The study of sound propagation in the wood-based composite materials

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ABSTRACT

For the study of sound propagation in several types of wood-based composite materials (WBCM) two different non-destructive testing methods were applied. Resonance frequency and sound velocity were applied on boards (particleboards, OSB, MDF) of industrial production. Each type of board was evaluated by measuring the sound velocity both parallel and perpendicular to the direction of production. In addition, sound velocity through the thickness of the board was measured. The elastic and mechanical characteristics of properties, as determined by resonance frequency and sound velocity were compared with those determined by static method. The used frequencies were 50, 100 and 200 kHz.

We also studied an influence of some variables such as specimen's width (20 to 200 mm) and thickness (16 to 96 mm) on the sound velocity for particleboards. It was shown that the sound velocity decreases in general with increases in specimen's thickness and width. By increasing of the relative air humidity (from 50 to 90%) and temperature (from minus 35^0 to $+70^0$C) of board we found a decrease of the sound velocity. The measurement of seven types of particleboards (with different density and thickness) brought different sound velocity for all board types.

INTRODUCTION

The physical and mechanical properties of wood-based composite materials (WBCM) are not constant. The reason has to do with the instability of technological process, and raw material, which became more and more diverse for the last years. Moreover, for the last years the capacity of production lines and the production speed have increased and the equipment became more complex. There are production plants, producing up to 20 different board types in 24 hours (Nielsen and Jensen 1994). As a consequence, the expenditure of time and materials due to product changes have grown. More than ever high and constant quality of WBCM plays an important role.

Therefore, reducing changability of the properties of WBCM is an important problem, since it makes possible not only improvement of the quality of products but also reduction in the expenditure of raw material and glue for its production. To provide the constant quality, the board producers need more information about fluctuations within the technological process.

Current quality control procedures used in WBCM plants have become labour intensive, expensive, and inefficient, since they involve the destructive testing of a very small percentage (approximately 1%) of material manufactured. As they do not permit the evaluation of every piece of material produced, high quality is often degraded by being placed in a lower quality category. The results of such measurements have random nature. Thus, much time is spent for their deriving, as the timeliness of adjustment of a manufacturing process is not ensured. Therefore, there is an imperative need for evaluation of material quality which is fast and accurate.

The non-destructive testing (NDT) techniques are capable of providing such an evaluation. These techniques have been used for many years in the forest products industry, and range from simple visual inspection, to more sophisticated mechanical or vibrational techniques (Ross and Pellerin 1994).

Among the different techniques that have been used with varying degrees of success in predicting the quality of WBCM, the most useful probably being determination of the velocity of compressional or other acoustic waves (Bucur 1995). The development of the sound velocity NDT method is based on the understanding of wave propagation phenomena. The application of sound velocity NDT method to determine the elastic and mechanical

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properties of WBCM is amply illustrated in the literature (Plotnikov and Niemz 1989; Ross and Pellerin 1994; Bucur 1995; Niemz and Poblete 1996; Bekhta, Chopyk and Niemz 1999).

As indicated by Bucur (1995) "the success of ultrasonic nondestructive methods is related primarily to understanding the phenomenon of ultrasonic wave propagation in testing material, and ultimately to defining how to use the results of the basic research to improve the technology".

The main objective for this research was to experimentally investigate the sound propagation in different WBCM. Moreover, the following tasks of research were to: 1) study the influence of the structure of material, their temperature and relative air humidity, specimen's width, and specimen's thickness of glued materials on sound propagation; 2) study the influence of the frequency on sound propagation; 3) evaluate the dynamic modulus of elasticity (MOE_{DYN}); 4) evaluate resonance frequency (RF) and sound velocity (SV) through material; 5) evaluate static modulus of elasticity (MOE_{DIN}) and modulus of rupture (MOR); 6) correlate MOE_{DYN} to MOE_{DIN}, and MOR; 7) correlate SV and RF to MOE_{DIN} and MOR; 8) compare resonance frequency and sound velocity method for evaluation of properties of WBCM.

MATERIALS AND METHODS

Materials. Commercial particleboards (PB) 16 mm thick, fiberboards (MDF) 17 mm thick and oriented strand boards (OSB) 18 mm thick were selected for the study. Fifty specimens from the each composite board type were cut (into size 50 x 400 mm) both in parallel and perpendicular to the direction of production, since the elastic properties for each direction differs. These specimens were tested using ultra sound and longitudinal resonance frequency.

The task of our study was also to identify the dependence of ultrasonic velocities on relative humidity and temperature. This experiment was conducted on 10 specimens (500 x 50 x 14 mm) with 8% moisture content at 6 different temperature levels in a temperature interval ranging from -30^0 to $+70^0$C and on 10 specimens (500 x 50 x 14 mm) with 20^0C temperature at 5 different relative humidity levels in a RH interval ranging from 50 to 90%.

