

Thermal Treatment, Moisture Content, and Vibration Direction's Effect on Dynamic Properties of Spruce Wood (*Picea abies*) for Musical Instruments

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The article examines the main and interactive effects of thermal modification (TM), relative humidity (RH), and direction of vibration on the density, modulus of elasticity (MOE) and shear modulus of spruce wood. Samples were thermally modified at 180, 200, and 230 °C and then equilibrated at 20%, 44%, 76%, and 88% RH. The MOE in the longitudinal direction and the shear moduli G_{LR} and G_{LT} were calculated from the natural frequencies of the first three lateral vibration modes of free-free specimen. E_{L-R} and G_{LR} were determined from the vibration frequencies when the specimens vibrated laterally in the longitudinal-radial plane, while E_{L-T} and G_{LT} were determined from vibration frequencies when the specimens vibrated in longitudinal-tangential plane. Density, MOE, and shear moduli decreased at the highest TM level by averages of 16%, 9.8% and 9.7%, respectively. Acoustic coefficients such as the sound velocity (c), the sound radiation coefficient (R) and the characteristic acoustic impedance (ACE) were determined. On average, c and R increased as a function of RH from 1% to 3% and from 10% to 15%, respectively, while ACE decreased from 7% to 13%. The test material was classified for making soundboards for musical instruments.

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INTRODUCTION

Literature Overview

Wood is an anisotropic material, although under certain conditions it can be considered orthotropic, with main properties in longitudinal (L), radial (R), and tangential directions (T) when the 3 mutual perpendicular axis are aligned with LRT direction (Kollmann and Côte 1975). The mechanical properties therefore differ considerably in these directions, with the difference between the longitudinal direction and the other two directions being the greatest. Usually, the elastic properties can be considered the same in the tensile and compressive directions and may exhibit non-linear behavior depending on the stress level, while the strength properties in the compressive direction differ from those in the tensile direction. Wood is also a hygroscopic material, such that the moisture content of the wood plays a vital role in the mechanical properties, as the mechanical properties of wood generally decrease with increasing moisture content (Brémaud and Gril 2021).

As wood is a natural biological material, it is also susceptible to insect attack and biological decomposition. Among the environmentally sustainable methods for

wood protection, thermal modification is increasingly used, which not only protects the wood against insect and mold attack, but also reduces the hygroscopicity and mechanical properties of the wood (Militz and Altgen 2014; Spear *et al.* 2021; Goli *et al.* 2023; Merhar *et al.* 2023). However, because the change in mechanical properties depends on the degree of thermal modification, many studies have investigated the effects of thermal modification on various mechanical properties (Zelinka *et al.* 2022).

The effects of the degree of thermal modification of Norway spruce and sycamore maple on the modulus of elasticity (MOE), density, and damping of the wood and calculated various acoustic parameters were studied by Danihelová *et al.* (2022). They modified the samples with three different degrees of modification and then equilibrated the samples at an equilibrium moisture content (EMC). They found that the density decreased and the MOE and specific MOE increased with the degree of thermal modification (TM). However, the statistical analysis showed that the thermal modification had no significant influence on these properties. They also found that the speed of sound c , damping ζ , the sound radiation coefficient R , the impedance z , and the acoustic conversion efficiency (ACE) increased with the degree of thermal modification. Ahmed and Adamopoulos (2018) investigated the effects of several different types of modifications for different tree species and the effects of relative humidity (RH) on the MOE, density, and damping of wood, while also determining the acoustic indicators. It was found that the different modifications had a significant effect on wood density and damping, while they had no significant effect on the modulus of elasticity.

The influence of temperature and time of exposure to thermal treatment on the MOE and density of ash wood was investigated by Andor and Lagaña (2018). The study showed a significant influence of time and temperature on MOE and density. The density decreased with the degree of modification, while the MOE first increased and then decreased.

The elastic and strength properties of thermally modified beech and birch wood were investigated by Boruvka *et al.* (2018). Like all other researchers, they found a decrease in density with thermal modification, while for the modulus of elasticity they found first an increase and then a decrease for beech and an increase in modulus with the degree of thermal modification for birch. Similarly, Arnold (2010) found an initial increase and then a decrease in the MOE with the degree of modification for spruce, while the decrease in MOE of thermally modified spruce was also confirmed by Buchelt *et al.* (2023).

The decrease in MOE with thermal modification at different rates and durations has also been observed by other researchers who have studied these effects in different tree species (Molinski *et al.* 2018; Wang *et al.* 2018; Nhacila *et al.* 2020; Kaymakci and Bayram 2021; Birinci *et al.* 2022; Kurul and Görgün 2022; Merhar *et al.* 2023; Nakagawa *et al.* 2024; Perçin *et al.* 2024; Aytin 2025; Shen *et al.* 2025).

In addition to knowledge of the basic elastic properties, the various acoustic factors calculated from the modulus of elasticity and density are also important for evaluating the suitability of different woods for the manufacture of musical instruments (Bucur 1995; Wegst 2006; Ahmed and Adamopoulos 2018; Merhar and Humar 2020; Da Silva Ribeiro *et al.* 2021; Danihelová *et al.* 2022). Apart from the fact that different woods have different mechanical properties, these can also be altered by thermal modification, so it is possible to influence the usability of a particular wood species that may have a fundamentally limited usability.

Theory of Resonance Vibration Modes in Beams

Engineering constants of wood can be determined in many ways, with static and dynamic methods (Viala *et al.* 2020; Merhar 2024) being the most commonly used. Among the dynamic methods, the resonance method predominates, in which various elastic properties can be determined on the basis of the natural vibrations of the sample in longitudinal, transverse or torsional vibrations.

According to Timoshenko beam theory, the modulus of elasticity and the shear modulus can be determined from the measured natural flexural frequencies of lateral vibration modes, obtained from impulse response of the excited rod. This relation is given by the equation (Thomson and Dahleh 1998),

$$E_x I \frac{\partial^4 z}{\partial x^4} + \rho S \frac{\partial^2 z}{\partial t^2} - \rho I \left(1 + \frac{s E_x}{G_{xz}}\right) \frac{\partial^4 z}{\partial x^2 \partial t^2} + \frac{\rho^2 I s}{G_{xz}} \frac{\partial^4 z}{\partial t^4} = 0 \quad (1)$$

where E_x and G_{xz} are the modulus of elasticity and the shear modulus in the x - z direction of the sample coordinate system according to Fig. 1.a; z is the transverse displacement; I , S and ρ are the moment of inertia, the cross-sectional area and the material density of the beam, respectively; and s is the shear factor, which depends on the geometry of the cross-section and the material properties, in this case a value of 1.2 was used.

