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SPECIFIC MODULUS AND DENSITY PROFILE AS CHARACTERIZATION CRITERIA OF PREFABRICATED WOOD COMPOSITE MATERIALS

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Abstract

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Wood based product industry has developed and modified a wide range of products to cater changing demands of construction industry. Development of a product necessitates characterization to ensure compliance to established standards. Traditionally a product was characterized by properties like bending properties, density and swelling factor etc. Whereas, advances in technology has introduced more sophisticated parameters which represent a combination of various classical factors and provide more practical and detailed information. In this study, we procured four different types of commercial products, viz. Gypsum board, cement board, oriented strand board and gypsum fiber board and tried to characterized them using density profile ratio and stiffness ratio. We observed some interesting empirical relations between various parameters as represented in various plots.

Keywords: specific modulus, composite materials, density profile, wood

INTRODUCTION

Changing requirements of construction industry necessitates inclusion of prefabricated and functionally optimized products. Various products have been developed to optimize specific characteristic to meet the demands. Product like cement board (Fan *et al*., 2006; Pereira *et al*., 2006), oriented strand board (WU, 1999; Painter *et al*., 2006; Jin *et al*., 2009), gypsum board and gypsum fiber board (Fowler, 1997; Lynn and Blaine, 2001) have been widely studied and utilized in construction industry.

Vertical density profile is relatively new technique in comparison to classical mechanical properties. Many attempts have been made to correlate it with other parameters (Harless *et al*., 1987; Wong *et al*., 1999; Winistorfer *et al*., 2000) and it widely reported to have empirical relation with MOR. An Ashby plot, is a scatter plot which displays two or more properties of many materials or classes of materials. it is very useful for the stiffness representation with Young's modulus on one axis and density on the other axis, with one data point on the graph for each candidate material. On such a plot, it is easy to find not only the material with the highest stiffness or that with the lowest density, but that with the best ratio of stiffness and density. Specific modulus has also been used to characterize various wood based composites (Bogoeva-Gaceva *et al*., 2007; DN and JP, 1999) and it is derived from basic quantities. We also, introduce a ratio which included data from density profile and absolute density. These derived quantities from basic values serve as sophisticated and complex quantities with special place in evaluation and application of composites.

MATERIALS AND METHODS

In this research commonly used composite materials in wood industry are evaluated. Samples of Cement board 18 mm thick (CKD18) produced by CIDEM Hranice, a. s. – CETRIS divison, Oriented strand board 18 mm thick (OSB18) produced by KRONOSPAN Jihlava, Gypsum board 18 mm thick

(SKD18) and 12.5 mm thick (SKD12.5) produced by RIGIPS s. r. o; Saint – Gobain concern, gypsum fiberboard 12.5 mm produced (SVD12.5) by Fermacell Gmbh were evaluated. Density, swelling, water absorption, density profile, hardness and bending properties were measured. All samples were conditioned in 65 ± 5% relative humidity and 20 ± 2 °C for time than uniform weight and moisture content was achieved.

Measurement of Density

Density evaluation was done according to EN 323 standard when all samples had square shape with edge length of 50 mm. For density measurement of gypsum boards and gypsum fiberboards EN 520 standards were used, where dimensions of samples were 400 × 300 mm². All samples were of specified dimensions and weight, density was calculated as per following equations:

$$V = a \times b \times c, (\mathrm{m^{-3}})$$

$$\rho = \frac{m}{V}. (\mathrm{kg \cdot m^{-3}})$$

Density Profile Ratio Specification

To achieve final comparison the density profile ratio is was defined, where minimal value (in the middle of board) and maximal value (peaks of density profile) were used in following equation:

$$pratio = \frac{\rho_{max} - \rho_{min}}{\rho_{min}}.$$

Specific Modulus Determination

Specific modulus was determined by following equation. The value represents the stiffness of material on gram per square centimeter.

