Predicting Wood Strength using Dielectric Parameters

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There are various methods for nondestructive imaging of the internal structure of wood. A microwave nondestructive method based on the dielectric properties of a medium is an area of great interest for predicting wood strength in the worldwide wood industry, but the reliable prediction of strength in wood still has not been solved in a satisfying manner. Hence, answering the question of how dielectric properties of the wood are related to strength may improve the efficiency of models for predicting structural performance of wood by microwaves. Relationships were evaluated in this work between dielectric parameters (dielectric constant, loss factor, and loss tangent) and the strength properties of wood. Samples were prepared from fir and oak wood. Dielectric measurement was performed at a frequency of 9.8 GHz using Von Hippel's Transmission Line Method. Wood density and some mechanical properties were then determined according to related ISO standards. The results showed that there were good relationships between the dielectric parameters and the MOR, MOE, IBS, and CS, especially for oak wood. The dielectric parameters were promising to predict wood strength with a high accuracy for oak but not fir, and the dielectric constant had a higher precision degree than the loss tangent and loss factor.

Keywords: Dielectric properties; Microwaves; Nondestructive evaluation; Wood strength

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INTRODUCTION

A major industrial use of wood is as a structural element, not only in familiar house construction but also in commercial and industrial structures such as roof systems and bridges. A major difficulty in the use of wood in engineered structures is uncertainty in the design data for the individual load-bearing members. This difficulty would vanish if each member could be rated reliably with respect to its mechanical quality, through the use of nondestructive tests. Nondestructive tests made on full-size products are the predictors employed in performance models. As strength can be measured directly only through destructive testing, improved efficiency in the nondestructive predictors is important for the continued use of wood (James *et al*. 1985; Ruud *et al.* 1991).

Nondestructive evaluation is an approach that identifies the physical and mechanical properties of materials without altering their end-use capabilities. Such evaluations rely upon nondestructive testing techniques to provide accurate information pertaining to the properties, performance, or condition of the material in question (Ross and Pellerin 1994; Horacek *et al.* 2012). Many nondestructive techniques are currently employed, some in production environments, others as diagnostic tools. The fundamental hypothesis for the nondestructive testing of wood materials was initiated by Jayne (1959), who proposed that the energy storage and dissipation properties of wood materials, which can be measured nondestructively by using a number of testing techniques, are controlled by the same mechanisms that determine the static behavior of such material. As a consequence, useful mathematical relationships between these properties and static, elastic, and strength behavior should be attainable through statistical regression analysis.

Industrial microwave wood sensing is a dynamic area offering affordable, nondestructive, non-contact, and bulk property measurements in a safe and noninvasive way (Hansson *et al.* 2005; Bogosanovic *et al.* 2010). However, a detailed study by Bogosanovic *et al.* (2010) showed that microwave techniques are still not commonly used. Alternative approaches to microwave wood testing are propagation modeling, measurement techniques, hardware implementation, and determination of wood properties. The technology is mature, but more effort is needed to research a solution suitable for an industrial environment. Wood is a heterogeneous, anisotropic media, and microwave transmission through a wood sample depends on several parameters, including moisture content, density, temperature, internal defects, and grain angle. Great variation in sample properties and the complex structures involved impose many problems that require advanced theoretical, empirical, and hardware solutions (Bogosanovic *et al.* 2010).

In order to correctly interpret microwave imaging, it is necessary to know the response of the material to electromagnetic fields. It is also necessary to understand the mechanism of contrast, the interaction between the sample and the probe, and to model and to measure the distribution of the electric and magnetic fields around the probe. Consequently, progress achieved in the basic knowledge of the dielectric properties of wood will allow new industrial applications of the microwave imaging technique (Bucur 2003).

Understanding the dielectric and structural properties of wood is essential for the successful development of a sensing technique. There are many reports on wood's dielectric properties (for example, Torgovnikov 1993 and Şahin 2002). In practice, dielectric properties are not the objective of the measurement; rather they are intermediate indicators of certain wood parameters of significant practical value. The permittivity of wood, measured at a certain frequency and sample temperature, strongly depends on moisture content and density (Şahin and Ay 2004). Effective permittivity takes into account the heterogeneity of the sample but can be strongly affected by the presence of defects, such as knots and branches, as well as the presence of white rot fungi and other wood degradations. In addition, the anisotropy of wood is strongly related to the grain direction in the lumber and its measurement provides indicators of wood quality (Bogosanovic and Emms 2014).

Microwave technology has also shown much promise for predicting the mechanical properties of wood but is not a reliable predictor of strength in sawn timber. There are several factors that influence the strength properties of timber, such as moisture content, density, grain angle of wood, and temperature. The strength of a piece of timber can be predicted if the parameters affecting the strength and the relationship between the parameters and strength are known (Heikkila *et al.* 1982). Lundgren (2005) concluded that if strength grading is done from microwave measurements alone, then it is necessary to have control of all factors that influence the measurement. Various studies have shown that moisture content and/or density (Tiuri *et al.* 1980; King and Yen 1981; James *et al.* 1985; Johansson *et al.* 2003; Hansson *et al.* 2005; Lundgren *et al.* 2006; Schajer and Orhan 2006: Lundgren 2007; Denzler and Arthaber 2014) could be predicted by microwaves. Additionally, the detection of grain angle (James *et al.* 1985; Shen *et al.* 1994; Leicester and Seath 1996; Bogosanovic *et al.* 2013; Denzler *et al.* 2013; Denzler and Weidenhiller 2015) is possible with microwave technology. Choffel *et al.* (1992) concluded that the response of a microwave sensor is related to the mechanical properties in wood. Microwave signals, after transmission through wood, contain information about the bending strength and the modulus of elasticity mainly from the correlation to density but also from the influence that structural variations in the wood have on microwaves (Lundgren 2007; Lundgren *et al.* 2007).