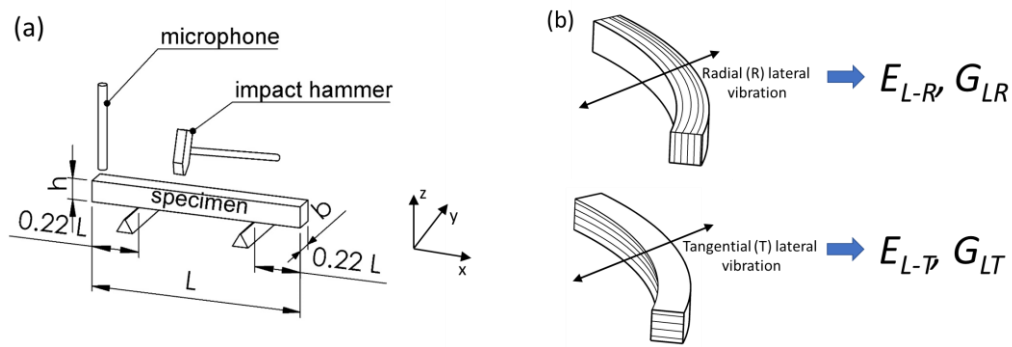


Fig. 1. Experimental setup for determination of engineering constants by resonance method: (a) Excitation, (b) lateral specimen vibration in longitudinal-radial (L-R) and longitudinal-tangential (L-T) vibration plane

The modulus of elasticity and the shear modulus can be calculated by the linear regression of the equation (Brancheriau and Bailleres 2002; Merhar 2020):

$$\frac{E_x}{\rho} - \frac{s E_x}{G_{xz}} \left[Q_f F_2(m) 4 \pi^2 \frac{S L^4 f_i^2}{I P_n} \right] = 4 \pi^2 \frac{S L^4 f_i^2}{I P_n} [1 + Q_f F_1(m)] \quad (2)$$

$$Q_f = \frac{I}{S L^2} \quad (3)$$

$$F_1(m) = \theta^2(m) + 6 \theta(m) \quad (4)$$

$$F_2(m) = \theta^2(m) - 2 \theta(m) \quad (5)$$

$$\theta(m) = m \frac{\tan(m) \tanh(m)}{\tan(m) - \tanh(m)} \quad (6)$$

$$m = \sqrt[4]{P_i} = (2i + 1) \frac{\pi}{2}, i \in N \quad (7)$$

where f_i is the i^{th} flexural natural frequency, and parameters m , $F_1(m)$, $F_2(m)$ and $\theta(m)$ are calculated based on index i for the i^{th} natural frequency.

Based on the vibration plane, modulus of elasticity in longitudinal direction E_{L-R} and the shear modulus G_{LR} are determined from the lateral vibrations of the specimens in the longitudinal-radial vibration plane (L-R) (Fig. 1b), and the modulus of elasticity E_{L-T} and the shear modulus G_{LT} are determined from the vibrations of the specimens in the longitudinal-tangential vibration plane (L-T).

The specific moduli of elasticity and specific shear moduli are calculated from the moduli of elasticity, shear moduli, and densities determined for each sample, whereby the moduli of elasticity and shear moduli are divided by the density of the sample. For the calculation of the acoustic coefficients, the average modulus of elasticity E_L from E_{L-R} and E_{L-T} can be calculated. Acoustic coefficients (Ono and Norimoto 1983) can then be calculated according to Eqs. 8 through 10:

$$c = \sqrt{\frac{E_L}{\rho}} \quad (8)$$

where c ($\text{m}\cdot\text{s}^{-1}$) is the speed of sound in the longitudinal direction,

$$R = \sqrt{\frac{E_L}{\rho^3}} \quad (9)$$

R ($\text{m}^4\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$) is the sound radiation coefficient,

$$z = c \cdot \rho \quad (10)$$

and z ($\text{MPa}\cdot\text{s}\cdot\text{m}^{-1}$) is characteristic acoustic impedance.

The Aim of the Study

The extensive literature shows that the influence of thermal modification on certain mechanical properties and thus indirectly on the acoustic properties of wood has been intensively researched. Despite the many studies known to the authors, there is no general study on the effect of different levels of thermal modification on the longitudinal MOE, density, and shear moduli for wood equilibrated at different relative humidity and vibrating in the L-T and L-R vibration planes. The aim of the study was therefore to determine a main and interaction effect on the above-mentioned properties and to calculate relevant acoustic parameters, such as the speed of sound c , the sound radiation coefficient R , and the characteristic acoustic impedance z , which can be used to assess the suitability of a particular piece of wood for the manufacture of individual parts of musical instruments.

EXPERIMENTAL

Specimen Preparation

Test samples were made from one board of Norway spruce wood (*Picea abies*) with the dimensions 4000 mm × 290 mm × 55 mm and constant growth ring width. The board was first cut into four pieces of 1 m length (Fig. 2a), of which one piece was untreated (group A) and the other three were thermally treated with the Silvapro method (Rep *et al.* 2012) at three different modification temperatures. The first (group B) was treated at 180 °C, the second (group C) at 200 °C and the last (group D) at 230 °C, with mass losses of 1.8 %, 4.0 %, and 10.6 % respectively. After modification, all pieces

were stored for six months at 22 °C and 65 % relative humidity in climatic chamber to allow the internal stresses to dissipate.

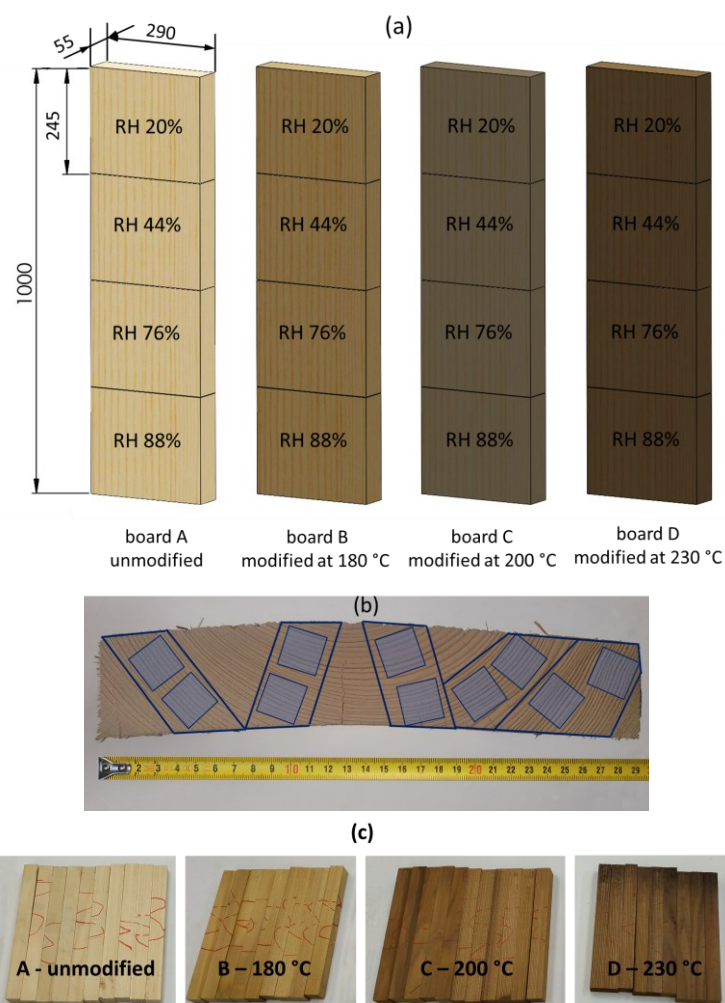


Fig. 2. Specimen preparation: (a) cutting from board, (b) specimen distribution across the board, and (c) prepared specimens

After equilibration, each piece was cut into four smaller pieces of 245 mm in length (Fig. 2b), from which 10 samples of 245 mm × 22 mm × 22 mm were cut. The individual groups of 10 samples were then equilibrated to a constant sample mass at 22 °C and relative humidity (RH) of 20%, 44%, 76%, and 88%. When the samples had reached equilibrium moisture content, they were cut to a final size of 200 mm × 20 mm × 20 mm (Fig. 2c). To determine the exact EMC of the samples, additional samples were prepared for each tested group. Moisture content was determined according to recommendations given in ISO 13061-1 (2014).