In order to verify that the ultrasonic technique was responsive to different parameters, several common variables, such as specimen's thickness (16, 32, 48, 64 and 96 mm) and width (20, 40, 60, 80, 100, 150 and 200 mm) and particleboard's structure (7 types of PB with different thickness and density), were selected to further investigate the effects of interactions between board variables and sound velocity.

An individual specimens of board were glued on thickness for the study of an influence of the thickness of board on the SV. For example, six individual specimens with the thickness 16 mm each of them were glued to get specimen with the thickness 96 mm.

An influence of the relative air humidity, temperature of board, width and thickness of board on the SV was studied only for particleboard.

All specimens were conditioned in a controlled environment of 65% relative humidity ±2% at $20^oC\pm2^oC$. Conditioning was deemed complete when sample mass did not deviate by more than ±0,1% over a 24 hour period. In addition, each specimen's weight, length, width, and thickness were recorded. The density of the specimens was determined by measuring the dimensions and the mass of specimens. All the specimens after subjecting them to nondestructive tests, were used to evaluate MOE by static methods. Tests to determine MOR were carried out on the same specimens subjected to MOE evaluation by static methods.

Methods. The density, moisture content, bending strength (MOR), and modulus of elasticity (MOE_{DIN}) were measured in accordance with DIN 52182, 52183 and 51286 relatively.

Resonance frequencies were measured using a MK5 industrial apparatus from Lemmens and methods by Görlacher (1984). The experimental setup shown in Figure 1 was employed. Flexural waves were produced by hitting at the board. The end of the board stayed free. According to Görlacher (1984) for flexural waves and mode I the equation 1 holds:

$$MOE_{RF} = \frac{4\cdot\pi^2\cdot l^4\cdot f^2\cdot\rho}{m_n^4\cdot i^2}\cdot\left(1+\frac{i^2}{l^2}\cdot K_1\right)\cdot10^{-9} \quad (1)$$

where: MOE_{RF} – dynamic modulus of elasticity (N/mm^2), calculated from resonance frequency; ρ - density (kg/m^3); l – length of the board (mm); f – frequency (s^{-1}); i – radius of inertia; $i^2=h^2/12$ (h=specimen height in mm) (mm^2); K_1 – constant, depending on the mode of the oscillation; m_n – constant, depending on the mode of the oscillation. For the mode I (first order of the oscillation) the following values were used: K_1=49,8; m_n=500,6.

The second technique used for nondestructive evaluation of the analyzed board was the system BP5 from Steinkamp/Bremen (Germany). The SV was determined by the duration of transmitted signal and the length of the sample. Figure 2 illustrates the ultrasonic testing setup. The measuring frequency used was 50 kHz.

Measuring was done by transmissions in-plane and out-of-plane of boards. The duration of transmission was measured in μs and velocity then calculated with the sample length. Using the relationship shown in equation 2 the dynamic MOE was calculated from sound velocity and raw density according to equation 3.

$$\nu = \sqrt{E/\rho} \quad (2)$$

$$MOE_{SV} = \nu^2 \cdot \rho \quad (3)$$

where: ν - sound velocity (m/s); MOE_{SV} – dynamic modulus of elasticity (N/mm^2), calculated from the sound velocity.

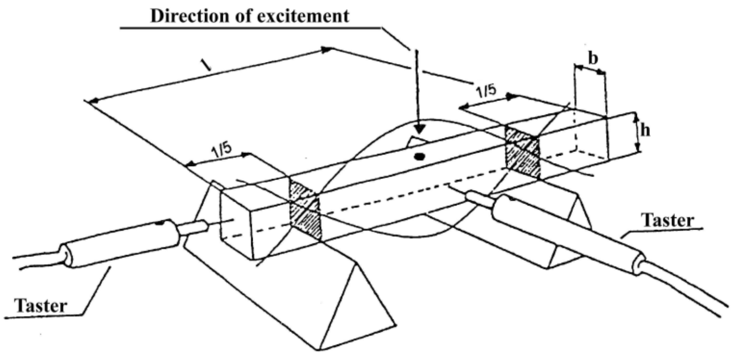

Fig. 1. Measuring device for the resonance frequency method

The third technique used for the sound velocity measuring was Card PCUS 10 NF from the Fraunhofer Institute for Nondestructive Evaluation Methods, Saarbrücken (Germany) with sensors from Krautkrämer, type K0,1G (cylindrical, diameter: 44,5mm). Signals were made observable on a screen with this instruments. Measurements were taken in transmission modus on the third wave. The amplification was set so that the wave filled 80% of the maximum screen height. Measurements were taken on the flank of the wave at 40% of the screen's height. Different frequencies were utilized to propagate ultrasonic wave through material. Transit time was measured for various WBCM specimens to determine wave speed. Sound velocity "ν" was determined by the equation

$$\nu = \frac{l}{\Delta t - \Delta t_0} \quad (4)$$

where: l – length of specimen; Δt – duration of transmission; Δt_0 – buffer road.