Since the properties in wood that affect microwaves are also related to strength, dielectric parameters have been tested in strength prediction applications. At the same time, the complex relations make it difficult to separate influences from different wood properties (Lundgren 2005; Lundgren *et al.* 2007). It is well known that the strength and dielectric properties of wood are influenced considerably by density, moisture content (MC), defects, slope of grain, temperature, *etc*. As the MC of wood decreases, the strength properties increase but the dielectric properties decrease. A similar correlation is also valid for the temperature. As density of wood increase, the strength and dielectric properties of wood increase. Therefore, the reciprocal correlations among the density-dielectric properties (Jain and Dubey 1988; Ay and Şahin 2004), density-strength (Hein and Lima 2012), the MC-dielectric parameters (Peyskens *et al.* 1984; Ay and Şahin 2004; Şahin and Ay 2004), MC-strength (Madsen 1975; Green *et al.* 1986), temperature-dielectric parameters (O'Sullivan 1976; Koubaa *et al.* 2008), and temperature-strength (Zhou and Zhong 2012) may be the most significant limitations to be overcome using dielectric parameters to reliably predict the strength properties of wood. A good model for the prediction of wood strength by dielectric parameters can be reached by the addition of the correlations of the strength-density the strength–MC, strength–temperature, dielectric properties-density, dielectric properties-MC, and dielectric properties–temperature.

In this context, predicting wood strength *via* microwaves involves many complicated physical phenomena. In order to optimize and control this process, one must understand the various phenomena involved. This understanding may be achieved with experimental measurements and by building models. Numerical models have little practical value for industrial purposes but they help to broaden the understanding of the response of the microwave measurement system to various wood properties. Hence, more emphasis on improving the efficiency of models is needed for predicting structural performance by microwave and efforts have been made to quantify the advantages of the approaches. More studies on how the dielectric properties of the wood are related to strength are also needed (Lundgren 2005). The basic principle for the mechanical strength grading of structural lumber by microwaves is generally to determine density, moisture content, and the grain angle of a board and to use these properties as indicators of wood strength. There have been no studies concerning the relationship between the dielectric parameters, static elasticity, and strength properties of wood. In the present study, mathematical models were developed to relate the dielectric properties to mechanical properties and density. Their accuracy in predicting wood strength was evaluated.

EXPERIMENTAL

Materials

Fir (*Abies nordmanniana*) and oak (*Quercus petraea*) timbers were chosen randomly from a timber supplier in Yenice, Karabük. The main criteria for their selection were the commercial importance of the timbers in the Turkish market and other factors related to the wood itself, such as density and anatomical features. The timber consisted of air-dried sawn boards of nominal dimensions 5×20 mm^2 and 100 mm in length. All the boards were planed, and 70 clear timber pieces with dimensions of 20×20×300 mm^3 were cut from the sapwood region of the timbers of each tree species. Then, a total 140 timber pieces (2 tree species × 70 samples) were placed in a climate room holding a temperature of 20±2 °C and 65 ±3 % relative humidity until they reached their constant weights.

Methods

Determination of strength properties and density of wood

The bending strength, the moduli of elasticity in bending, the impact bending, and the compression strength tests were performed according to ISO 3133 (1975), ISO 3349 (1975), ISO 3348 (1975), and ISO 3787 (1976), respectively. The density of the specimens was determined according to ISO 3131 (1975).

Dielectric measurement

Following the mechanical tests, one specimen was cut from each timber piece for dielectric measurement using mechanical tests. The dimensions of the specimens used were dependent on the internal dimensions of the waveguide section. The test specimens were bar-shaped and fitted exactly in the opening at the end of the waveguide, where contact between the specimen and the short circuit plate occurred. The dimensions of the specimens were as close as possible to 2.28×1.02×1.03 cm^3. A total of 140 specimens, 35 from each mechanical property test, were tested for relationships between each property and dielectric parameters. Before dielectric measurement, the specimens were again placed in a climate room holding a temperature of 20 ±2 °C and 65±3 % relative humidity until they reached their constant weights. By regular control of the weight, the specimens that had already reached their equilibrium moisture content were selected and weighed and then the measurements were carried out. The measurements were made at room temperature (20 to 24 °C).

The dielectric properties of the test materials were determined by means of a slotted waveguide and standing wave ratio meter (SWR meter). The apparatus is represented schematically in Fig. 1. The microwave frequency was kept constant at 9.8 GHz in the X-band region. This frequency was chosen because of its importance in potential applications. The method was based upon Von Hippel's transmission line method for low loss dielectric materials (Chatterjee 1988). The test specimens were placed in the extremity of the waveguide, represented in Fig. 2.

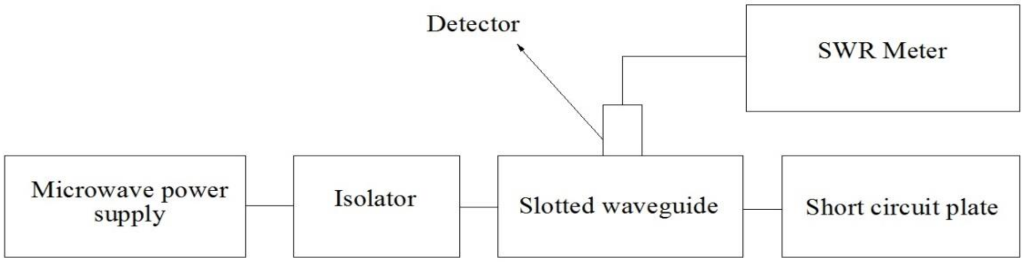

Fig. 1. Equipment used for the determination of the dielectric properties of specimens

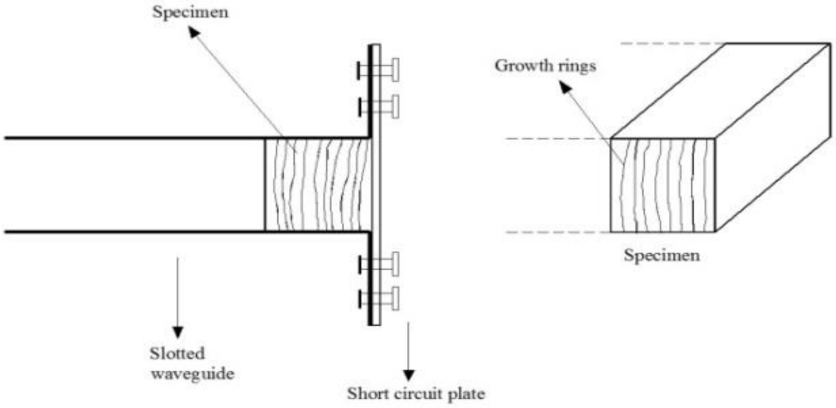

Fig. 2. Placement of the test specimens in the waveguide

After conducting the measurements, the air-dry density of the specimen was determined after calculation of the air-dry volume and weight. The microwave data were worked up with an ordinator after the dielectric characteristics of each sample were printed out.

