RESONANCE AND TIME-OF-FLIGHT METHODS FOR EVALUATING THE MODULUS OF ELASTICITY OF PARTICLEBOARDS AT DIFFERENT HUMID CONDITIONS

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ABSTRACT

Non-destructive testing of wood panels by either resonance or time-of-flight (TOF) methods provides possibilities for predicting their static bending properties. In the present study, three non-destructive devices (BING - Beam Identification by Non-destructive Grading by CIRAD, Montpellier, France, Fakopp Ultrasonic Timer and Sylvatest TRIO) were used for measuring the dynamic stiffness of different particleboard types. Fakopp Ultrasonic Timer and Sylvatest TRIO produce ultrasonic pulses to measure the sound velocity while BING uses resonance frequencies. Commercially produced particleboards with different thickness and densities were used to measure the dynamic modulus of elasticity (MOE_{dyn}) in two directions (parallel and perpendicular to the production line) and at three different humidity levels (dry - 35%, standard - 65% and wet - 85% RH in constant temperature of 20°C). MOE_{dyn} of particleboards were correlated with the static moduli of elasticity (MOE_{stat}) and rupture (MOR_{stat}). It was found that the non-destructive methods gave higher MOE_{dyn} values in both production directions than that of MOE_{stat} values. MOE_{dyn} was found to decrease from dry to wet conditions. A very strong and statistically significant correlation existed between MOE_{dyn} and static bending properties. MOE_{dyn} correlated stronger to MOE_{stat} than MOR_{stat}. At different humidity level, all three methods- Fakopp Ultrasonic Timer, BING and Sylvatest TRIO analyses showed good predicting capabilities to estimate MOE_{stat} and MOR_{stat} of different particleboard types with high level of accuracy.

KEYWORDS: Ultrasonic velocity, vibration methods, static bending, dynamic modulus of elasticity, wood panels.

INTRODUCTION

Wood panels are widely used in furniture manufacturing and for construction purposes. In wood-based panel industry, the main goal is to produce panels with high and consistent quality. An understanding of the fundamental mechanical properties is needed in order to specify their particular applications. One of the properties is modulus of elasticity (MOE), which describes the material's stiffness and it is a key indicator used for evaluating the mechanical properties of wood panels. A high value of MOE indicates a high resistance of the material to deformation (Liang and Fu 2007). To determine the stiffness and strength properties of materials, small samples are destructively tested in a testing machine according to standard methods. This type of evaluation process is time-consuming, expensive and more importantly destructive in nature. Thus, special attention was given on different types of non-destructive tests, and mainly acoustic methods have been applied within the last decade for standing trees (Tsehaye et al. 2000a, Amishev and Murphy 2008, Lindström et al. 2009, Wang 2013), logs (Jang 2000, Tsehaye et al. 2000b, Matheson et al. 2002, Dickson et al. 2004, Edlund et al. 2006), lumber (Brancheriau and Baillères 2003, Baltrušaitis and Mišeikytė 2011, Øvrum 2013). On the contrary, little attention has been paid on the non-destructive evaluation of wood panels (Dunlop 1980, Bekhta and Marutzky 2007, Niemz and Mannes 2012, Guan et al. 2015).

Usually, non-destructive testing is carried out by using two acoustic methods; the time-of-flight (TOF) and the resonance method. TOF relies on the evaluation of propagation time of a pulse of ultrasound or a stress wave across the material while the resonance method is based on the free vibration frequency of the material under forced harmonic vibration. The resonance method provides more information on the elastic properties of materials and it is more reliable than the TOF method. Most of the resonance-based acoustic tools have a built-in fast Fourier transformation program that can analyze the acoustic signals. The dynamic modulus of elasticity (MOE_{dyn}) is obtained from the acoustic velocity or the resonance frequency data. It is reported that the ultrasonic pulse transit time gives the highest MOE_{dyn}, which is followed by the stress wave transit time, and then the longitudinal and flexural vibration frequency (Hassan et al. 2013, Wang 2013, Chauhan and Sethy 2016, Legg and Bradley 2016). Acoustic tools based on the two non-destructive methods have proved to provide a rapid, reliable and simple measure of MOE_{dyn} for trees, logs, lumber and wood-based panels, and have also shown good potential to predict their static bending properties (static moduli of elasticity MOE_{stat} and rupture MOR_{stat}).

Several researchers have compared MOE_{dyn} or acoustic wave velocity with MOE_{stat} or MOR_{stat} of wood panels, and have reported good to strong association between them (Ross and Pellerin 1988, Han et al. 2006, Guan et al. 2015). However, values of MOE_{dyn} varied depending on the method used. Moreover, moisture has an influence on the sound wave and resonance properties of wood panels as they can swell considerably in humid conditions. However, moisture influence is more predictable for solid wood than wood panels. As for example, the stress wave velocity in solid wood is affected by about 1% per percent of MC change in the hygroscopic range (Han et al. 2006). However, such linear relationship is not observed in wood panels due their complex nature and large thickness swelling in humid conditions and thus are less predictable in higher moisture range.