$$pratio = \frac{\mathrm{MOE}}{\mathrm{Density}}.$$

Measurement of Swelling Properties

Swelling parameters was measured according to EN 317, EN 520, EN 15283 – 2, Samples dimension and weight were measured and placed in distilled water (Ph 7 and 20 °C temperature) for 24 hours. Interval of 2 hours and 24 hours for evaluation of swelling were used and water absorption after 2 and 24 hours in water was obtained respectively:

$$G = \frac{t_2 - t_1}{t_1} \times 100. (\%)$$

Swelling of panel (G); thickness before water soaking (t_1); Thickness after water soaking (t_2).

$$WA = \frac{m_2 - m_1}{m_1}. (\%)$$

Water absorption (WA); weight before water absorption (m_1); weight after water absorption (m_2).

Measurement of Density Profile

All samples by density profile are specified. Samples with dimensions 50 × 50 mm² were in X – ray denselab machine evaluated, where density in cross section is statistically evaluated by denslab software.

Measurement of Hardness

Hardness of boards were measured as per EN 49 0136 standards. Conditioned samples with dimensions 50 × 50 mm² were used for evaluation. In test the metal sphere was pushed into the sample, where radius and force used for pushing is used for hardness specification:

$$H_w = \frac{4 \times F}{3 \times \pi \times r^2}. (\mathrm{N \cdot mm^{-2}})$$

Hardness (H_w); Force used for pushing of sphere in material (F); radius of sphere (r).

Measurements of Bending Properties

Bending properties were determined according to EN 310. Samples with length defined as a twenty-time thickness plus fifty and with width 50 mm were tested in three-point bending test. Two groups of samples were produced, one group of test samples were produced along the boards and second group across the board to obtain full specification which can be varying in these directions. Zwick®Z050 for mechanical testing was used and connected with testXpert software provided data evaluation. The Modulus of rupture (MOR) and modulus of elasticity (MOE) was calculated as per:

$$MOR = \frac{3 \times F_{max} \times l_1}{2 \times b \times t^2}.$$

Being F_{max} maximum load [N], l_1 distance between the centers of two supports [mm], b the width of the test specimen [mm], t thickness of the test specimen [mm].

$$MOE = \frac{l_1^3 \times (F_2 - F_1)}{4 \times b \times t^3 \times (U_2 - U_1)}.$$

Being l_1, b and t as above, $(F_2 - F_1)$ the increment of load in elastic region of the load-deformation curve, where F_1 was 10% and F_2 40% of the maximum load F_{max}. $(U_2 - U_1)$ is the increment of deflection corresponding to $(F_1 - F_2)$ in load-deformation curve.

The measured data was analyzed using STATISTICA 10 software. First, the exploratory data analysis (EDA) was carried out. Based on these methods, the data were evaluated for their degree of symmetry and kurtosis, local concentration of data, outliers and consistence with normal distribution. The Q–Q plot with the implemented Shapiro-Wilk test was also used to assess the normal distribution.

RESULTS

Density

In Tab. I, the density measurement is included, where highest value of density by CTD material 18 mm thick was reported (1355 kg·m^{-3}). The lowest value with OSB 18 mm thick was achieved (581 kg·m^{-3}).

Swelling of Boards

For total swelling determination the same samples size and conditions were utilized. Swelling in percent is reported in Tab. I. The highest values of swelling after 2 hours was observed for OSB (8.75%) and SKD (6.82%). SKD with thickness 12.5 mm showed a swelling of 6.82% and SVD with 12.5 mm showed 2.24%. The lowest value was shown by CTD, where the swelling of 0.62% was observed. On the other hand swelling after 24 hours provided different results. Difference of OSB swelling factor for the interval of 2 and 24 hours was significant, the value of swelling was increased by more than twice (19.45%). On the other hand, the swelling change of CTD was not significant for the interval of 2 and 24 hours.