Data analyses

The data were analyzed using linear regression generated using IBM SPSS Statistics 19. The regression analysis was used to develop a mathematical model for predicting mechanical properties using dielectric parameters.

RESULTS AND DISCUSSION

The results of the modulus of elasticity, strengths, and dielectric properties at 9.8 GHz of fir and oak are given in Table 1.

The dielectric constant, loss factor, and loss tangent were compared directly with the corresponding mechanical properties and the density. Statistical correlation analyzed by linear regression was used to examine the relationship between the dielectric parameters and the mechanical properties and density. This study was done with samples carefully controlled to a certain relative humidity, which ought to minimize uncontrolled variations in moisture content. The moisture content of samples were 11.4 (variance coefficient: 0.02) or fir and 12.8 (variance coefficient: 0.03) for oak (Table 1). Since the variance coefficients of samples were rather slow, the moisture content was not included as another term in the model.

Table 2 shows the results of regression analysis. The results graphically represented in Figs. 3 to 5 were obtained by testing different equations by using "curve estimation" with IBM SPSS 19 and taking the best fit to the experimental values. Linear equations of type $y = a + bx$ provided the best fitted curves for the experimental data for dielectric parameters and mechanical properties. There were good correlations between the dielectric parameters and strength properties and density, especially for oak. Fir showed relatively poor correlations with dielectric parameters and mechanical properties when compared to oak (Table 2). The relationships between the dielectric constant and strength properties and density were higher than that of the loss factor and of loss tangent.

Table 1. Results of the Density, Modulus of Elasticity, Strengths, and Dielectric Properties of Specimens ^{a}

	Fir			Oak		
Wood Properties	Mean	(SD)^b	Range	Mean	(SD)	Range
Moisture Content (%)	11.4	(0.239)	11.0-12.0	12.8	(0.34)	11.8-12.9
Density (g/cm^3)	0.394	(0.021)	0.350-0.440	0.694	(0.093)	0.510-0.860
Modulus of Elasticity (N/mm^2)	5355.7	(747.7)	3823.2-6827.0	8474.8	(1280.1)	6254.7-10799.6
Modulus of Rupture (N/mm^2)	56.9	(4.8)	48.2-66.2	91.4	(14.8)	67.2-115.1
Compression Strength (N/mm^2)	38.1	(3.1)	31.1.0-43.2	52.3	(7.2)	40.1-63.8
Impact Bending Strength (kpm/cm^2)	0.26	(0.04)	0.18-0.33	0.45	(0.16)	0.25-0.78
Dielectric Constant	1.805	(0.154)	1.55-2.04	3.010	(0.307)	2.35-2.35
Dielectric Loss Factor	0.120	(0.029)	0.08-0.27	0.408	(0.077)	0.24-0.54
Dielectric Loss Tangent	0.064	(0.007)	0.05-0.08	0.133	(0.015)	0.10-0.16

^{a} Number of specimens measured (n) was 35
^{b} Mean: Arithmetic mean, SD: Standard Deviation

Figure 3 shows the relationship between the dielectric constant and the corresponding mechanical strength of fir and oak wood. A linear positive correlation was observed between the dielectric constant and the mechanical properties. The coefficients of determination (R^2) between dielectric constant and MOR, MOE, IBS, and CS were found to be 0.46, 0.35, 0.36, and 0.35 for fir and 0.78, 0.74, 0.65, and 0.69 for oak, respectively.

Figure 4 shows the relationship between the dielectric loss factor and the corresponding mechanical strength and density of fir and oak wood. The dielectric loss factor displayed slightly lower correlations with the mechanical properties than the dielectric constant. The coefficients of determination (R^2) between the dielectric loss factor and MOR, MOE, IBS, and CS were 0.45, 0.42, 0.29, and 0.33 for fir and 0.76, 0.71, 0.59, and 0.68 for oak, respectively.

Figure 5 shows the relationship between the dielectric loss tangent and the corresponding mechanical strength of fir and oak wood. The coefficients of determination (R^2) between the dielectric loss tangent and MOR, MOE, IBS, and CS were 0.40, 0.34, 0.24, and 0.22 for fir and 0.63, 0.59, 0.55, and 0.55 for oak, respectively. Although the useful relationships were determined between mechanical properties and the dielectric loss tangent for oak, the loss tangent of fir displayed weak correlations with mechanical properties.

Table 2. Results of Linear Regression Analysis (*y* = *a* + *bx*)