Swelling of wood panels is complicated as it is often accompanied with internal bond failures that lead to changes of their internal structure (Wu and Piao 1999). It is thus needed to establish correlations between the acoustic properties and stiffness/strength of wood panels in different humid conditions, which will enable more safe predictions of their behavior in the intended end uses. Temperature also influences the bending strength and stiffness of wood-based panels

(Bekhta and Marutzky 2007), so it should be taken into account for a proper non-destructive evaluation by acoustics. Several other factors need to be considered in non-destructive testing of wood panels, such as the size, shape and variability of the particles, the spatial variation in orientation, the distribution of binder and additives, the size, shape and variation of cavities, and the layering and density variation through the panel thickness (Bodig 2000). Since wood panels are multiphase products, intensive care should be taken in selecting the proper non-destructive method for a specific panel type that more closely responds to the controlling variables of interest (e.g. wave velocity, MOE_{dyn}, shear modulus).

Application of non-destructive acoustic testing for wood-based panels is still in infancy but could be very useful in contemporary quality control of the production for fast determinations of stiffness and strength properties of different panel types. The main objective of this paper was to evaluate the potential of three acoustic tools based on TOF and resonance methods for assessing the mechanical performance (static bending properties) of commercially produced particleboards as effected by their moisture content. Predictions of MOE_{stat} and MOR_{stat} of the particleboards exposed to three humid conditions (dry, standard and wet) were based on MOE_{dyn} values determined by TOF and resonance methods.

MATERIALS AND METHODS

Commercial wood panels

Four (4) types of commercially produced particleboards with different binders, thicknesses and densities were used in this study. The particleboards were collected from factories in Slovakia, Sweden and Poland. Their details are presented in the following Tab. 1.

Tab. 1: Types of particleboards used in the study. Values in parenthesis are the standard deviation of density measured after conditioning at 20˚C and 65% RH.

Type of particleboard	Type of glue used	Thickness (mm)	Density (g·cm^{-3})
Standard particleboard (PB1)	UF	16	0.60 (0.03)
High density particleboard (PB2)	UF	20	0.72 (0.01)
Non-load bearing particle board (PB3)	pMDI	19	0.66 (0.00)
Load bearing particle board (PB4)	pMDI	19	0.69 (0.01)

PB: particleboard; UF: urea formaldehyde; pMDI: polymeric diphenylmethane diisocyanate.

Three climatic conditions were considered for this study: dry (20˚C, 35% RH), standard (20˚C, 65% RH) and wet (20˚C, 85% RH). Both static (MOE_{stat} and MOR_{stat}) and dynamic MOE_{dyn} were measured in samples acclimatized at those three climatic conditions. The samples were considered to be acclimatized when the difference between two weightings within 24 hours were smaller than 0.1% mass of the sample. Moisture content MC (SS-EN 322) and density (SS-EN 323) of the samples were measured after acclimatization at dry, standard and wet conditions.

Two panel directions were considered for determining the bending (static and dynamic) properties viz. parallel and perpendicular. Two different directions, three climatic conditions and six replications produced a total of 36 samples for each board type (see Tab. 2).

Tab. 2: Dimensions (length × width × thickness) and number of samples for different tests in three different climatic conditions.

Board type	Direction	Dimension (mm)	Number of samples
PB1	‖ & ⊥	370 × 50 × 16	36
PB2	‖ & ⊥	450 × 50 × 20	36
PB3	‖ & ⊥	430 × 50 × 19	36
PB4	‖ & ⊥	430 × 50 × 19	36

‖: parallel direction; ⊥: perpendicular direction.

Non-destructive testing

Resonance method

For the resonance method, the BING system was used. This is a non-destructive testing device designed to evaluate the mechanical properties of rigid materials using vibration analysis (Brancheriau and Baillères 2002). Main element of the system is the measurement software BING® (version 9.6.2), which controls a data acquisition logger (PicoScope 4224, UK), processes data and delivers results. In this purpose, a free-free flexural vibration test setup was used (Fig. 1).
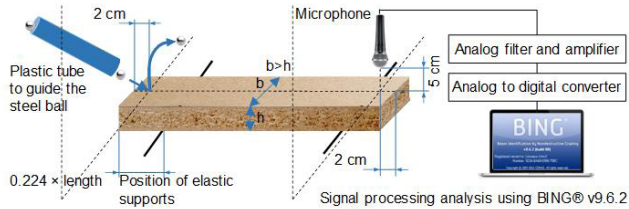

Fig. 1: Schematic representation of the experimental setup for measuring the vibrational properties of particleboards. Note: b and h are the width and height of the sample, respectively.