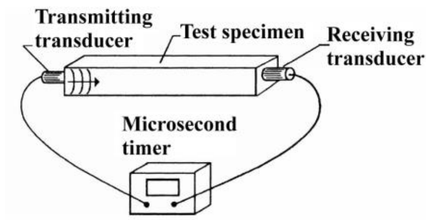

Fig. 2. Ultrasonic measurement system used to measure sound velocity in various wood composites

The specimens were fastened into a fixing apparatus as shown in Fig.3 to ensure consistent measuring conditions. The pressure applied was 25 N. The Ultrasonic Coupling Medium, ZG-F from Krautkrämer was used.

A linear regression analyses were used to examine the relationship between measured non-destructive parameters and the mechanical properties of the material tested. Non-destructive parameters included sound velocity (SV), resonance frequency (RF), dynamic modulus of elasticity (MOE_{DYN}).

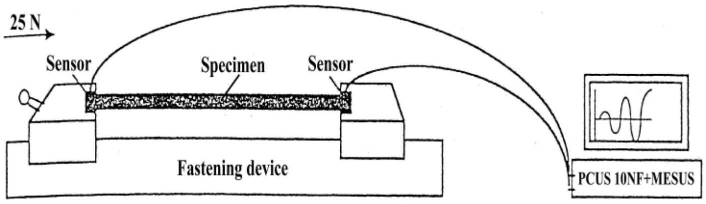

Fig. 3. Experimental setup for the sound velocity method

A linear regression analysis was performed to establish relationships between SV/RF and MOE/MOR.

RESULTS AND DISCUSSION

Influence of measuring direction. SV and RF measured with different apparatus in both parallel and perpendicular directions for OSB, MDF and PB are summarised in Table 1.

Sound velocity in the various WBCM ranged from approximately 2118 to 3294 m/s. These values were largely dependent on the material direction through which the waves were propagated. In the parallel direction of production, the wave speeds ranged from 2271 to 3294 m/s, whereas speeds from 2118 to 2991 m/s, were observed in the perpendicular direction of production.

It can be seen that sound velocity values along the perpendicular direction were smaller than the corresponding values in the parallel direction for MDF, PB and OSB, indicating the anisotropic properties of the

Table 1. Acoustic properties of different composite materials

Material Type	RF [Hz]	SV*[m/s] through the thickness of board and frequency 50 kHz	SV [m/s] measured in-plane of board with			
			BP 5 and frequency 50 kHz	PCUS 10 NF and frequency		
				50 kHz	100 kHz	200 kHz
Parallel Direction						
MDF	284 (14)	942 (20)	2618 (62)	2608 (86)	2611 (74)	2677 (76)
PB	242 (13)	644 (33)	2271 (48)	2112 (69)	2128 (83)	-
OSB	404 (8)	907 (45)	3294 (74)	-	-	-
Perpendicular Direction						
MDF	274 (10)	923 (37)	2555 (55)	2509 (36)	2529 (43)	2602 (50)
PB	219 (7)	660 (34)	2118 (24)	1961 (56)	1992 (64)	-
OSB	279 (9)	912 (45)	2991 (60)	-	-	-

*Values in parentheses are standard deviations based on fifty specimens

products. For MDF the difference was less significant, indicating more uniform properties between the two principal directions.

Among the products tested, OSB had the largest SV at a given frequency level. At 50 kHz frequency, the velocity averaged about 3294 m/s for OSB in parallel direction. The speed reduced to about 2271 m/s in perpendicular direction. But it should be noted that the SV through the thickness of all types of board practically does not average independing on the direction of production.

MOE and MOR prediction. The mechanical properties of the different composite materials are given in the Table 2. It can be seen that the values of MOE, calculated directly from the resonance frequency and sound velocity according to equation (1) and (3), differ from the values from the static testing of MOE_{DIN}. A linear regression analysis was performed to establish MOE_{DIN}-SV, MOE_{DIN}-RF, MOR-SV, MOR-RF, MOE_{DIN}-MOE_{SV}, MOE_{DIN}-MOE_{RF}, MOR-MOE_{SV}, MOR-MOE_{RF} relationships for the materials tested. Table 3 and 4 list the results of regression analysis. The relationships were linear for most materials in both parallel and perpendicular directions.

The best models for prediction of MOE for MDF and PB are given by the sound velocity in parallel to the direction of production. The correlation coefficients were R^2=0,86 and R^2=0,71 accordingly. For OSB in parallel direction the better correlation exists between static MOE and resonance frequency (R^2=0,53). A good correlation exists between MOR and SV for MDF (R^2=0,75). The prediction of MOR for PB and OSB using both SV and RF with simple linear regression gives very poor results. The best result for PB is found using the SV in parallel direction (R^2=0,42).