		Fir				**Oak**			
Independent variables (x)	Dependent variables (y)	R^2	F	*a*	*b*	R^2	F	*a*	*b*
Dielectric Constant	MOR	0.46	28.81	18.885	21.106	0.78	119.79	-40.690	43.238
	MOE	0.35	17.78	200.635	2855.140	0.74	86.61	-2546.17	3605.045
	IBS	0.36	18.52	-0.005	0.143	0.65	63.36	-1.067	0.504
	CS	0.35	18.40	16.565	11.59	0.69	76.71	2.526	16.795
	D	0.74	94.21	0.169	0.123	0.79	124.54	-0.322	0.331
Loss Factor	MOR	0.45	27.68	35.378	189.833	0.76	109.58	29.327	153.706
	MOE	0.42	24.16	2108.18	28520.38	0.71	82.44	3275.872	12854.19
	IBS	0.29	13.40	0.154	0.926	0.59	49.38	-0.358	1.928
	CS	0.33	16.43	32.638	42.300	0.68	71.56	23.392	72.493
	D	0.56	41.99	0.280	0.971	0.78	119.04	0.211	1.181
Loss Tangent	MOR	0.40	22.24	24.744	522.196	0.63	57.53	-5.856	742.850
	MOE	0.34	17.27	706.070	72288.62	0.59	47.44	338.714	62084.27
	IBS	0.24	10.84	0.055	3.157	0.55	40.74	-0.943	10.144
	CS	0.22	9.67	25.223	197.141	0.55	40.51	4.782	357.081
	D	0.46	28.61	0.230	2.589	0.64	59.346	-0.057	5.688
Density	MOR	0.73	93.60	-15.701	186.223	0.93	495.29	3.940	127.167
	MOE	0.65	61.23	-5281.5	27249.67	0.84	181.59	1258.311	10481.50
	IBS	0.73	92.23	-0.374	1.601	0.81	146.71	-0.786	1.772
	CS	0.66	64.57	-8.391	117.465	0.82	190.03	-0.290	75.589

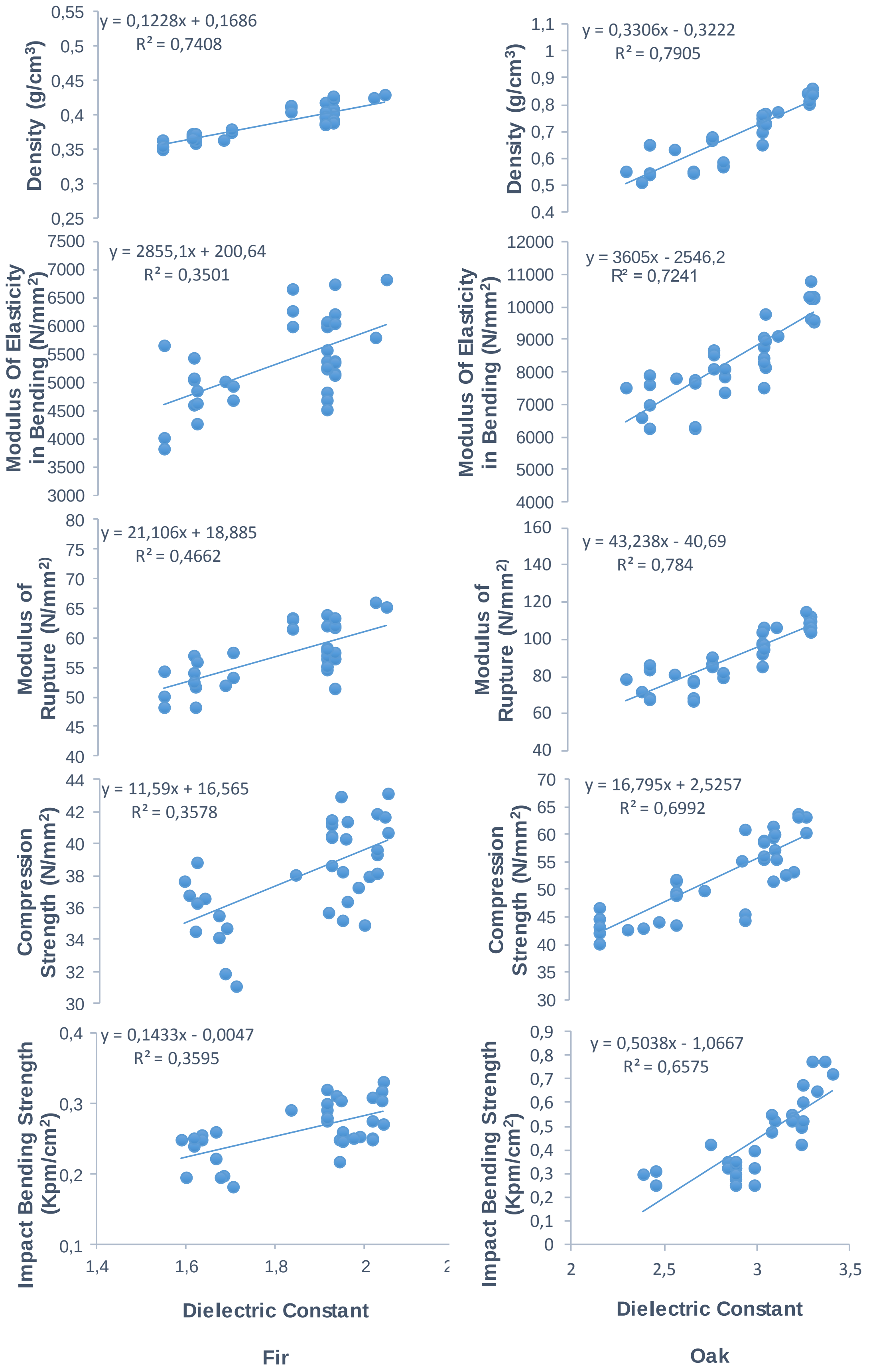

Fig. 3. Relationship between the dielectric constant and the mechanical properties