Each test piece was placed on two elastic supports on nodal points (0.224 × length) from the both ends of the sample to allow free vibrations. A small stainless steel ball (diameter 14 mm and mass 11.2 g) was dropped at one flat end to produce an exciting impulse. On the other end, an omnidirectional microphone was placed to measure the acoustic signal radiated by the impact. The signals were transmitted via PicoScope, and acoustic classification and signal-processing analysis was performed by the BING® software at a signal sampling frequency of 40000 Hz and with a spectral acquisition of 16384 points.

The first four modes of vibration were used for determining the dynamic modulus of elasticity (MOE_{dyn}). More details about the motion equation and method can be found in Hein et al. (2012). The test was repeated four times for every sample with two times in each side and the average was calculated.

Time–of–flight method

Two different ultrasonic testing devices were used for the TOF method; Fakopp Ultrasonic Timer (Fakopp Enterprise Bt., Hungary) and Sylvatest TRIO (CBS-CBT, France). Both devices use a single pass measurement of time and involve two transducers (sender and receiver) connected to the testing equipment with cables. The devices create ultrasonic excitation and then it is measured the time needed for the ultrasonic impulse to travel from one transducer to another. For Sylvatest TRIO, the result (ultrasonic propagation time) was the average of four impulses in

a sequence. To get a more accurate result, three measurements were performed; two at the top and bottom surface layers and one at the core layer of the particleboard samples (Fig. 2). The average data of the three measurements were used for the calculation of velocity. For Fakopp Ultrasonic Timer, two special triangle-shaped piezoelectric sensors were placed on the flat sides of the samples. Measurements of the propagation time were performed on both the top and bottom surfaces of the samples and the average data was used for the calculation of the ultrasonic wave velocity (Fig. 2).

Fig. 2: Measurement of ultrasonic wave velocity on different positions of the particleboard sample by Sylvatest TRIO and Fakopp Ultrasonic Timer.

The acoustic velocity for each sample was calculated using the following formula:

$$V = \frac{D}{T} \times 1000 \tag{1}$$

where: V is the ultrasonic velocity (m·s⁻¹), D is the distance of the transducers (mm) and T is the time needs to travel from the sender to the receiver transducer (µs). Then, V (m·s⁻¹) and density ρ (g·cm⁻³) were used to calculate the MOE_{dyn} (MPa) with the following formula:

$$MOE_{dyn} = \rho V^2 \tag{2}$$

Static bending test

A universal testing machine (MTS 810, MTS System Corporation, USA) was used for the three-point bending test following the standard SS-EN 310. Uniaxial load was applied on the flat side of the samples. The loading rate was adjusted so that the maximum load was reached within 60 ± 30 s. During the bending test, the deflection and load were recorded until the fracture of the sample. From the load-deflection curve, the modulus of elasticity (MOE_{stat}) and modulus of rupture (MOR_{stat}) were calculated.

Data analysis

The MOE_{dyn} data of different samples in three climatic conditions were analyzed using the statistical software package IBM SPSS Statistics, Version 23 (IBM Corporation, New York, USA). One-way analysis of variance (ANOVA) was applied to determine whether MOE_{dyn} were significantly different among the sample categories. A 5% level of significance was used to detect differences and when a significant difference was found, Duncan's multiple-range test was performed. To measure the significance of relationships among the static and dynamic data, regression analysis was performed at 95% confidence level using Microsoft Excel 2016 program (Microsoft, Redmond, WA, USA).

RESULTS AND DISCUSSION

Static bending

MOE_{stat} and MOR_{stat} are important properties that measure respectively the elastic behavior and resistance to bending when the particleboard is under static load. Therefore, these properties determine largely the applicability of particleboards as structural components in furniture and other constructions. Tab. 3 summarizes the moisture content, density, static bending MOE_{stat} and MOR_{stat} in both parallel and perpendicular of particleboard's production line at the three selected humid conditions.

Tab. 3: Equilibrium moisture content (EMC), density, static bending strength (MOR_{stat}) and stiffness (MOE_{stat}) of the particleboard types after conditioning in three different humid conditions at constant temperature 20°C. Values in parenthesis are the standard deviations.