Vibration Measurements

The samples were freely supported at a distance of 0.22 L and 0.77 L (Fig. 1a) and excited with a hammer to vibrate freely. Each sample was excited in radial direction (R) and then in tangential direction (T), so that the samples vibrated in longitudinal-radial and longitudinal-tangential vibration planes, respectively. The emitted sound waves, which were the result of excited boards vibrations, were measured using a Bruel & Kjaer (Nærum, Denmark) type 4939 microphone, an NI-USB-6361 (Austin, TX, USA) DAQ card and LabVIEW (Austin, TX, USA) software at a sampling rate of 50 kHz, and an acquisition time of 1 s. For every measured response of each sample, a

fast Fourier transform (FFT) was used to generate frequency spectra of the impulse response of the sample (Fig. 3) with a resolution of 1 Hz, which is sufficient for an accurate calculation of the moduli, as all measured frequencies were higher than 2000 Hz.

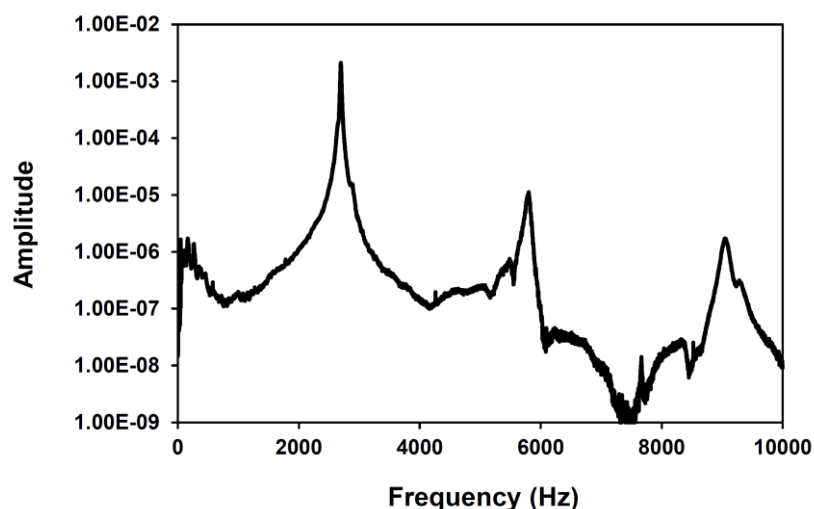


Fig. 3. Averaged frequency spectrum of specimen impulse response

For each combination of variables used in the experiment, 10 measurements were made, resulting in 10 frequency spectra. The spectra were averaged, and the first three natural frequencies were manually extracted and the engineering constants were calculated using Eqs. 2 to 10.

Statistical Analysis

The average and standard deviation of the modulus of elasticity, shear modulus, and density for each group were calculated. An ANOVA test (F -test) was performed using SPSS software to determine the significance of the main factors and their interactions, assuming 5% as the significance level (p -value).

RESULTS AND DISCUSSION

The equilibrium moisture contents (EMC) of unmodified and modified samples at different relative humidities are shown in Table 1. The EMC increased with RH at all thermal modification rates and decreased with thermal modification rate. Similar results have been obtained by several researchers (Arnold 2010; Buchelt *et al.* 2023). The degradation of hemicelluloses started at 120 °C (Poncsák *et al.* 2007; Wang *et al.* 2018), but significant degradation occurred above 180 °C (Sivonen *et al.* 2002; Hakkou *et al.* 2006), which led to a decrease in free hydroxyl groups responsible for hygroscopicity (Hosseinaei *et al.* 2012; Özgenç *et al.* 2017; Wang *et al.* 2018).

Table 1. EMC at Specific RH and Degrees of TM

TM	RH			
	20%	44%	76%	88%
A (unmodified)	7.2	9.9	13.3	19.1
B (modified 180 °C)	5.0	6.6	10.7	16.2
C (modified 200 °C)	4.0	5.7	8.8	11.8
D (modified 230 °C)	3.8	5.7	8.5	10.5

The average measured values and standard deviations for the modulus of elasticity, shear modulus and density are shown in Tables 2 and 3, while Figs. 4 and 5 show the measured modulus of elasticity and shear modulus for all samples together with their densities, respectively. Although the samples were cut from a single board, the range of densities (Table 3, Figs. 4 and 5) for all groups of samples was considerable. Regardless of the degree of thermal modification and RH, an increased trend in MOE with density was clear, with the significant effect of density confirmed by ANOVA analysis ($p = 0.000$), as was the significant effect of RH ($p = 0.000$), while ANOVA did not confirm the significant effect of modification ($p = 0.286$) or the effect of vibration direction ($p = 0.571$) on the MOE.

Table 2. Average Values (Standard Deviations) of MOE in Longitudinal Direction and Shear Modulus of Specimen E_{L-R} , G_{LR} and E_{L-T} , G_{LT} at Different RH and TM (A, B, C, D)

	E_{L-R} (MPa)				E_{L-T} (MPa)			
	RH (%)				RH (%)			
TM	20	44	76	88	20	44	76	88
A	18532	17003	17583	18737	18069	17419	17478	16286
	(2264)	(2733)	(3023)	(659)	(2508)	(2480)	(1928)	(2268)
B	17063	17132	15200	14100	16276	17337	16189	14347
	(1842)	(800)	(1793)	(1617)	(1423)	(1074)	(1355)	(1568)
C	16622	17267	17026	15374	17514	17661	16899	15552
	(1695)	(1666)	(1654)	(2034)	(1454)	(1861)	(1604)	(1500)
D	16889	16193	16008	15055	16983	16269	16168	15707
	(2253)	(622)	(1155)	(2073)	(1315)	(1349)	(1584)	(1376)
	G_{LR} (MPa)				G_{LT} (MPa)			
	RH (%)				RH (%)			
TM	20	44	76	88	20	44	76	88
A	736	760	786	634	798	750	648	629
	(108)	(94)	(176)	(47)	(54)	(48)	(39)	(35)
B	848	779	805	755	979	744	705	755
	(190)	(92)	(105)	(143)	(307)	(123)	(149)	(315)
C	840	828	754	736	783	757	730	687
	(111)	(130)	(111)	(121)	(97)	(64)	(88)	(97)
D	745	730	863	720	668	704	863	649
	(115)	(83)	(124)	(75)	(142)	(61)	(167)	(92)

Table 3. Average Values (Standard Deviations) of Density (in kg/m³) at Different RH and TM (A, B, C, D)

TM	RH (%)			
	20	44	76	88
A	479	475	478	493
	(34)	(36)	(31)	(34)
B	481	442	448	457
	(45)	(25)	(30)	(37)
C	444	452	462	462
	(28)	(26)	(28)	(29)
D	437	426	464	439
	(29)	(23)	(10)	(25)

The increase of shear modulus with density was less pronounced than in MOE, both in the LR and LT directions. However, the ANOVA analysis confirmed a significant effect of relative humidity ($p = 0.000$), density ($p = 0.000$), thermal modification ($p = 0.000$), and vibration direction ($p = 0.003$), as the shear moduli are generally different in the LR and LT directions (Kollmann and Côte 1975).