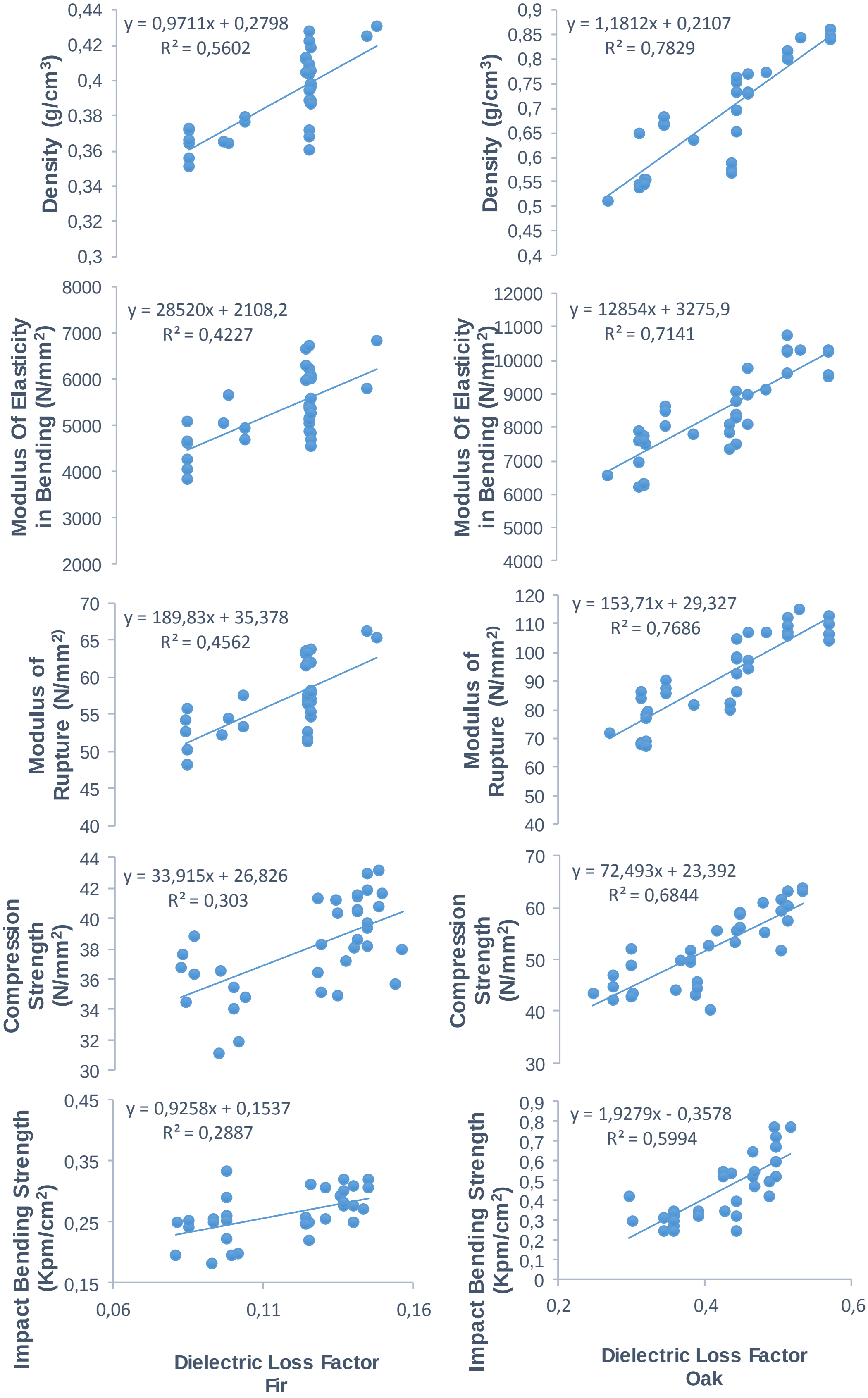

Fig. 4. Relationship between the dielectric loss factor and the mechanical properties

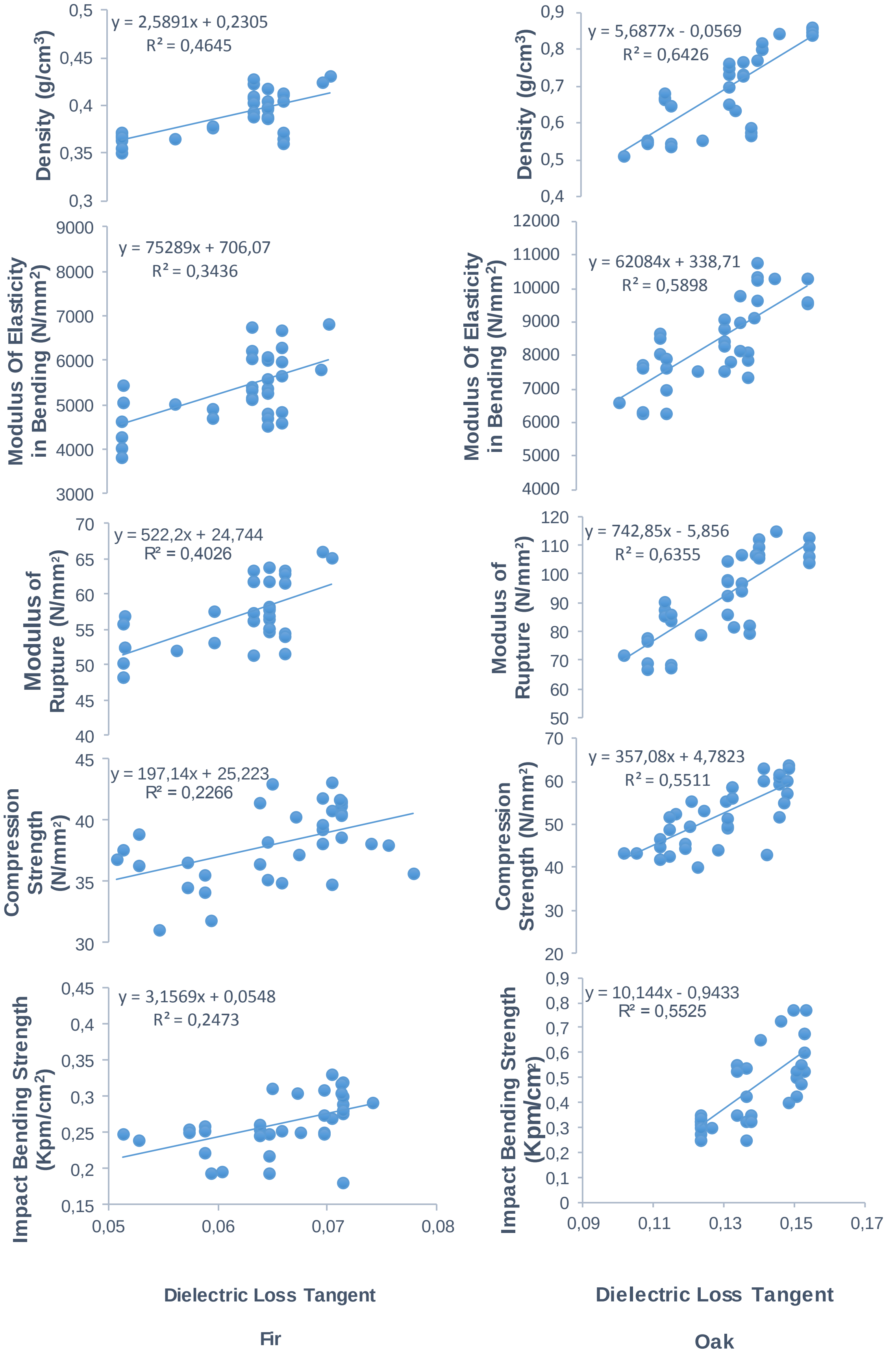

Fig. 5. Relationship between the dielectric loss tangent and the mechanical properties

