflections [26].

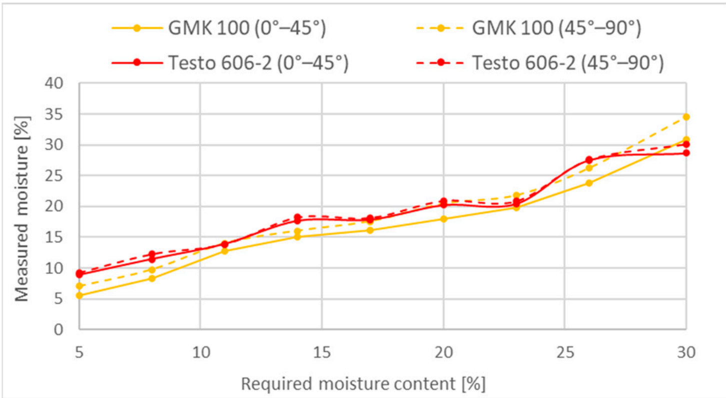

Figure 11. Comparison of the measured values of the moisture meters (GMK 100, Testo 606-2) on the MC of softwood (S—spruce) in the transverse direction in the moisture range of 5% to 30% with respect to the ring deflection in the range of 0–45° (radial) and 45–90° (tangential).

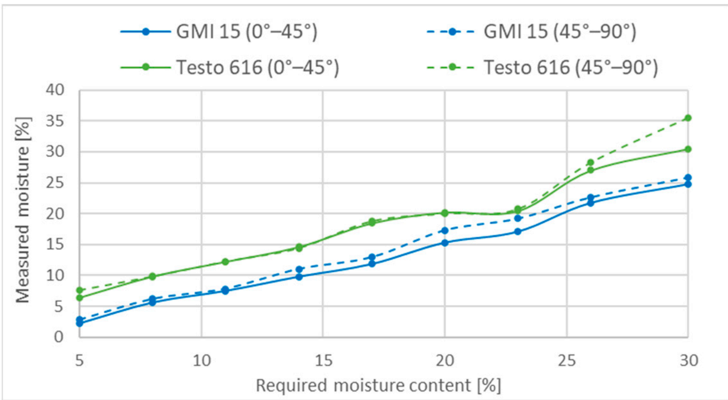

Figure 12. Comparison of the measured values of the moisture meters (GMI 15, Testo 616) on the MC of softwood (S—spruce) in the transverse direction in the moisture range of 5 to 30% with respect to the ring deflection in the range of 0–45° (radial) and 45–90° (tangential).

Very similar results were detected between the two groups of samples with different ring deflections for the resistance method using the Testo 606-2 (4.3% difference), which allow us to validate the claim that electrical resistance is not affected by the deflection of the annual rings in the transverse direction. Forsén and Tarvanainen (2002) reported that the effects of fibre orientation, electrode type, and density are only insignificant effects for measurement errors in applying the resistance method [17].

For the beech samples tested, no effect of ring deflection on the measured MC was found. These findings could be interpreted by the difference in softwood and hardwood macroscopic structure. In softwood, the annual rings consist of early and late parts of rings with differences in their densities, contrary to the beech-like scattered ring-porous species which does not show any macroscopic differences in the rings, and, regarding density, its structure is more uniform.

5. Conclusions

In this study, two wood species, spruce (*Picea abies* (L.) Karst.) and beech (*Fagus sylvatica*), were used for indirect moisture measurement (in the range of 5% to 30%) by four commercial moisture meters using capacitive methods (GMK 100, Testo 616, and GMI 15 m) and resistance methods (Testo 606-2).

Regarding the types of meters, all the tested meters showed a close correlation to the gravimetric method, reaching values of correlation coefficient of 96% to 100% for the resistance method with the Testo 606-2; for the capacitance methods, values ranged from 96% to 98% for the Testo 616, 98% to 100% for GMK 100 and 94% to 100% for GMI 15. Based on the ANOVA test performed, all factors (wood species, moisture levels, methods and measurement directions) showed significant differences compared to values from the gravimetric method.

The resistance methods showed that the direction of measurement had a significant effect in the moisture range below 17 wt.%, where the values in the transverse direction were higher than in the longitudinal. Above the MC of 17 to 30 wt.%, no significant differences were observed in the measured values. For the capacitive methods (Testo 616 and GMK 100), very similar results were found for MC up to 20 wt.% for both types of measuring directions. At higher MCs above 20%, a dominant effect of the measuring direction was observed for all the tested capacitance methods. Lower MC values for all three tested capacitive meters were found in the transverse directions, including both tested wood species.

The resistance method did not have any significant measurement dependency on the bulk density (softwood and hardwood) in the transverse direction; conversely, a significant difference in the longitudinal direction was found with nearly three times higher differences compared to gravimetric MC values measured for the hardwood samples. As expected, the effect of bulk density for the capacitive methods was proven. Except for GMI 15, the meters showed higher differences in measured MC values compared to gravimetric for the hardwood samples.

Due to differences in the wood grain orientation of in-built wood members during moisture measurement in the transverse directions, the influence of the annual ring deflection (in the radial and tangential plane) was experimentally verified. No effect was found for the hardwood species whose macroscopic structure differs from the softwood species. For the spruce samples, the effect occurred only for the capacitive methods. A higher value with differences of 12.8% for GMK 100 and 10.6% for GMI 15 in the tangential directions was found.

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