Board type		Dry, 35% RH				Standard, 65% RH				Wet, 85% RH			
		EMC (%)	Density (g·cm⁻³)	MOE_{stat} (MPa)	MOR_{stat} (MPa)	EMC (%)	Density (g·cm⁻³)	MOE_{stat} (MPa)	MOR_{stat} (MPa)	EMC (%)	Density (g·cm⁻³)	MOE_{stat} (MPa)	MOR_{stat} (MPa)
PB1	‖	6.7	0.60	2891	11.36	9.9	0.60	2421	10.91	14.0	0.60	1871	8.89
		(0.01)	(0.03)	(225)	(1.04)	(0.04)	(0.03)	(233)	(1.37)	(0.12)	(0.02)	(157)	(0.84)
	⊥		0.59	2381	10.35		0.60	2067	9.61		0.61	1498	7.69
			(0.00)	(167)	(1.17)		(0.00)	(110)	(0.97)		(0.01)	(235)	(0.95)
PB2	‖	7.1	0.72	3943	19.61	9.7	0.73	3503	19.25	13.3	0.73	2812	17.04
		(0.03)	(0.01)	(110)	(1.31)	(0.02)	(0.01)	(103)	(0.90)	(0.26)	(0.01)	(71)	(0.82)
	⊥		0.72	3788	19.19		0.72	3319	18.29		0.73	2675	16.11
			(0.01)	(41)	(0.48)		(0.01)	(29)	(0.71)		(0.01)	(31)	(0.36)
PB3	‖	7.2	0.65	2657	12.51	10.2	0.65	2324	12.04	13.6	0.66	1913	10.01
		(0.02)	(0.00)	(43)	(1.21)	(0.05)	(0.00)	(43)	(0.70)	(0.04)	(0.00)	(42)	(0.61)
	⊥		0.65	2452	12.65		0.65	2140	11.71		0.66	1746	9.33
			(0.01)	(101)	(1.17)		(0.01)	(133)	(0.66)		(0.01)	(51)	(0.85)
PB4	‖	6.7	0.69	2954	15.17	10.0	0.70	2655	14.56	13.7	0.70	2132	11.63
		(0.08)	(0.01)	(112)	(1.02)	(0.05)	(0.01)	(166)	(0.99)	(0.13)	(0.01)	(80)	(0.57)
	⊥		0.68	2685	14.40		0.70	2285	12.98		0.70	1870	10.63
			(0.03)	(54)	(0.53)		(0.01)	(40)	(0.71)		(0.01)	(32)	(0.98)

‖: parallel direction; ⊥: perpendicular direction.

In all particleboards, static bending properties parallel to the production line showed higher values than perpendicular to the production line. As expected the high-density particleboard (PB2) had the highest values than the other types. At standard condition (20°C and 65% RH), MOE_{stat} and MOR_{stat} values for PB2 boards were 8-11% and 8-14% higher, respectively. With increasing humidity and consequently MC from the dry to the wet condition, the bending properties decreased for all types of particleboards. The reduction was more pronounced from the standard to wet condition. Similar humidity and MC effects were also found elsewhere for wood panels (Wu and Suchsland 1997, Pritchard 2001) as well as for wood (Gerhards 1982). Particleboards are formed under pressure and the adhesive holds the particles in a compressed state, which means that they are self-stressed in compression perpendicular to the grain of the wood fibers. MC changes lead to relaxation of stresses and recovery of the locked-in deformations resulting in increase of board dimensions and some change in the moment of inertia (Oliver 1981). In addition, the decrease of stiffness and strength is directly affected by the humidity changes but the magnitude depends on the type of adhesive. An experiment by Dinwoodie (1978) reported that urea-formaldehyde bonded boards subjected to humidity change from 30% to 90% RH retained only 58% and 45% of their initial MOR_{stat} and MOE_{stat} respectively, whilst boards

bonded with melamine urea-formaldehyde, phenol formaldehyde and sulphite liquor retained at least 73% and often more than 90% of their initial property value.