Table 2. Comparison of MOE_{DYN}, MOE_{DIN}, and MOR for different composite materials

Material Type	MOR* [N/mm²]	MOE_{DIN} [N/mm²]	MOE_{RF} [N/mm²]	MOE_{SV} [m/s] with			
				BP 5 and frequency 50 kHz	PCUS 10 NF and frequency		
					50 kHz	100 kHz	200 kHz
Parallel Direction							
MDF	42,3 (3,1)	3929 (294)	5561 (604)	5297 (263)	5253 (355)	5267 (305)	5534 (315)
PB	13,1 (1,2)	2406 (147)	3817 (478)	3511 (227)	3038 (260)	3087 (293)	-
OSB	39,7 (4,1)	6300 (324)	7825 (391)	7184 (349)	-	-	-
Perpendicular Direction							
MDF	38,5 (3,2)	3558 (283)	4994 (429)	4968 (281)	4788 (201)	4864 (222)	5153 (270)
PB	12,5 (1,0)	2014 (89)	3052 (216)	3019 (96)	2590 (166)	2674 (184)	-
OSB	22,7 (2,5)	2860 (128)	3782 (251)	5982 (300)	-	-	-

*Values in parentheses are standard deviations based on fifty specimens

It was found that a high degree of correlation exists between dynamic and static MOE. A good correlation also has been found for MDF in both directions and for PB in parallel direction, between the MOE, tested by sound velocity, and the MOE, tested by static method (R^2=0,88, R^2=0,86 and R^2=0,86 accordingly). For OSB in parallel direction for MOE tested by resonance frequency, we have obtained an R^2=0,64 with MOE_{DIN}. The correlation coefficient is higher here for resonance frequency than for sound velocity.

Table 3. Regression results on relationship between bending MOE (N/mm^2), MOR (N/mm^2) and SV (m/s). Model: MOE or MOR=a + b*SV

Material Type	Parallel Direction			Perpendicular Direction		
	a	b	R^2	a	b	R^2
			MOE_{DIN} – SV relationship			
MDF	-7519,3	4,3697	0,86	-7679,7	4,3982	0,73
PB	-3455,7	2,5805	0,71	-549,59	1,2103	0,10
OSB	3909,4	0,7259	0,03	-130,83	1,0001	0,22
			MOE_{DIN} – MOE_{SV} relationship			
MDF	-1587,9	1,0407	0,88	-1048	0,9271	0,85
PB	304,2	0,5985	0,86	338,14	0,555	0,36
OSB	4016,5	0,3179	0,12	1519,7	0,2241	0,28
			MOR – SV relationship			
MDF	-72,246	0,0437	0,75	-87,752	0,0494	0,70
PB	-23,115	0,0159	0,42	-1,7635	0,0067	0,03
OSB	51,542	0,0036	0,01	-7,6921	1,0102	0,06
			MOR – MOE_{SV} relationship			
MDF	-13,025	0,0104	0,77	-14,027	0,0106	0,84
PB	0,1136	0,0037	0,51	1,4834	0,0037	0,13
OSB	32,995	0,0009	0,01	5,4642	0,0029	0,12

Table 4. Regression results on relationship between bending MOE (N/mm^2), MOR (N/mm^2) and RF (Hz). Model: MOE or MOR=a + b*RF

Material Type	Parallel Direction			Perpendicular Direction		
	a	b	R^2	a	b	R^2
			MOE_{DIN} – RF relationship			
MDF	1902,1	7,1341	0,12	-1327,6	17,843	0,34
PB	1329,6	4,453	0,15	1456,2	2,5509	0,04
OSB	-4727,7	27,232	0,53	1145,9	6,1454	0,17
			MOE_{DIN} – MOE_{RF} relationship			
MDF	2564	0,2458	0,26	962,74	0,5211	0,59
PB	1839,2	0,1485	0,23	1527,2	0,1594	0,15
OSB	1608,6	0,5966	0,64	1897,2	0,255	0,24
			MOR – RF relationship			
MDF	23,951	0,0642	0,08	-16,487	0,20006	0,32
PB	3,9742	0,0377	0,17	-0,1419	0,0579	0,18
OSB	-4,9947	0,1104	0,05	6,1264	0,0596	0,05
			MOR – MOE_{RF} relationship			
MDF	29,267	0,0023	0,20	9,3626	0,0058	0,54
PB	8,5924	0,0012	0,23	4,8257	0,0025	0,30
OSB	-14,409	0,0032	0,10	14,493	0,0022	0,05

The prediction of the MOR is done by correlating the dynamic MOE calculated for each non-destructive test method with the MOR. The best result for the prediction of MOR, using linear regression models was achieved for MDF in both directions of production with the dynamic MOE, calculated from the sound velocity. In this case, RF would not be a good predictor of MOE and MOR for MDF and PB.