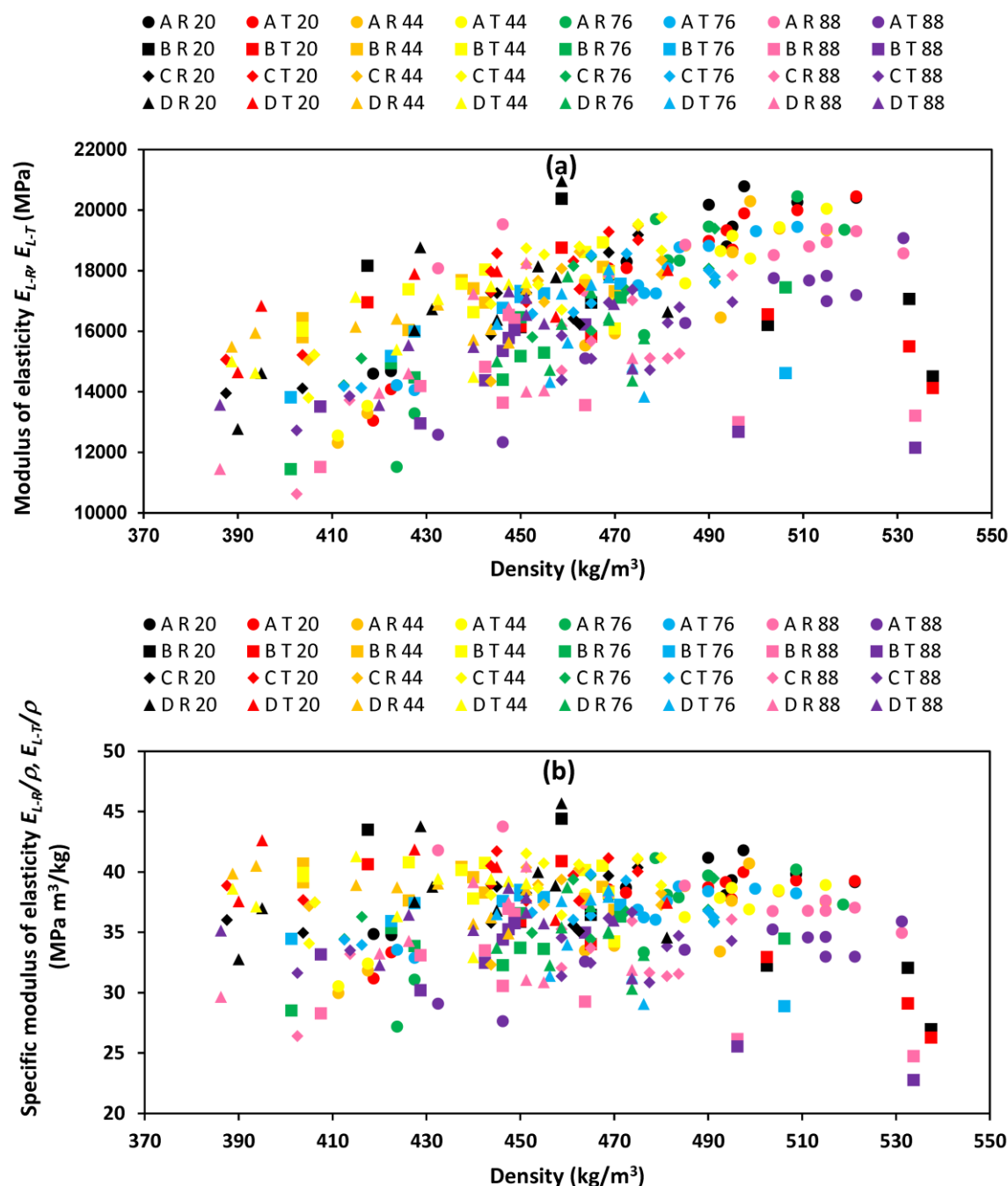


Fig. 4. Modulus (a) and specific modulus (b) of elasticity in longitudinal direction of specimens lateral vibrating in longitudinal-radial (E_{L-R}) and longitudinal-tangential (E_{L-T}) vibration planes together with their densities under various levels of thermal modifications and relative humidities. First letter in legend represents degree of thermal modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C); the second letter represents vibration plane of samples (R – radial for E_{L-R} , T – tangential for E_{L-T}); the number represents RH

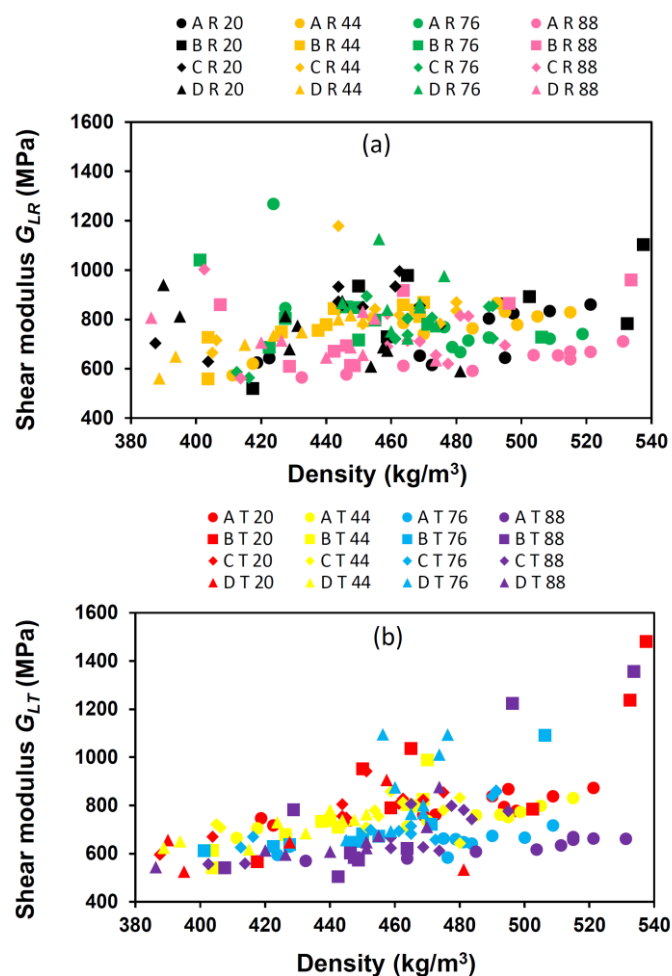


Fig. 5. Shear modulus G_{LR} (a) and G_{LT} (b) with densities of samples under various levels of thermal modification, RH, and vibration directions. First letter in legend represents degree of thermal modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C); the second letter represents vibration direction of samples (R – radial, T – tangential); the number represents RH