The reduction in strength properties is due to the effect of mechanical stressing set up by alternate swelling and shrinkage of adjacent particles (Halligan and Schniewind 1974, Dinwoodie 1978). Both MOE_{stat} and MOR_{stat} are affected by various processing parameters like the board density, surface density and particle size, particle alignment, moisture content, and particularly by the nature of adhesives used (Kollmann et al. 1975, Jian and Lu 2017). The higher MOE_{stat} and MOR_{stat} values observed in the parallel than in the perpendicular direction for all particleboard types in all humid conditions could be explained by the particle orientation in respect to the direction of the production line. Parallel to the production line, the orientation of particles with their fibers along the grain provide increased strength and stiffness to resist stress while loading of particles against the grain in the perpendicular direction results in lower flexure values (Han et al. 2006, Buyuksari 2012, Ayrilmis et al. 2010). In addition, the fine particles of the panel's face layers need the core layer as a strengthening element. Panels with core layer particles with parallel orientation affects and enables the core layer to resist it from deformation and failure when subjected to the bending loads (Benthien and Ohlmeyer 2018).
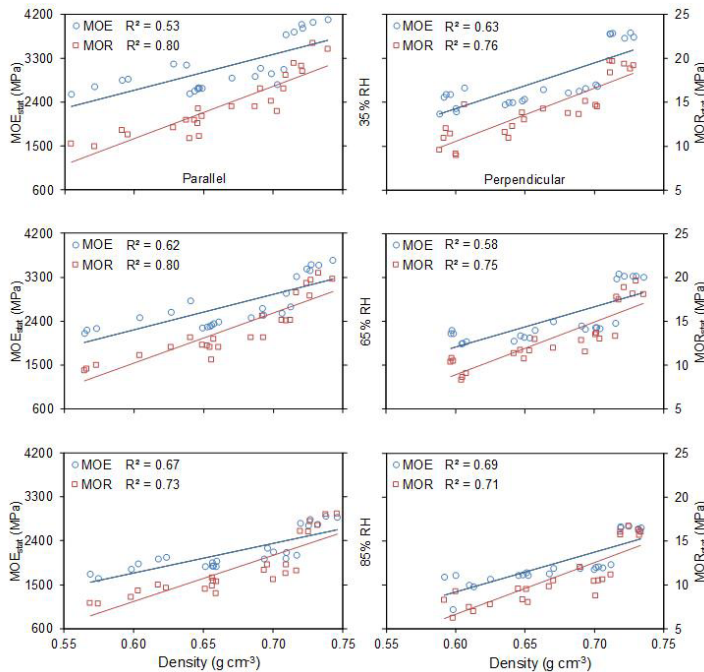

Fig. 3: Relationship of static bending properties (MOE$_{stat}$, MOR$_{stat}$) with density for the particleboard types acclimatized at three humid conditions.

Fig. 3 shows the relationship of MOE_{stat} and MOR_{stat} with the density of all particleboard types at each humid condition. In every humid condition, linear regression models of MOE_{stat} and MOR_{stat} with the density showed significant positive relationships ($p < 0.05$).

As revealed by the coefficients of determination, the relationship of density was stronger with MOR_{stat} than with MOE_{stat}. Our findings are in agreement with previous studies (Wong

et al. 1998, Rachtanapun et al. 2012, Guan et al. 2016), which reported an increase in MOE_{stat} and MOR_{stat} with increasing board density. The surface board density plays an important role on the MOR_{stat} since bending stresses are higher at the surfaces. Furthermore, MOR_{stat} values are highly dependent on the vertical density gradient where different values can be obtained for equal average board densities simply by changing the processing parameters (Wong et al. 1998).

However, in this study, the mean board density was used for analysis, and therefore no conclusions can be made on the effect of density gradient on the bending performance of the particleboard types. Linear regressions model was used to determine how well the MOR_{stat} is related with MOE_{stat} values in parallel and perpendicular samples (Fig. 4). It showed strong positive and significant relationships ($p < 0.05$) for every humid condition, particleboard direction (parallel and perpendicular) as well as when all data were grouped together. Strong correlation between bending strength and modulus of elasticity is also reported for wood (Olsson et al. 2012, Baar et al. 2015) and wood-based panels (McNatt et al. 1990, Jian and Lu 2017).
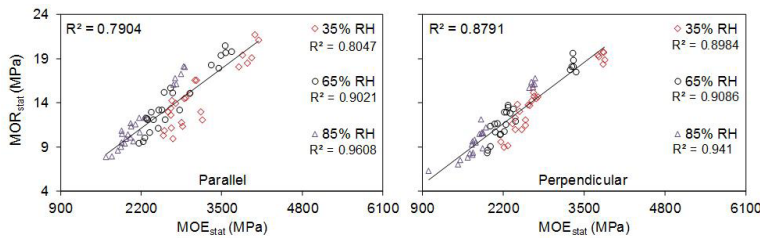

Fig. 4: Relationship of MOE_{stat} and MOR_{stat} for the particleboard types acclimatized at three humid conditions.

Dynamic modulus of elasticity

MOE_{dyn} represents the mean stiffness value of a sample whilst MOE_{stat} represents the local stiffness of the material at the highly stressed areas of a specific test setup. The MOE_{dyn} values measured for the different particleboard types at dry, standard and wet conditions by the different resonance and TOF methods are presented in Tabs. 4-6.

Tab. 4: Dynamic modulus of elasticity (MOE_{dyn}) of the particleboard types, after conditioning in three different humid conditions at constant temperature 20°C, measured by BING in transversal vibration (resonance method). Values in parenthesis are the standard deviations.