Total Absorption of Water by Materials

In Tab. I are the observed results of total water absorption after 2 hours. SKD 12.5 mm presented highest water absorption, where the total absorption of 62.78% was reported. SKD 18 mm has water absorption 48.58%. On the other hand the lowest values of CTD 18 mm were reported (9.02%). Water adsorption of OSB at 34.17% was found and 29.57% for SVD.

Density Profile

Density profiles of various materials are reported, whereas OSB presented peak density near of the surface, CTD showed a fluctuating density profile and nearly constant density profile by SVD and SDK (Fig. 1).

Hardness Test

Highest hardness of 57.53 MPa shown by CTD (18 mm). SVD (31.52 MPa) and OSB (33.09 MPa) achieved statistically insignificant results among each other. The lowest value of 10.81 MPa was reported by SDK. All results are shown in Tab. II.

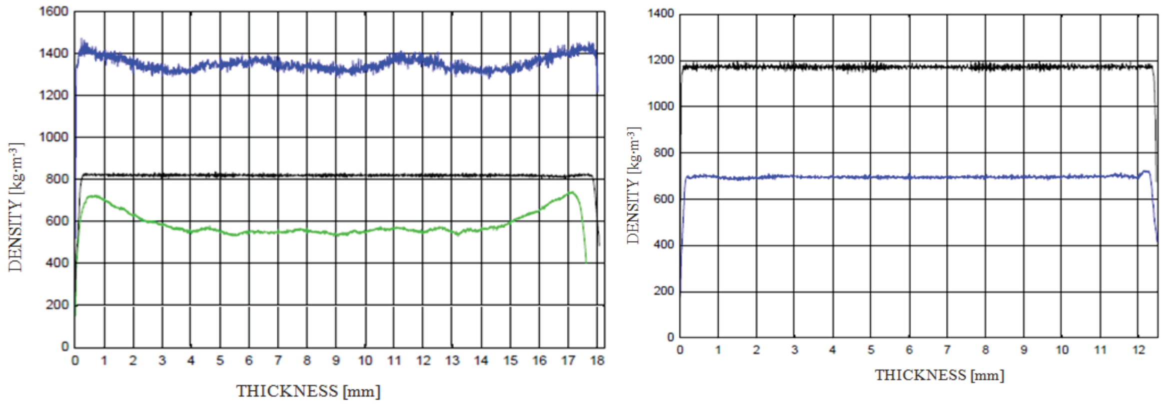
Bending Properties

The highest value of MOR was presented by OSB, where both directions were tested. Longitudinal direction reported 24 MPa and transversal direction 14.42 MPa. The MOR 9.45 MPa was found with CTD 18 mm. By SDK and SVD of 12 mm thickness was found to have a value on the similar level of 5.86 and 5.63 MPa. On the other hand the lowest value 4.28 MPa was reported by SDK. All results are in Tab. II.

MOE evaluation provided data which are included in Tab. II CTD 18 mm provided highest