Effect of Thermal Modification on Density

The average densities at different RH and modification levels are shown in Fig. 6. The density decreased with the degree of thermal modification, where the ANOVA test showed a significant effect of modification ($p = 0.000$) and RH ($p = 0.009$) on the density. Density increased with RH for all samples, although the increasing trend was different for different degrees of modification, which is also consistent with the literature (Molinski *et al.* 2018; Wang *et al.* 2018; Nhacila *et al.* 2020; Kurul and Görgün 2022; Buchelt *et al.* 2023; Nakagawa *et al.* 2024). The positive trend was pronounced in the unmodified samples, while in group B it was even negative at the beginning. The reason for the different trends is the different initial density of the unmodified samples. As mentioned, all samples were cut from a single board with identical growth rings and no visible defects, but there were still variations in density within the board (Table 3). Therefore, it is likely that the group of samples B at 20% RH had a higher basic density than the group of samples at 44% RH, even though the moisture content of the samples at 44% was higher than at 20%. The same reason applies to the unmodified samples, where the density of the sample group at 44% and 76% was so much lower than at 20% that the effect of the lower initial density was greater than the increase in density due to the increase in wood moisture content. This

problem could be solved by first determining the density of all samples at the same initial RH and then exposing the samples to the target RH.

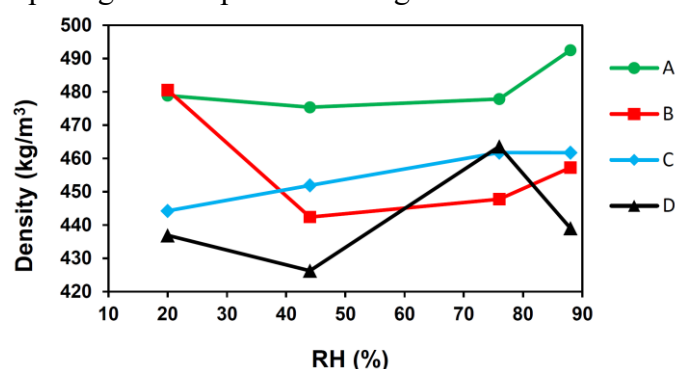


Fig. 6. Average density values at different RH and modification levels (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C)

The effect of the different initial densities can also be seen in Fig. 7, which shows the effect of thermal modification on density, with density decreasing as the degree of thermal modification increases. According to Wang *et al.* (2018), a significant decrease in density begins at 170 °C, where the hemicelluloses begin to degrade and release acetic acid (AA), which increases with increasing temperature and duration of modification, while a higher concentration of AA as a catalyst further accelerates the degradation process. According to González-Peña *et al.* (2009), the mass loss is strongly correlated with a decrease in the proportion of cellulose, holocellulose, and hemicellulose and an increase in the proportion of lignin, and the decrease in mass also depends on the duration of thermal modification. The tendency of decreasing density is therefore observed at all RH, although the decrease in density is greater in the thermal modification of group B than in the thermal modification of group C, which in turn is due to the initially lower basic densities of group B than of group C. A possible solution would be to modify the procedure by first producing samples in the final dimensions, determining their densities and then thermally modifying them. In this way, the effect of the thermal modification on the density change could be accurately determined, but an accurate determination of the elastic modulus and shear modulus would no longer be possible. The thermal modification led to the appearance of both larger and smaller cracks on the surface of the samples. In this case, where a larger sample was modified, this was not a problem as smaller samples were cut from the larger sample, but without the cracked surface. The samples were therefore intact and undamaged, and the elastic and shear moduli determined were realistic. However, in the case of a cracked specimen, the modulus of elasticity and shear modulus would not be accurate.

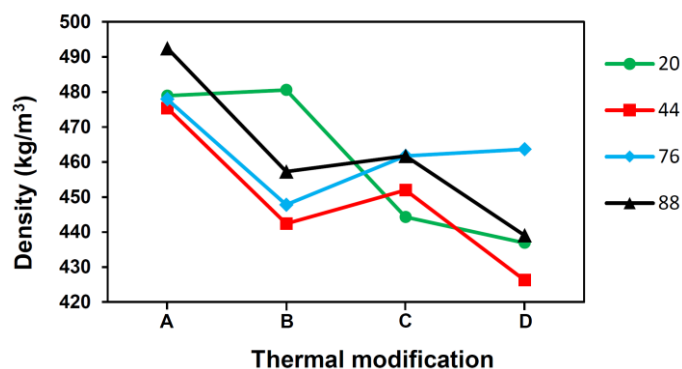


Fig. 7. Average density values at different thermal modification levels and RH (22%, 44%, 76%, and 88%)

Effect of Thermal Modification on Modulus of Elasticity

The mean values of the modulus of elasticity E_{L-R} , E_{L-T} and the specific modulus for each group are shown in Fig. 8, where both the modulus of elasticity and the specific modulus decrease with relative humidity. The decrease in the specific modulus with relative humidity was greater than that of the elastic modulus because the density increased with relative humidity while the modulus decreased with relative humidity. The E_{L-T} determined from the vibrations in the tangential direction was also greater than E_{L-R} determined from the vibrations in the radial direction in most cases, but the ANOVA confirmed no significant effect of direction ($p = 0.571$). Although there were 8 to 9 annual rings per thickness or width in the sample (Fig. 1b), the location of earlywood and latewood still seemed to have an influence on the size of the E_{L-R} and E_{L-T} . For specimens vibrating in the L-T vibration plane, the proportion of earlywood and latewood had the same influence across the thickness, as earlywood and latewood were found in equal proportions in the outer layers, whereas for specimens vibrating in the L-R vibration plane, either earlywood or latewood was present on the outer sides of the samples. However, as the proportion of latewood was much lower than that of earlywood, in most cases there was a higher proportion of earlywood on the outer surfaces of the samples, so that the stiffness was lower. In some samples, however, the outer surface consisted of latewood, resulting in a higher modulus of elasticity determined from the specimens vibrating in the radial direction, as the MOE of latewood can be up to 4 times higher than that of earlywood (Golovin *et al.* 2023).