Board type	Direction of board	Dry, 35% RH MOE_{dyn} (MPa)	Standard, 65% RH MOE_{dyn} (MPa)	Wet, 85% RH MOE_{dyn} (MPa)
PB1	‖	3631a (212)	3376a (189)	2683b (132)
	⊥	3294a (274)	3048a (242)	2398b (195)
PB2	‖	5754a (71)	5408b (54)	4461c (62)
	⊥	5301a (217)	4980a (202)	4102b (191)
PB3	‖	3527a (142)	3260b (146)	2721c (101)
	⊥	3185a (58)	2945b (39)	2432c (37)
PB4	‖	3808a (66)	3428b (58)	2867c (28)
	⊥	3615a (17)	3250b (14)	2689c (17)

‖: parallel direction; ⊥: perpendicular direction.

Mean values followed by different letter within a row indicate that there is a significant difference ($p \leq 0.05$) as determined by ANOVA and Duncan's multiple range test.

Tab. 5: Dynamic modulus of elasticity (MOE$_{dyn}$) of the particleboard types, after conditioning in three different humid conditions at constant temperature 20°C, measured by Fakopp Ultrasonic Timer (TOF method). Values in parenthesis are the standard deviations.

Board type	Direction of board	Dry, 35% RH MOE$_{dyn}$ (MPa)	Standard, 65% RH MOE$_{dyn}$ (MPa)	Wet, 85% RH MOE$_{dyn}$ (MPa)
PB1	‖	4184a (207)	3944a (174)	3316b (126)
	⊥	3606a (165)	3276b (163)	2897c (144)
PB2	‖	5822a (110)	5617b (103)	4870c (69)
	⊥	5383a (53)	5327a (166)	4505b (161)
PB3	‖	3918a (132)	3732a (127)	3222b (132)
	⊥	3520a (61)	3353b (98)	2948c (59)
PB4	‖	4469a (95)	4102b (78)	3525c (63)
	⊥	4132a (39)	3846b (25)	3307c (22)

‖: parallel direction; ⊥: perpendicular direction.

Mean values followed by different letter within a row indicate that there is a significant difference (p ≤ 0.05)
as determined by ANOVA and Duncan's multiple range test.

Tab. 6: Dynamic modulus of elasticity (MOE$_{dyn}$) of the particleboard types, after conditioning in three different humid conditions at constant temperature 20°C, measured by Sylvatest TRIO (TOF method). Values in parenthesis are the standard deviations.

Board type	Direction of board	35% RH MOE$_{dyn}$ (MPa)	65% RH MOE$_{dyn}$ (MPa)	85% RH MOE$_{dyn}$ (MPa)
PB1	‖	3273a (200)	3230a (179)	2713b (121)
	⊥	3000a (195)	2925a (162)	2449b (112)
PB2	‖	4815a (115)	4905a (103)	4251b (102)
	⊥	4556a (99)	4604a (105)	3987b (128)
PB3	‖	3400a (112)	3223a (161)	2864b (119)
	⊥	2998a (51)	2923a (62)	2603b (60)
PB4	‖	3903a (167)	3652a (119)	3307b (122)
	⊥	3647a (57)	3416b (52)	3095c (40)

‖: parallel direction; ⊥: perpendicular direction.

Mean values followed by different letter within a row indicate that there is a significant difference (p ≤ 0.05)
as determined by ANOVA and Duncan's multiple range test.

As expected, the increase of humidity from dry to wet conditions resulted in decreased MOE$_{dyn}$ due to the elevated EMC of particleboards. The trend was noticed in each particleboard type for all the acoustic methods used (Tab. 4-6). At 85% RH, MOE$_{dyn}$ of the particleboard types determined by both the resonance and TOF methods was found significantly lower than that was in 35% and 65% RH (ANOVA and Duncan's multiple range test, P ≤ 0.05). MOE$_{dyn}$ in TOF methods is directly related to the acoustic velocity (see formula 2). Resonance frequency and ultrasonic velocity of wood panels decrease with an increase in moisture content, and thus proportionally influence the MOE$_{dyn}$ (Bucur 2006). A similar trend has also been reported for solid wood (Llana et al. 2014). This phenomenon can be explained by the hypothesis that at dryer state, molecular chains in the amorphous regions of the cell wall are unusually distorted with the presence of microvoids between the molecular chains resulting in lower internal friction, which corresponds to higher MOE$_{dyn}$. With increasing moisture content, water molecules are embedded

in the microvoids and rearrange the distorted molecular chains. However, with further increase in moisture content, water acts as a plasticizer allowing additional molecular movement and the cohesive forces between molecules are decreased. That results in a higher internal friction leading to a decrease in MOE_{dyn} (Akitsu et al. 1993).