I: *Descriptive statistics of physical properties*

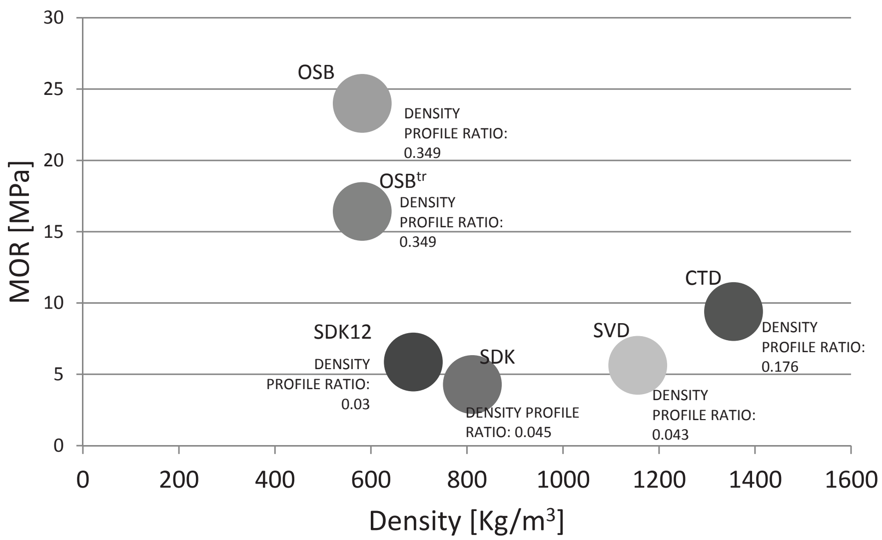
Physical properties	Material	min	Max	mean	st.dev.
Density [kg/m^3]	CTD18	1312.68	1432.15	**1355.29**	25.06
	OSB18	502.9	638.73	**581.82**	26.63
	SKD18	797.87	824.96	**811.14**	7.41
	SKD12.5	665.58	701.07	**688.22**	7.16
	SVD12.5	1090.15	1185.12	**1155.63**	20.54
Density profile [kg/m^3]	CTD18	1253.21	1473.25	**1351.44**	
	OSB18	553.12	742.5	**587.1**	
	SKD18	801.18	836.75	**815.34**	
	SKD12.5	703.59	724	**691.6**	
	SVD12.5	1152.31	1199	**1169.22**	
Swelling2h [%]	CTD18	0.06	2.27	**0.62**	0.05
	OSB18	1.95	13.82	**8.75**	3.8
	SKD18	4.04	5	**4.29**	0.28
	SKD12.5	6.44	7.49	**6.82**	0.23
	SVD12.5	1.32	3.07	**2.24**	0.51
Swelling24h [%]	CTD18	0.05	2.43	**0.67**	0.05
	OSB18	11.2	24.87	**19.45**	11.2
Total water absorption	CTD18	8.08	10.26	**9.02**	0.51
	OSB18	30.63	37.31	**34.17**	1.74
	SKD18	47.62	49.99	**48.58**	0.59
	SKD12.5	58.5	67.62	**62.78**	2.08
	SVD12.5	28.28	32.83	**29.57**	1.13



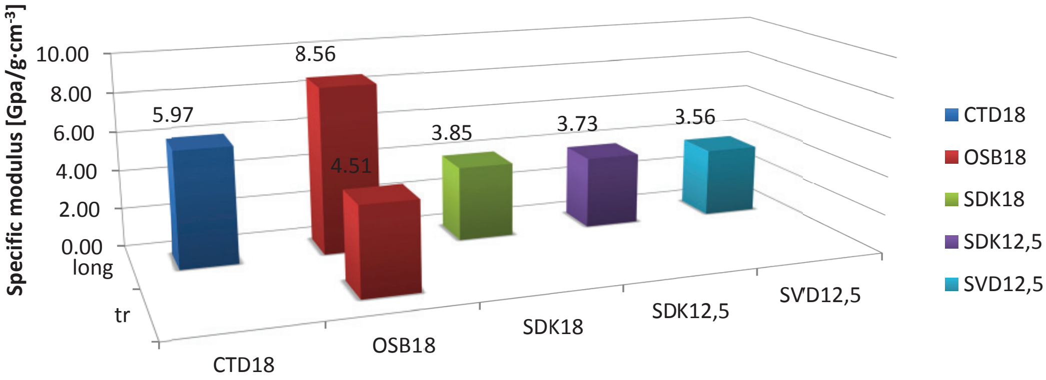
1: *Density profile specification (Blue left – CTD18; black left – SKD18; green left – OSB18; black right – SVD12; blue right; SKD12)*

II: *The mechanical properties specification; Modulus of elasticity (MOR), modulus of rupture (MOR)*