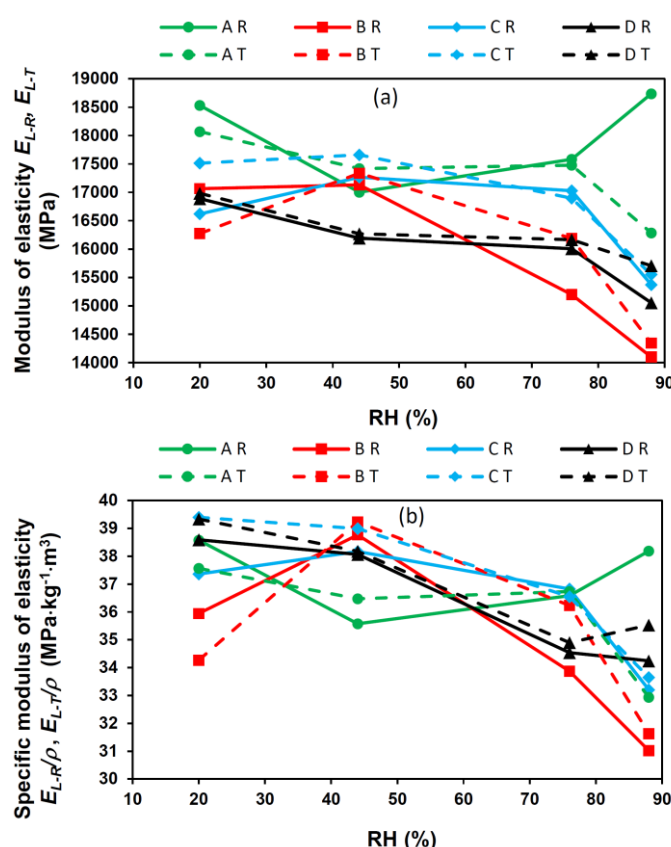


Fig. 8. (a) Modulus of elasticity E_{L-R} , E_{L-T} and (b) specific modulus of elasticity E_{L-R}/ρ , E_{L-T}/ρ at different RH, modification levels and vibration direction. First letter represents level of modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C); the second letter represents vibration plane of samples (R – L-R plane for E_{L-R} , T – L-T plane for E_{L-T})

The effect of thermal modification on the MOE and specific MOE can be better seen in Fig. 9, where the MOE decreased with the degree of thermal modification due to the breaking of hydrogen bonds during TM above 180 °C (Wang *et al.* 2018). Wang *et al.* found that the proportion of cellulose and hemicellulose decreased above 150 °C, while the proportion of lignin increased at the same time. According to González-Peña *et al.* (2009), the decrease in mass was associated with a decrease in cellulose content, and there was also damage to the crystalline cellulose, which is associated with a decrease in the MOE in the longitudinal direction (Bergander and Salmen 2000; Wang *et al.* 2018). Similar to density (Fig. 7), the decrease in MOE was greater in B level of TM than in level C. However, this does not mean that the modification level B had a greater influence on the decrease of MOE than level C. Rather, the reason lies in the lower base density of the samples in group B than in group C, because the MOE is strongly correlated with the density.

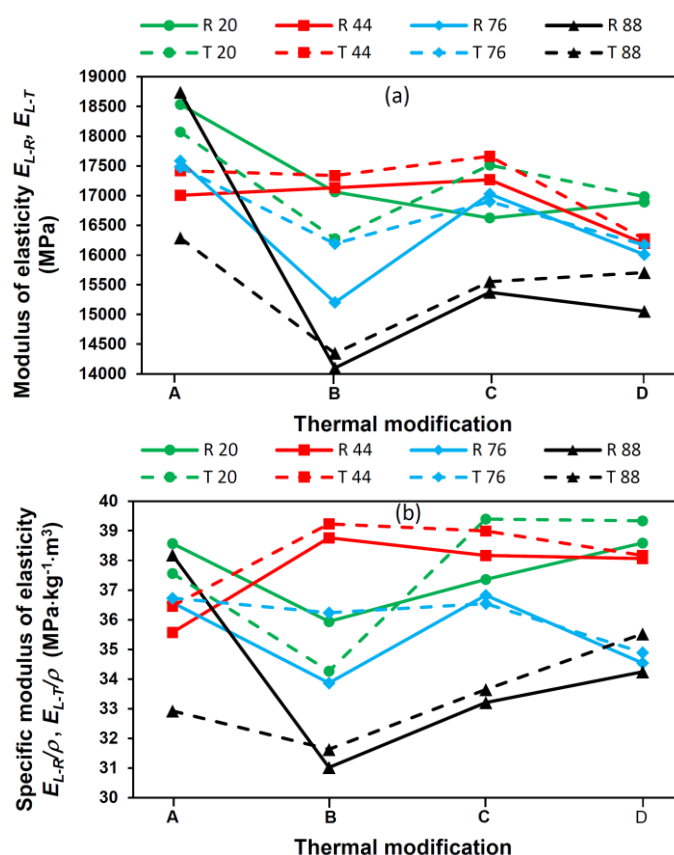


Fig. 9. (a) Modulus of elasticity E_{L-R} , E_{L-T} and (b) specific modulus of elasticity E_{L-R}/ρ , E_{L-T}/ρ at different levels of thermal modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C), vibration direction, and RH. First letter in legend represents vibration direction of samples (R – radial for E_{L-R} , T – tangential for E_{L-T}); the number represents RH

The influence of the degree of modification can be better recognized in Fig. 9b, where the specific MOE is plotted and increases with the level of modification. However, because the decrease in density with increasing degree of modification was greater than the decrease in MOE, the specific MOE increased with the degree of modification. The latter observation is particularly important in cases where it is desirable to maximize stiffness in relation to the mass of the product. This is because the stiffness of the element per mass increases as the degree of modification increases. Of course, this trend cannot continue indefinitely with the rate of TM, as the strength of thermally modified wood decreases. Therefore, elements with increased stiffness can

only be used for constructions where the strength is not crucial, but the stiffness itself is more important, as is the case with some musical instruments.

Effect of Thermal Modification on Shear Modulus

The average values of the shear moduli and the specific shear moduli are shown in Fig. 10a and 10b, respectively. Both G_{LR} , G_{LT} and specific G_{LR}/ρ , G_{LT}/ρ values decreased with RH. Shear modulus G_{LR} , which was determined for vibrations in the L-R vibration plane has higher values than the shear modulus G_{LT} , which was determined for vibrations in the L-T vibration plane, which is consistent with the literature (Kollmann and Côte 1975). The decrease in the shear modulus value can be attributed to the same reasons as the decrease in the MOE value due to thermal modification, *i.e.*, the reduction and degradation of the cellulose and the breaking of the hydrogen bonds.