The regression analyses demonstrated that the best relationships were observed between the dielectric parameters and MOR. However, the correlations between the dielectric parameters and MOE were still very high but less significant than MOR. Good correlations were also determined between IBS and the dielectric constant, loss factor, and loss tangent, but they were still inferior to the results for MOR and MOE. The correlations between CS and the dielectric constant, loss factor, and loss tangent were similar to the correlation of IBS.

The relationship between the dielectric parameters and the strength properties were found to be similar to the density-strength relationships, albeit slightly lower (Table 2). This was expected, due to a very strong correlation between the density and the dielectric parameters (Table 2). The correlation coefficient (R^2) between the density and MOR, MOE, IBS, and CS were 0.73, 0.65, 0.73, and 0.66 for fir and 0.93, 0.84, 0.81, and 0.82 for oak (Table 2), respectively. The existence of a linear relationship between wood density and strength has been demonstrated by several investigators (O'Sullivan 1976). Similarly, it has been found that within the range of density found in most species, an approximately linear relationship exists between strength and specific gravity. Cown *et al.* (1992) reported that the density of wood is recognized as the key factor influencing wood strength. According to Schniewind (1989), much of the variation in wood strength, both between and within species, can be attributed to differences in wood density.

The correlations between the dielectric constant and density were also very strong, with the R^2 0.74 for fir and 0.79 for oak (Fig. 3). The relationships between the dielectric loss factor and density, with R^2 of 0.56 for fir and 0.78 for oak (Fig. 4), were a bit lower than that between the dielectric constant and density. The coefficients between the loss tangent and density (0.46 for fir and 0.64 for oak) (Fig. 5) were similar to or smaller than the values obtained for the loss factor. A positive linear relationship between density and dielectric parameters has been explained in previous studies (Peyskens *et al.* 1984; Jain and Dubey 1988; Şahin 2002; Ay and Şahin 2004). Dense woods have a higher solid volume and a correspondingly lower air volume than less dense woods. When an alternating voltage is applied to a dielectric, the molecules tend to align themselves with the field, and the movement depends on the internal binding forces in the material (Vermaas *et al.* 1974). There are fewer polar groups in less dense woods, meaning that the dielectric properties of less dense woods are lower than those of denser woods (Ay and Şahin 2004).

As can be seen from the above results, fir showed poor correlations with dielectric parameters and mechanical properties relative to oak (Table 2). The results indicated that the general trends of the dielectric and mechanical properties of the wood species is identical to trends of density variation. The greater coefficients in oak may be explained by the higher variation in density within the oak samples themselves, which were 0.510 to 0.860 for oak and 0.350 to 0.440 for fir (Table 1). This is an indication that the weaker relationships between the dielectric parameters and mechanical properties of fir wood were mainly the result of the lower variability of density within the fir samples. Also, it can be seen that, for fir wood, the dielectric parameters displayed considerably lower correlation with strength than with density (Table 2). In this context, it can be claimed that the relationship between the strength and dielectric parameters of wood found in this study were strongly related to the density-strength relationship as well as the intrinsic characteristics of the species. It can therefore be said that the differences in the behavior of wood species may be related to one or more of their specific characteristics. Among these, the density and ultramicroscopic structure of wood may be decisive. Observation confirms the data found in the literature on this subject. Lundgren (2007) and Lundgren *et al.* (2007) concluded that microwave signals, after transmission through wood, contain information about the bending strength and the modulus of elasticity mainly from the correlation to density, but also from the influence of structural variations in the wood on microwaves.

Since the correlation between the dielectric parameters and the density of the wood was very high, it may be concluded that the correlations between the dielectric parameters and the strength or stiffness properties were caused by the density-strength relationship of the wood; therefore it can be said that the relationship between the dielectric parameters and the wood strength is mainly governed by the density-strength relationship. It should be pointed out, however, that when the coefficients of determination between the density and strength and those between the dielectric parameters and strength are compared (Table 2), it can be seen that the dielectric parameters had a relatively lower correlation with the strength than the density, especially for fir wood. The reasons for these results are attributable to the effects of the properties of cell walls, the macrostructure of each wood species, such as the arrangement of the cell wall and lumen, the specific molecular structure of the cell walls, and the anisotropy of the cell wall substances of each wood species on the dielectric and strength properties because the effects of the wood strength factors can be different or similar to dielectric properties. The dielectric behaviors of wood are markedly influenced by the ultrastructure (chemical composition, micro fibril angle existing in the middle lamella of the secondary wall of cells and crystalline region of cellulose, *etc.*) and macrostructure of wood species (Norimoto 1976; Torgovnikov 1993). The arrangement of the wood polymers and macrostructure also influences the strength properties of the cell wall (Bergander and Salmén 2002; Gindl and Teischinger 2002; Oh 2011; Hein and Lima 2012; Hein *et al*. 2013; Zhang *et al.* 2013).