It should be noted that the dynamic methods all give higher values for MOE than DIN testing. Figure 4 shows a clear difference for OSB between dynamic and static MOE in parallel and perpendicular to the direction of production. The similar trend is observed for PB.

Influence of frequency. It was found that with increasing frequency the sound velocity also rises (Fig.5). But it was not possible to demonstrate a clear influence of higher frequency (200 kHz for PB, 100 kHz and 200 kHz for OSB) on sound velocity. The results were subject to considerable fluctuations. Only low frequency 50 kHz was able to sufficiently penetrate the OSB. The reason for this could be that the PB and OSB are not a homogenous materials due to its distinctive density profile perpendicular to the board surface. The MDF is more homogenous material with uniform fibers, with less volume of voids between fibers than PB and OSB.

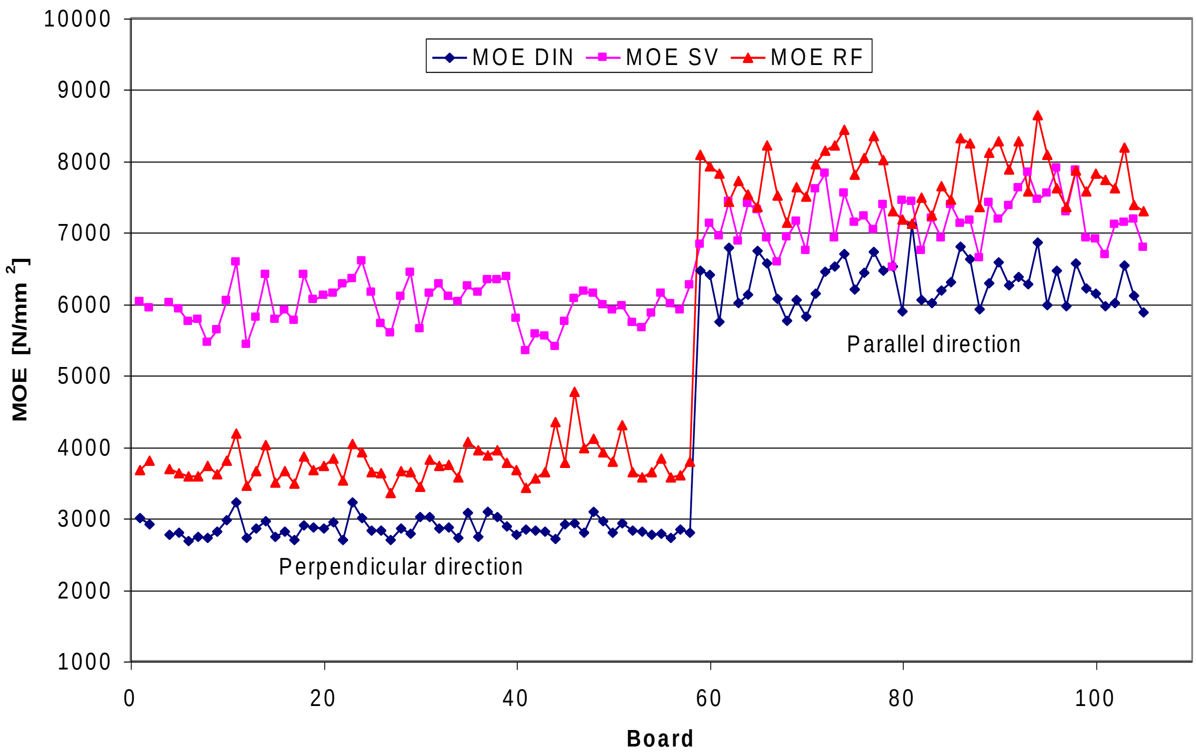

Fig. 4 Comparison static MOE – dynamic MOE for all methods for OSB

Influence of temperature and relative air humidity. The mechanical properties of WBCM are strongly affected by the fluctuation of relative humidity and temperature. In order to understand the interaction of WBCM with environmental conditions it is necessary to consider different levels of temperature and relative humidity which induce moisture content fluctuation.

A very good correlation has been found between the sound velocity (both in-plane and through the thickness of board) and the temperature of PB specimens (R^2=0,99 and R^2=0,97 accordingly). As can be seen from the Figure 6 the sound velocity is reduced with the rise of the temperature of board. It can be explained that with rise of temperature the elastic properties of wood are changed, namely the elastic modulus of elasticity is lowered, and therefore the sound velocity is reduced.