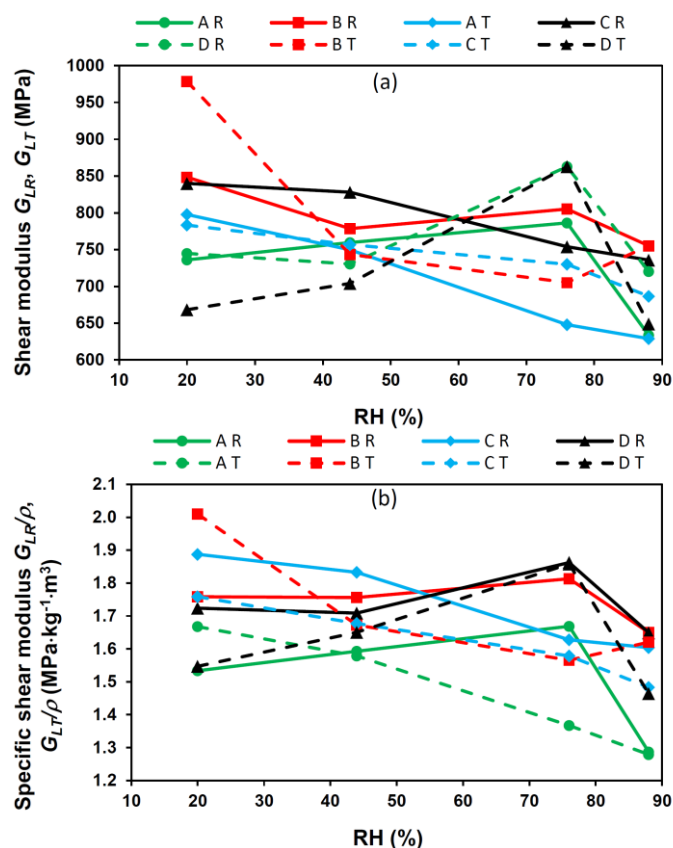


Fig. 10. (a) Shear modulus G_{LR} , G_{LT} , and (b) specific shear modulus G_{LR}/ρ , G_{LT}/ρ at different RH, modification levels and vibration direction. First letter in legend represents level of modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C); the second letter represents vibration direction of samples (R – radial for G_{LR} , T – tangential for G_{LT})

The effect of thermal modification on the size of the shear modulus G_{LR} , G_{LT} , and the specific shear modulus G_{LR}/ρ , G_{LT}/ρ is illustrated more clearly in Fig. 11a and 11b, respectively. The effect of thermal modification on shear modulus was not as pronounced as for MOE, or the trend is even slightly positive, whereas it was negative for MOE. However, as the density decreased with TM, the trend for specific G_{LR}/ρ , G_{LT}/ρ was even more positive, which means that the shear stiffness per unit mass also increased with increasing thermal modification rate and had a positive effect.

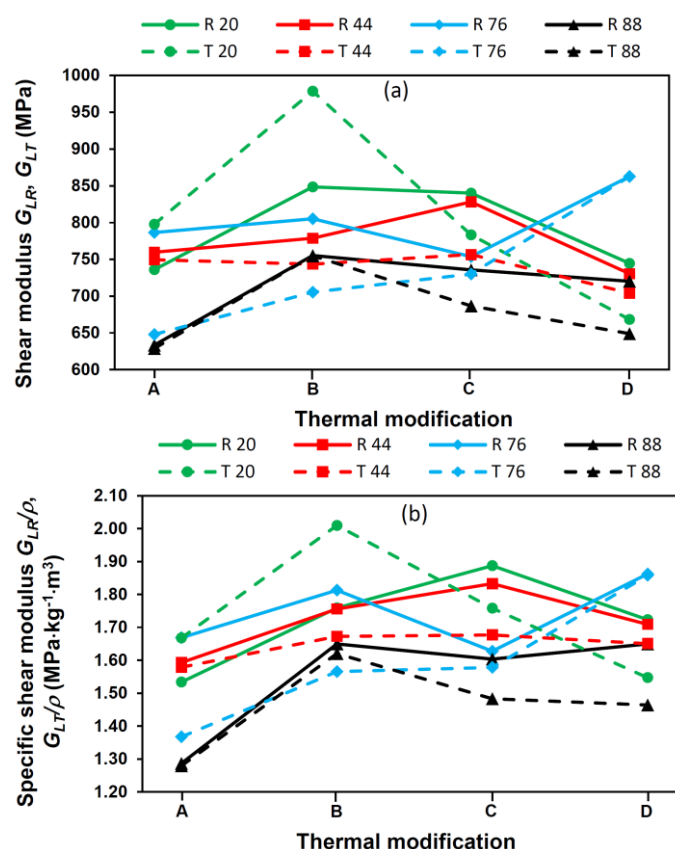


Fig. 11. (a) Shear modulus G_{LR} , G_{LT} , and (b) specific shear modulus G_{LR}/ρ , G_{LT}/ρ at different levels of thermal modification (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C), vibration direction and RH. First letter in legend represents vibration direction plane of samples (R – L-R for G_{LR} , T – L-T for G_{LT}); the number represents RH

Effect of Thermal Modification on Speed of Sound

The average values of the modulus of elasticity E_L obtained from the modulus E_{L-T} and E_{L-R} were used to calculate the sound velocities for various combinations of thermal modification and RH (Fig. 12a). The maximum sound velocities were approximately 6200 m/s at the highest TM and lowest RH and decrease with increasing RH, while they increased with TM (Fig. 12b), which is consistent with the literature (Danihelová *et al.* 2022).

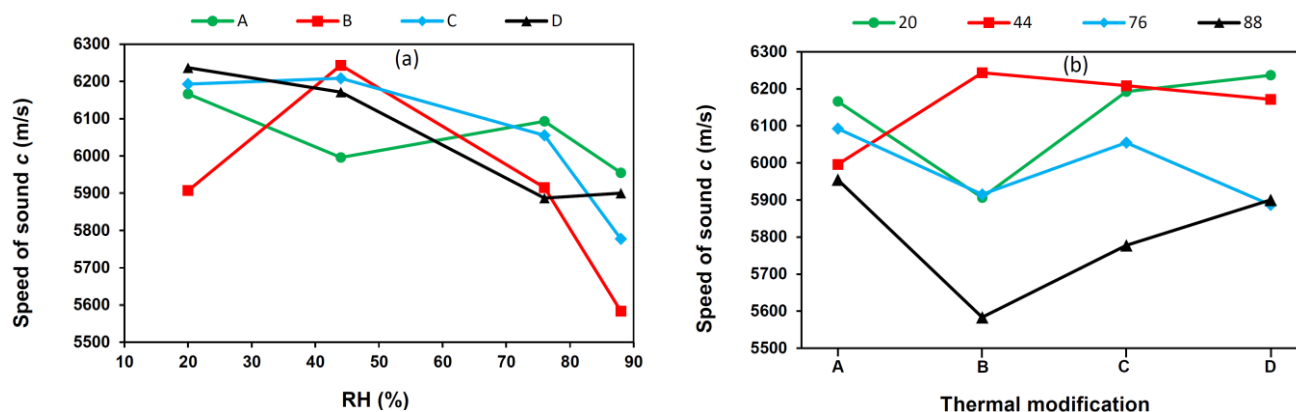


Fig. 12. Speed of sound: (a) At different RH and levels of thermal modification. (b) At different thermal modification levels and RH (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C)

Both TM ($p = 0.002$) and RH ($p = 0.000$) had a significant effect on sound velocity. Different wooden musical instruments require different sound velocities, typically between 3000 and 6500 m/s, with resonant woods typically requiring high velocities. Therefore, for soundboards, woods with sound velocities between 4000 m/s and 6500 m/s, densities between 300 kg/m³ and 500 kg/m³ and MOE between 8000 and 18000 MPa (Wegst 2006) are desired, where the tested material would be suitable to produce soundboards under the required conditions.