CONCLUSIONS

1. Good correlations were found between the dielectric parameters and strength properties, especially for oak wood.
2. The relationships between the dielectric constant and strength properties were higher than that of the loss factor and of loss tangent.
3. The best relationships were observed between the dielectric parameters and MOR. However, the correlations between the dielectric parameters and MOE, CS, and IBS were still very high.
4. The results showed that density had a large effect on the relationship between the dielectric parameters and wood strength. The effect was comparable to that of the type of wood and the variation in density within a wood species. It was also observed that the characteristics of wood species, such as ultrastructure and chemical composition *etc*., may be another factor that governs these relationships.
5. The results indicated that wood strength prediction through the use of dielectric parameters seems possible and that the dielectric constant had a higher degree of precision than the loss tangent and loss factor.
6. As wood is an inhomogeneous material, there can be discontinuities in density (defects etc.), and moisture content. Discontinuities in the material may result in a huge deviation of predictions from the real values. Also, temperature is another factor that

appeared to impose limitations on the use of dielectric parameters as predictors of wood strength. Such issues tend to make microwave analysis approach less reliable for routine testing. Further work is required before this can be realized in a measurement system.

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REFERENCES CITED

Bergander, A., and Salme´n, L. (2002). "Cell wall properties and their effects on the mechanical properties of fibers," *J. Mater. Sci.* 37, 151-156. DOI: 10.1023/A: 1013115925679

Bogosanović, M., Anbuky, A. A., and Emms, G. W. (2013). "Microwave nondestructive testing of wood anisotropy and scatter," *IEEE Sensors J.* 13(1), 306-313. DOI: 10.1109/JSEN - 2012.2211192.

Bogosanović, M., Anbuky, A. A., and Emms, G. W. (2010). "Overview and comparison of microwave noncontact wood measurement techniques," *J. Wood Sci.* 56(5), 357-365. DOI: 10.1007/s10086-010-1119-0.

Bogosanović, M., and Emms, G. W., (2014). "Utilizing wave polarization in microwave characterization of heterogeneous anisotropic materials with application to the wood industry," In: *Proceedings of the 8th International Conference on Sensing Technology*, Sep. 2-4, Liverpool, UK.

Bucur, V. (2003). *Nondestructive Characterization and Imaging of Wood*, Springer Verlag, Berlin. DOI: 10.1007/978-3-662-08986-6.

Chatterjee, R. (1988). *Advanced Microwave Engineering Special Advanced Topics*, Ellis Horwood, Chichester, England. ISBN-13: 978-0130045324.

Choffel, D., Goy, B., Martin, P., and Gapp, D. (1992). "Interaction between wood and microwaves–automatic grading application," in: *1st International Seminar on Scanning Technology and Image Processing on Wood*, Luleå University, Skellefteå, Sweden, 1-8.

Cown, D. J., Young, G. D. and Burdon, R. D. (1992). "Variation in wood characteristics of 20 year old half - sib families of *Pinus radiata*," *New Zealand Journal of Forestry Science* 22(1) 63-76. DOI: 10.1007/s11295-013-0639-3.

Denzler, J., and Weidenhiller, A. (2015). "Microwave scanning as an additional grading principle for sawn timber," *Eur. J. Wood Prod.* March, 1-9. DOI: 10.1007/s00107-015-0906-0.

Denzler, J. K., Koppensteiner, J., and Arthaber, H. (2013). "Grain angle detection on local scale using microwaves," *Int. Wood Prod. J.* 4(2), 68-74. DOI: 10.1179/2042645313Y.0000000030.

Denzler, J. K., Lux, C., and Arthaber, H. (2014). "Contactless moisture content and density evaluation of sawn timber using microwave transmission," *Int. Wood Prod. J.* 5(4), 200-206. DOI: 10.1179/2042645314Y.0000000066.

Gindl, W., and Teischinger, A. (2002). "Axial compression strength of Norway spruce related to structural variability and lignin content," *Composites Part A Applied Science and Manufacturing* 33 (12), 1623-1628. DOI: 10.1016/S1359-835X(02)00182-3.

Green, D. W., Link, C. L., DeBonis, A. L., and McLain, T .E. (1986). "Predicting the effect of moisture content on the flexural properties of southern pine dimension lumber," *Wood and Fiber Science* 18(1), 134-156.

Hansson, L., Lundgren, N., Antti, L. and Hagman, O. (2005). "Microwave penetration in wood using imaging sensor," *Journal of International Measurement Confederation* 38(1), 15-20. DOI: 10.1016/j.measurement.2005.03.007.

Heikkila, S., Jakkula, P., and Tiuri, M. (1982). "Microwave methods for strength grading of timber and for automatic edging of boards," in: *Proceedings of the 12th European Microwave Conference*, 599-603. DOI: 10.1109/EUMA.1982.333126.

Hein, P. R. G., and Lima J. T. (2012). "Relationships between microfıbril angle, modulus of elasticity and compressive strength in *Eucalyptus* wood," *Maderas.Ciencia y Tecnología* 14(3), 267-274. DOI: 10.4067/S0718-221X2012005000002.

Hein, P. R. G., Silva, J. R. M., and Brancheriau, L. (2013). "Correlatıons among mıcrofıbrıl angle, densıty, modulus of elastıcıty, modulus of rupture and shrınkage ın 6-year-old *Eucalyptus urophylla* × *E. grandis*," *Maderas. Ciencia y Tecnología* 15(2), 171-182. DOI: 10.4067/S0718-221X2013005000014

Horáček, P., Tippner, J., and Hassan, K. T. (2012). "Nondestructive evaluation of static bending properties of scots pine wood using stress wave technique," *Wood Research* 57(3), 359-366.

ISO 3133. (1975). "Wood- Determination of ultimate strength in static bending," International Organization for Standardization, Geneva, Switzerland.

ISO 3348 (1975). "Wood -- Determination of impact bending strength," International Organization for Standardization, Geneva, Switzerland.

ISO 3349. (1975). "Wood - Determination of modulus of elasticity in static bending," International Organization for Standardization, Geneva, Switzerland.

ISO 3787. (1976). "Wood - Test methods -- Determination of ultimate stress in compression parallel to grain," International Organization for Standardization, Geneva, Switzerland.

ISO 3131. (1975). "Wood - Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

Jain, V. K., and Dubey, Y. M. (1988) "Dielectric constant of some Indian timbers in axial direction at microwave frequencies," *J. Ind. Acad. Wood Sci.* 19, 25-36.