Like MOE_{stat}, higher MOE_{dyn} was observed in samples parallel to the production line than perpendicular (Tabs. 4-6). The reason behind this result is the highest resonance frequency and ultrasonic velocity parallel to the grain (Bucur 2006, Han et al. 2006). The higher values of MOE_{dyn} parallel to the production line of particleboards meant that higher number of wood particles along the grain were aligned in this direction. When different methods were compared, the mean values of the MOE_{dyn} based on flexural vibration and TOF methods (Tabs. 4-6) were higher than MOE_{stat} (Tab. 3) for each particleboard type and humid condition. As average, BING, Fakopp Ultrasonic Timer and Sylvatest TRIO gave respective MOE_{dyn} values 29%, 37% and 27% higher than MOE_{stat} values. Moduli of elasticity determined using speed of sound measurements are in general higher than values determined by static experiments (Bucur 2006, Niemz and Mannes 2012, Hassan et al. 2013, Guan et al. 2015, Chauhan and Sethy 2016). Like wood, the difference between MOE_{dyn} and MOE_{stat} is attributed to the viscoelastic behaviour and damping properties of particleboards. According to Halabe et al. (1997), materials exhibit elastic behaviour when a force is applied for a very short duration and behave as a viscous liquid when a force is applied for longer time. As static bending test takes long duration compared to the TOF or resonance test, higher moduli of elasticity are obtained by the later methods. MOE_{stat} represents a local stiffness while the MOE_{dyn} represents a mean value over the full specimen. Overall, MOE_{dyn} was found to be the highest when Fakopp Ultrasonic Timer was used, and it was about 11% and 16% higher respectively than MOE_{dyn} obtained by BING and Sylvatest TRIO. The considered layer for the measurements might explain the difference between the two ultrasonic TOF methods (Fakopp Ultrasonic Timer, Sylvatest TRIO) on a three-layered particleboard, which is not characteristic and does not represent the whole section (Dunlop 1980). Low-density middle layers have the greatest effect on sound propagation time. A sound wave needs more time to travel across a low-density middle layer, and thus provides different results than the surface layers of higher density. In this contrast, Fakopp Ultrasonic Timer sound velocity results were the average of measurements done on both surfaces of the particleboards whilst an average of three layers (two faces and core layer) was used for Sylvatest TRIO. The addition of the low-density core layer into the final average in Sylvatest TRIO might explain the differences noted between the two ultrasonic testing methods. However, the prediction of MOE_{stat} from MOE_{dyn} values depends on the good correlation between them. Barbu et al. (2014) showed strong correlations between the density of the surface layer and the MOE_{stat} and MOR_{stat} for particleboards and medium density fibreboards (MDF). Sound velocity in the panel direction is dominated by the surface layers with higher densities and mainly influence MOE_{stat} and MOR_{stat} (Kruse 1997) whilst the porous core layer influences sound velocity perpendicular to the panel surface (Hilbers et al. 2009). However, both methods tested here were able to capture the structural differences among the particleboards types. As for example, the high-density particleboard (PB2) gave the highest values.

Linear regression analysis was employed to determine how well a particular acoustic method could predict the MOE_{stat} or MOR_{stat} values by the MOE_{dyn} values on samples with different directions (parallel and perpendicular) and EMC levels (Tab. 7). Significant positive relationships (confidence level of 0.05) were found between MOE_{dyn} and MOE_{stat} for samples in the parallel and perpendicular production directions acclimatized in different humid conditions. This result is in well agreement with a previous study (Han et al. 2006). The coefficients of determination (R^2) ranged from 0.889 to 0.995 for the different acoustic methods. All three methods, Fakopp

Ultrasonic Timer, BING and Sylvatest TRIO, performed well to predict MOE_{stat}. Linear regression models between MOR_{stat} and MORdyn also showed positive relationships. Those developed regression models were found statistically significant at the 0.05 confidence level for most of the relationships on samples at different relative humidity levels. The coefficients of determination (R^2) ranged from 0.852 to 0.994. Sylvatest TRIO performed better than the other two methods in predicting MOR_{stat}.

Tab. 7: Regression analysis results on the relationships between static moduli of elasticity (MOE_{stat}) and rupture (MOR_{stat}), and dynamic modulus of elasticity (MOE_{dyn}). Model: MOE_{stat} or MOR_{stat} = Intercept + Slope × MOE_{dyn}.