Effect of Thermal Modification on Sound Radiation Coefficient

The sound radiation coefficient R (Fig. 13) showed a similar trend to the velocity, decreasing with RH and increasing with TM. ANOVA confirmed the significance of both TM ($p = 0.000$) and RH ($p = 0.000$) with a maximum value of approximately 14.5 m⁴/(kg·s) for the samples with the highest TM at the lowest RH. The trend is consistent with the literature (Danihelová *et al.* 2022) and the wood for soundboards is expected to have a high value between 8 m⁴/(kg·s) and 16 m⁴/(kg·s) (Wegst 2006).

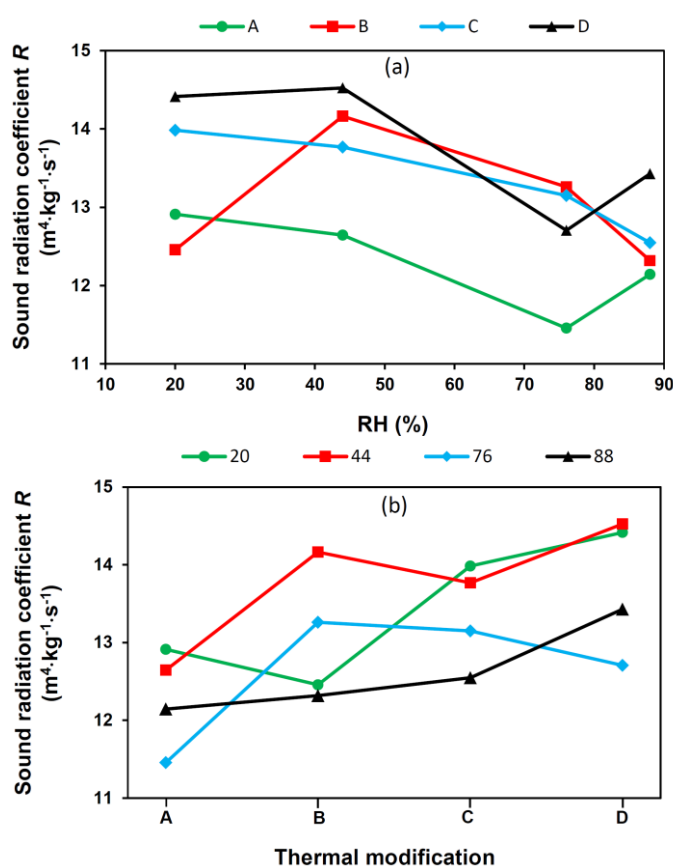


Fig. 13. Sound radiation coefficient R : (a) At different RH and levels of thermal modification; (b) At different thermal modification levels and RH (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C)

Effect of Thermal Modification on Characteristic Acoustic Impedance

The characteristic acoustic impedance z showed slightly different trends (Fig. 14) and decreased with both RH and TM. The results deviated slightly from the literature, which reports that the characteristic acoustic impedance increases with TM (Danihelová *et al.* 2022). Here too, the samples with the highest TM value had the lowest values, which were between 2.6 and 2.75 MPa·s/m. The literature indicates that values between 1.2 and 3.4 MPa·s/m (Ahmed and Adamopoulos 2018) are generally

desirable for the manufacture of musical instruments, whereby the tested samples fulfil the requirements for the manufacture of musical soundboards.

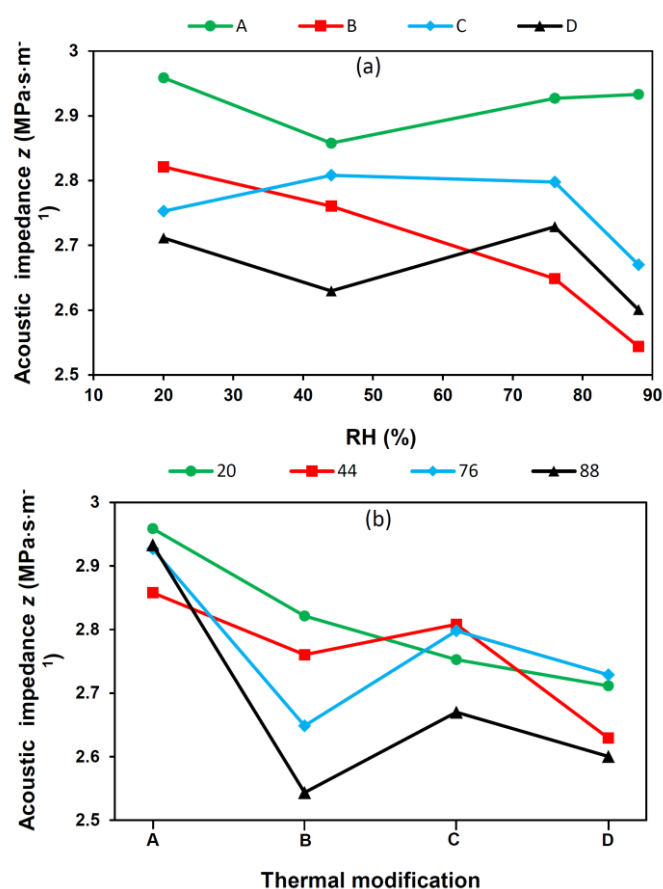


Fig. 14. Acoustic impedance z : (a) At different RH and levels of thermal modification; (b) At different thermal modification levels and RH (A – unmodified, B – modified at 180 °C, C – modified at 200 °C, and D – modified at 230 °C)

CONCLUSIONS

In this study, the effect of thermal modification of spruce wood on the changes in density, modulus of elasticity and shear modulus in different directions and at different equilibrium moisture contents was investigated in detail. Despite numerous studies on the effects of thermal modification, the authors are of the opinion that no studies have yet been carried out that take into account all the factors investigated in this study.

The study confirmed the already known influence of the decrease in density, modulus of elasticity, and shear modulus with increasing degree of thermal modification. As the density decreases more with thermal modification than the modulus of elasticity and shear modulus, the specific modulus and specific shear modulus increase with thermal modification, which indicates that thermal modification has a positive influence on the stiffness properties.

Various acoustic indicators were calculated from the basic parameters, whereby the speed of sound in the longitudinal direction, the sound radiation coefficient and the characteristic acoustic impedance were positively influenced by the thermal modification. Based on the research carried out, manufacturers of wooden musical

instruments can determine the combination of thermal modifications that best meets their requirements in terms of modulus of elasticity, density, or a combination of both, expressed by different acoustic coefficients. In general, however, thermal modification level D, *i.e.* modification at 230 °C, was found to be the most suitable modification, as it had the most favourable influence on all specific moduli as well as on all acoustic coefficients.

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