James, W. L., Yen, Y. H., and King, R. J. (1985). *A microwave method for measuring moisture content, density and grain angle of wood*, Forest Products Laboratory Research Note FPL-0250, 1-9.

Jayne, B. A. (1959). "Vibrational properties of wood as indices of quality," *Forest Products Journal* 9(11), 413-416.

Johansson, J., Hagman, O., and Fjellner, B. A. (2003). "Predicting moisture content and density distribution of scots pine by microwave scanning of sawn timber," *J. Wood Sci.* 49(4), 312-316. DOI: 10.1007/s10086-002-0493-7.

King, R. J. and Yen, H. (1981). "Probing amplitude, phase, and polarization of microwave field distributions in real time," *IEEE Transactıons on Mıcrowave Theory and Technıques* 29(11), 1221-1231.

Koubaa, A., Perré, P., Hutcheon, R. M., Lessard, J. (2008). "Complex dielectric properties of the sapwood of aspen, white birch, yellow birch, and sugar maple," *Drying Technology* 26, 568-578. DOI:10.1080/07373930801944762.

Leicester, R. H. and Seath, C. A. (1996) "Application of microwave scanners for stress grading," in: *4th International Wood Engineering Conference,* New Orleans, USA, Vol. 2, 435-440.

Lundgren, N. (2005). *Modelling Microwave Measurements in Wood,* Licentiate Thesis, Division of Wood Science and Technology Skellefteå Campus Luleå University of Technology Skeria 3, SE-931 87 Skellefteå, Sweden.

Lundgren, N. (2007). *Microwave Sensors for Scanning of Sawn Timber,* Doctoral Thesis, Lulea University of Technology, Skelleftea, Sweden.

Lundgren, N., Brännström, M., Hagman, O., and Oja, J. (2007). "Predicting the strength of Norway spruce by microwave scanning: A comparison with other scanning techniques," *Wood and Fiber Science* 39(1), 167-172.

Lundgren, N., Hagman, O. and Johansson, J. (2006). "Predicting moisture content and density distribution of Scots pine by microwave scanning of sawn timber II: Evaluation of models generated on a pixel level," *J. Wood Sci.* 52(1), 39-43. DOI: 10.1007/s10086-005-0724-9

Madsen, B. (1975). "Moisture content – strength relationship for lumber subjected to bending," 2(4), 466-473.

Norimoto, M. (1976). "Dielectric properties of wood," *Wood Research* 59/60, 106-152.

Oh, S. W. (2011). "Relationship between anatomical properties and modulus of rupture (MOR) of *Larix kaempferi* Carr.," *J. Agric. Life Sci.* 45(1), 9-14.

O'Sullivan, P. (1976). "The influence of initial espacement and thinning regime upon wood density in Sitka spruce (*Picea sitchensis* (Bong.) Carr)," M. Agr. Sc. Thesis, University College Dublin, Dublin, Ireland.

Peyskens, E., Pourcq, M., Stevens, M., and Schalck, J. (1984). "Dielectric properties of softwood species at microwave frequencies," *Wood Sci. Technol*. 18, 267-280. DOI: 10.1007/BF00353363.

Ross, R. J., and Pellerin, R. F. (1994). *Nondestructive Testing for Assessing Wood Members in Structures, a Review*, Gen. Tech. Rep. FPL-GTR-70, Madison, WI. Department of Agriculture, Forest Service, Forest Products Laboratory, 1-40.

Ruud, C. O., Bussiere, J. F., and Green, R. E. (1991). *Nondestructive Characterization of Materials IV,* Plenum Press, New York.

Schajer, G. S., and Orhan, F. B. (2006). "Measurement of wood grain angle, moisture content and density using microwaves," *Holz Roh Werkst.* 64(6), 483-490. DOI: 10.1007/s00107-006-0109-9.

Schniewind, A.P. (1989). *Concise Encyclopedia of Wood and Wood-Based Materials,* Pergamon Press, Oxford, UK. ISBN-13: 978-0080347264.

Shen, J., Schajer, G.S., and Parker, R. (1994). "Theory and practice in measuring wood grain angle using microwaves," *IEEE Trans Instrum. Meas.* 43, 803-809. DOI: 10.1109/19.368063.

Şahin, H. (2002). *Dielectric Properties of Natural and Impregnated Wood Species at Microwave Frequencies.* Ph.D. Thesis, Karadeniz Technical University, Trabzon.

Şahin, H., and Ay, N. (2004). "Dielectric properties of hardwood species at microwave frequencies," *J. Wood Sci.*50, 375-380. DOI: 10.1007/s10086-003-0575-1.

Şahin, and Ay, N. (2004). "Dielectric constant of Turkish timbers in the longitudinal direction at a 9.8 GHz frequency," *Forest Products Journal* 54(10), 65-68.

Tiuri, M., Jokela, K., and Heikkila, S. (1980). "Microwave instrument for accurate moisture and density measurement of timber," *J. Microwave Power* 15, 251-254. DOI: 10.1109/EUMA.1979.332663.

Torgovnikov, G. I. (1993). *Dielectric Properties of Wood and Wood- Based Materials*. Springer, Heidelberg. ISBN: 978-3-642-77455-3.

Vermaas, H. F., Pound, J., and Borgin, K. B. (1974). "The loss tangent of wood and its importance in dielectric heating," *South African Forestry Journal* 89(1), 5-8.

Zhang, S. Y., Wang, C. G, Fei, B. H., Yu, Y., Cheng, H. T., and Tian, G. L. (2013). "Mechanical function of lignin and hemicelluloses in wood cell wall revealed with microtension of single wood fiber," *BioResources* 8(2), 2376-2385. DOI: 10.15376/biores.8.2.2376-2385

Zhou, H., and Zhong, Y. (2012). "Relationship between temperature and bending properties of Chinese larch wood," in: *Biobase Material Science and Engineering (BMSE), 2012 International Conference*, Changsha, 250-253, DOI:10.1109/BMSE.2012. 6466223.

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