Testing method	RH (%)	Parallel direction			p-value	Perpendicular direction			p-value
		Intercept	Slope	R^2		Intercept	Slope	R^2	
MOR_{stat} - MOE_{dyn} relationship									
BING	35	880.030	0.534	0.981	0.006*	282.620	0.661	0.992	0.004*
Fakopp		33.816	0.669	0.991	0.004*	-306.220	0.753	0.978	0.011*
Sylvatest		163.850	0.766	0.888	0.058ns	-237.760	0.863	0.945	0.028*
BING	65	749.930	0.511	0.960	0.020*	291.790	0.608	0.991	0.005*
Fakopp		26.165	0.621	0.988	0.006*	42.640	0.610	0.986	0.007*
Sylvatest		196.120	0.674	0.995	0.002*	-72.960	0.728	0.975	0.013*
BING	85	587.210	0.501	0.970	0.015*	152.600	0.618	0.961	0.019*
Fakopp		88.143	0.561	0.981	0.010*	-337.180	0.669	0.971	0.015*
Sylvatest		130.090	0.625	0.988	0.006*	-240.300	0.721	0.962	0.019*
MOR_{stat} - MOE_{dyn} relationship									
BING	35	1.148	0.003	0.869	0.068ns	0.454	0.036	0.875	0.064ns
Fakopp		-4.202	0.004	0.899	0.052ns	-3.185	0.004	0.912	0.045*
Sylvatest		-5.425	0.005	0.996	0.002*	-3.322	0.005	0.935	0.032*
BING	65	1.345	0.003	0.852	0.077ns	0.160	0.004	0.894	0.055ns
Fakopp		-3.442	0.004	0.886	0.059ns	-1.893	0.004	0.959	0.021*
Sylvatest		-2.959	0.005	0.961	0.020*	-2.594	0.005	0.946	0.027*
BING	85	-1.198	0.004	0.950	0.026*	-1.906	0.004	0.958	0.021*
Fakopp		-5.223	0.005	0.952	0.024*	-5.473	0.005	0.974	0.013*
Sylvatest		-5.181	0.005	0.994	0.003*	-4.873	0.005	0.978	0.011*

* Significant regression equation at the 0.05 level (two-tailed); ns- non significant regression equation; R^2- coefficient of determination.

Previous studies (Liang and Fu 2007, Chauhan and Sethy 2016) showed better relationships of MOE_{stat} and MOE_{dyn} when MOE_{dyn} was measured with resonance frequency by the Fast Fourier Transform (FFT) technique than with the TOF techniques (ultrasonic, stress wave). This is because the resonance speed by the vibration method is the function of the volume weighted average stiffness of the entire sample whilst in TOF methods, the high frequency waves travels at a relatively faster speed in stiffer and denser material (Chauhan et al. 2005). However, for particleboard, notifiable differences among the tested methods were not observed. In addition, this study showed that the differences in MOE_{dyn} measured by any of these three methods was not constant over the entire MOE_{stat} or MOR_{stat} range. The slope of the equations relating MOE_{dyn} to MOE_{stat} or MOR_{stat} was different in all three cases and was the lowest in BING and the highest in Sylvatest TRIO, which is in agreement with Chauhan and Sethy (2016). Previous studies (Bos

and Casagrande 2003, Hassan et al. 2013) showed that the correlation coefficients between the MOE_{dyn} and MOE_{stat} are higher than those between the MOE_{dyn} and MOR_{stat}. This fact was also observed in the current study.

CONCLUSIONS

This study investigated the potential for predicting the bending properties of different particleboard types by using resonance and time-of-flight methods at three different humid conditions (dry, standard and wet). The overall conclusions of the study are given below:

(1) Both MOE_{stat} and MOR_{stat} decreased with increases in particleboards' moisture content. Bending properties increased with the density of the particleboards. Linear relationships were found between both MOE_{stat} and MOR_{stat} with density for every humid condition.

(2) At a given humid condition, higher MOE_{stat} and MOR_{stat} values were observed in samples parallel compared to samples perpendicular to the production line. Overall, samples parallel to production line had MOE_{stat} and MOR_{stat} respectively 12% and 8% higher than the samples perpendicular to the production line.

(3) Positive linear relationships were found between MOE_{stat} and MOR_{stat} at dry ($R^2 = 0.83$), standard ($R^2 = 0.90$) and wet ($R^2 = 0.93$) conditions.

(4) All three methods (BING, Fakopp Ultrasonic Timer and Sylvatest TRIO) showed higher MOE_{dyn} values in samples parallel than in samples perpendicular to the production line. MOE_{dyn} of particleboards decreased as their moisture content increased, and was statistically significant lower at the wet than at the dry condition.

(5) The mean values of MOE_{dyn} were higher than MOE_{stat} for each particleboard type and humid condition. Overall, MOE_{dyn} was found 29%, 37% and 27% higher than MOE_{stat} when BING, Fakopp Ultrasonic Timer Sylvatest TRIO were used respectively.

(6) The obtained strong and statistically significant MOE_{stat}-MOE_{dyn} and MOR_{stat}-MOE_{dyn} linear relationships at almost every humid condition and production direction suggested that the resonance and TOF methods could be useful in practical quality control for predicting the static bending properties of particleboards. All tools showed exceptional ability to predict MOE_{stat} while Sylvatest TRIO provided better MOR_{stat} prediction results than Fakopp Ultrasonic Timer and BING.

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