The equation between the velocity of sound and temperature written as:

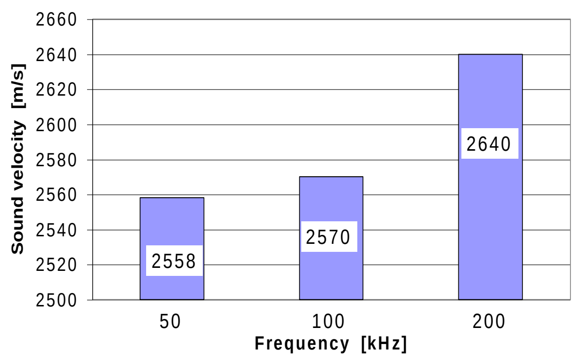

Fig. 5. Influence of the frequency on the sound velocity for MDF

in-plane of board $$SV = -3{,}848 \cdot T + 2370{,}6$$ (R^2=0,99)

through the thickness of board $$SV = -2{,}4386 \cdot T + 761{,}44$$ (R^2=0,97)

where: T – temperature of board.

The effect of temperature on the RF has not been investigated.

As for the results concerning the influence of RH on the sound velocity in PB (Fig.7) note that the ultrasonic velocity generally is reduced as board relative humidity rises (50% to 90%), as expected from the know effect of humidity on the elastic properties of board. At 50% RH, the velocity averaged about 2289 m/s. The speed reduced to about 1960 m/s at the 90% RH level. There was about 14 percent reduction in SV for the 40 percentage units increase in board RH. As shown, for every percent of RH increase, SV decreased about 8,2 m/s.

Influence of the thickness and width of specimen. It was found that sound velocity rises with increasing frequency and decreasing thickness of boards. But, the total average values of SV for all specimens differ little.

It has been also found in the experiments that the width of the PB specimens in the tested width range (from 20 to 200 mm) does not affect the values of the sound velocity (see Table 5) under frequency 50 kHz. With increase of the frequency from 50 to 200 kHz the SV rises, but if for width 20 mm the SV ranged from 1832 to 3569 m/s, then for width 200 mm the SV ranged from 1887 to 1975 m/s. Note that with increase of width of specimens and increase of frequency more strongly attenuation of penetrated signal is observed.

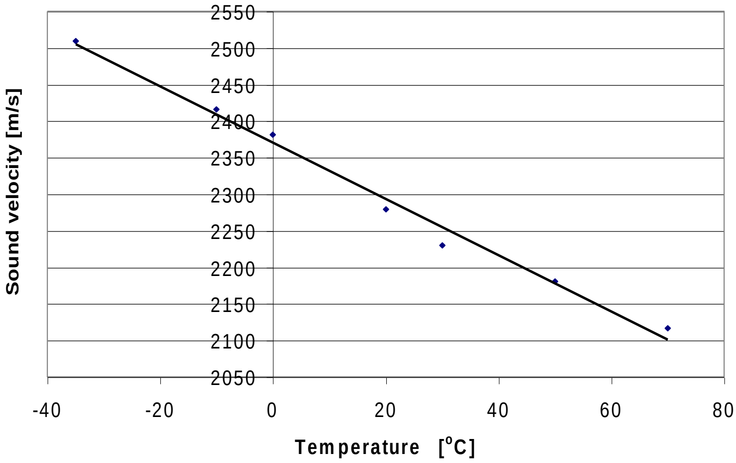

Fig. 6. Influence of the temperature on the sound velocity in-plane of particleboard

Influence of board's structure. The measurements of 7 types of PB (with different density and thickness) brought different sound velocity for all board types. The results of this experiment are shown in Figures 8, 9.

The structure of board was estimated by combined parameter such as surface density (surface density = density x thickness of board). Figure 8 shows the relationships between the average density and sound velocity in-plane and through the thickness of board. It can be seen that there is only a weak correlation between the sound velocity and average density. The experimental correlation coefficient established between the sound velocity and the surface density was higher (R^2=0,79). Therefore, surface density could be used to quality control of PB with different structure. Note that the sound velocity generally increases linearly with decreasing surface density and with increasing average density of board.

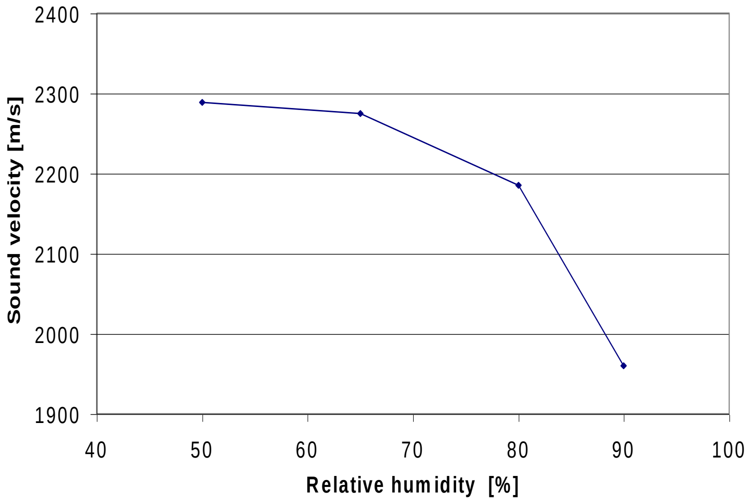

Fig. 7. Influence of the relative humidity on the sound velocity for particleboards

Tabele 5. Sound velocity about different width of specimen

Dimensions of specimen [mm]	Density [kg/m^3]	Sound velocity [m/s] about frequency 50 kHz	100 kHz	200 kHz
20 x 20 x 16	664 (14)	1832 (93)	2437(374)	3569 (764)
40 x 40 x 16	677 (17)	1910 (140)	2198 (220)	2611 (283)
60 x 60 x 16	673 (15)	2201 (97)	2391 (250)	2901 (175)
80 x 80 x 16	678 (15)	2232 (75)	2494 (163)	2809 (132)
100 x 100 x 16	675 (20)	2195 (96)	2395 (140)	2614 (142)
150 x 150 x 16	689 (7)	2073 (148)	2312 (208)	2411 (203)
200 x 200 x 16	659 (6)	1887 (90)	1924 (131)	1975 (139)

*Values in parentheses are standard deviations based on twenty specimens

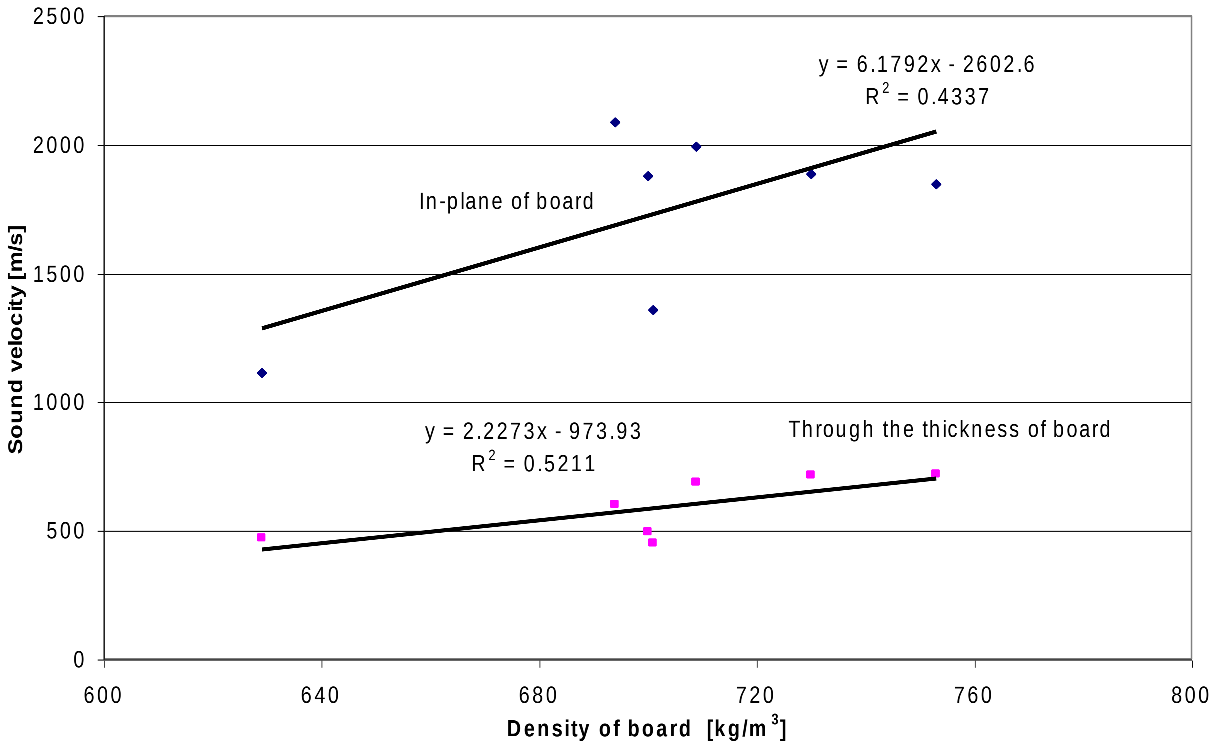

Fig. 8. Influence of board density on the sound velocity in particleboards

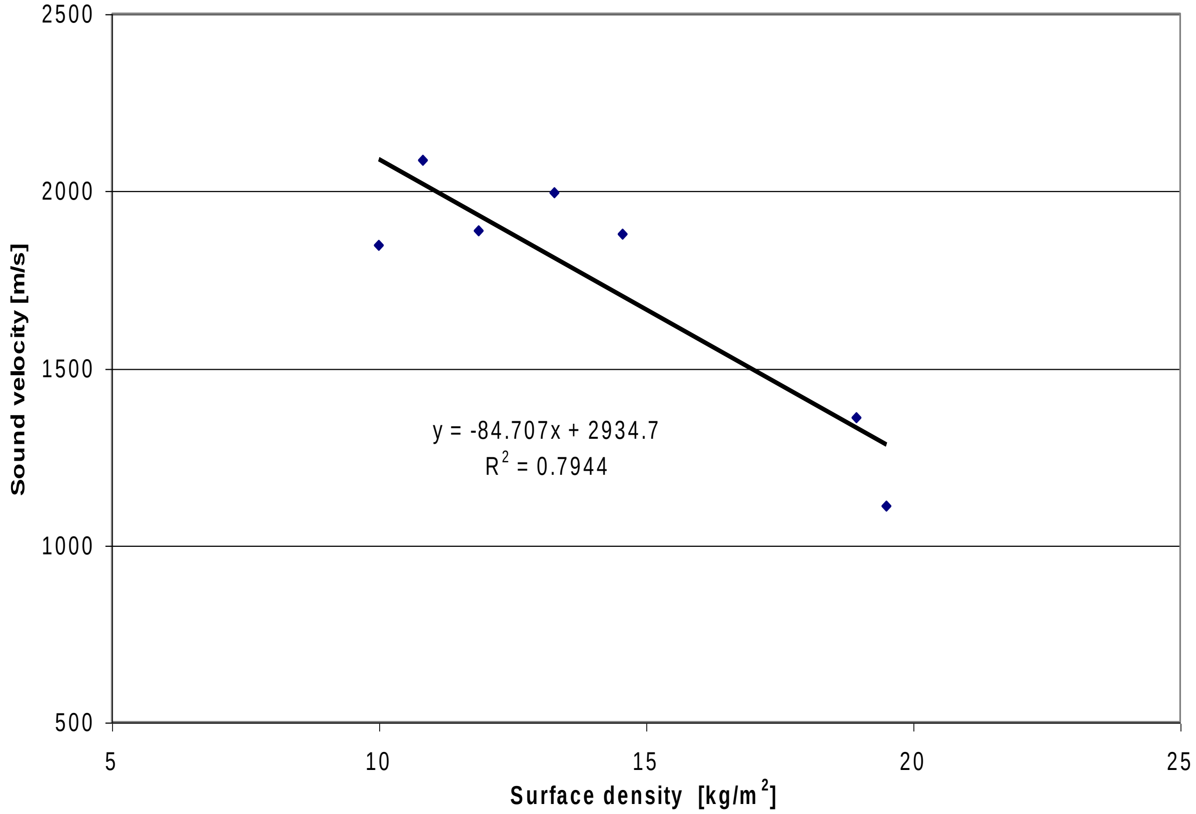

Fig.9. Influence of the surface density on the sound velocity in particleboards

CONCLUSIONS

Based on the results presented in the study, the following conclusions can be made:

1. Sound velocity in the various WBCM ranged from approximately 2118 to 3294 m/s. These values were largely dependent on the material direction through which the waves were propagated. The larger values of sound velocity are observed for measurements parallel to the direction of production. Among the materials tested, OSB had the largest sound velocity. The resonance frequency data for all type of materials from this study show a similar trend as the sound velocity data. Sound velocity through the thickness for all types of materials practically does not average independing on the direction of production.
2. There is a close relationship: a) between MOE_{DIN}, MOR and sound velocity for MDF (both direction of production); b) between MOE_{DIN} and sound velocity for PB (in parallel direction of production). Only a weak correlation exists: a) between MOR and SV for PB (in parallel direction); b) between MOE_{DIN} and RF for OSB (in parallel direction). A very poor correlation exists: a) between MOE_{DIN}, MOR and SV for OSB; b) between MOE_{DIN}, MOR and RF for MDF and PB. In this case, only sound velocity method can be used to obtain useful predictions of MOE, MOR for MDF and PB.
3. A strong correlation was observed between static and dynamic MOE, calculated from the sound velocity for MDF and PB. For OSB a better relationship was found between static and dynamic MOE, calculated from resonance frequency. Note that the values of MOE, calculated directly from the resonance frequency and sound velocity were higher than the values from the static testing of MOE.
4. A good correlation was found between MOR and dynamic MOE, calculated from sound velocity, only for MDF. For the comparison between MOR and dynamic MOE_{SV}/MOE_{RF} only a weak correlation exists.
5. At 100 and 200 kHz frequencies were observed a significant attenuation of signal that it was impossible to measure the sound velocity in PB and OSB.
6. Results on the relationships among sound velocities, temperatures and relative humidity may help in developing an apparatus for *in situ* testing of WBCM. The temperature calibration can easily be done in an on-line system for NDT with ultra sound. There might be some problems with curing effects though, if the boards are tested shortly after pressing.
7. The thickness of board and width of specimen do not affect on the sound velocity under 50 kHz frequency. With decreasing width of specimen and increasing values of frequency to 100 or 200 kHz the values of sound velocity increases.
8. The surface density can be used to quality control of PB with different structure.

Finally, it is important to note again that the sound velocity technique is a powerful tool for wood composites in industry.

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