Mechanical properties	material	min	Max	Mean	st.dev.
	CTD18	46.37	76.57	**57.53**	7.97
	OSB18	21.33	50.57	**33.09**	6.76
Hardness [MPa]	SKD18	15.27	17.22	**15.97**	0.43
	SKD12.5	10.18	11.34	**10.81**	0.28
	SVD12.5	26.16	36.59	**31.52**	2.52
	CTD18	2.06	11.57	**9.45**	1.95
	OSB18	19.75	29.78	**24**	2.88
MOR [MPa]	OSB^{TR}	16.42	14.49	**18.24**	1.24
	SKD18	4.01	4.62	**4.28**	0.15
	SKD12.5	5.19	6.45	**5.86**	0.39
	SVD12.5	4.78	6.66	**5.63**	0.56
	CTD18	6109.08	9454.99	**8086.66**	821.4
	OSB18	4287.93	5804.96	**4981.58**	408.7
MOE [MPa]	$OSB18^{TR}$	699.85	2987.82	**2625.27**	190.01
	SKD18	2505.9	3304.29	**3124.28**	187.2
	SKD12.5	2679.34	313.08	**2564.77**	83.28
	SVD12.5	4435.88	745.67	**4117.55**	190.29



2: *Ashby plot of MOR based on density, correlated with density profile ratio*



3: *Specification of various panels by specific modulus*

performance of 8086 MPa followed by OSB (4981 MPa in longitudinal direction) and 2625 MPa in transversal direction. By SDK 12.5 mm was MOE 2564 MPa achieved.

Specification of MOR by Density and Density Profile Ratio

Density ratio in form of Ashby plot is in Fig. 2. In this graph the viable comparison based on density profile is successfully presented. Although the materials CTD; SVD and SDK occurring higher mean density then OSB, they have significantly lower MOR. That means they most likely will be crashed by lower forces than OSB despite the higher density i.e. weight.

Specific Modulus

The specific modulus presented by mean MOE on g·cm^{-2} are shown in Fig. 3, whereas highest values are shown by OSB in longitudinal (long) direction, followed by CTD and with almost half values are presented boards with gypsum bonding. On the other hand the OSB in transversal direction is significantly lower, compared to the longitudinal direction, therefore the favorable usage direction must be considered.

DISCUSSION

The obtained results overviewed basic as well as derived property parameters of commonly utilized materials in wood-building constructions. Firstly, the density as a utilization criterion is evaluated, wherein density profile provides strong and precise basis for prediction of material properties. Major properties, modulus of rupture (MOR) and modulus of elasticity (MOE) are widely reported to be connected with the density (Wong *et al.*, 1999; Steward and Lehman, 1973; Kelly *et al.*, 1977). The highest values of total density were showed by CTD 18 mm thick and SVD 12.5 mm thick, where density exceed 1000 kg·m^{-3}. On the other hand comparatively low density was observed for OSB (581.82 kg·m^{-3}). Swelling of materials was presented as a change of thickness after 24 hours water soaking. CTD of 18 mm thick presented lowest swelling of 0.65%, SVD swelling was found to be 2.24%, SDK presented swelling after 2 hours 4.29% for 18 mm and 6.82% for 12.5 mm. All of this data fits into range specified by manufacturing company and commercial needs which has limit of 4 to 8% (Rigips). Highest values of swelling was shown by OSB, where swelling represented change 8.75% after 2 hours and 19.45% after 24 hours. Furthermore, this data also follows standardized specifications as reported by manufacturer.

High density of materials is related to the material structure and quantity of material. Total density is influenced by gypsum or cement in structure also. On the other hand the comparative data in Fig. 2. assess the importance of density profile formation. Highest values of density profile ration are shown by OSB in longitudinal direction although the total density of panel was not the highest. The difference of MOR between OSB and other panels may be caused also by low density profile ratio derived from flat and even density profile. The OSB presented by uneven density profile with high peak density and low density in the center. The high peak density performs better in bending stress due to higher stiffness. Nevertheless orientation must be considered due to significant change of MOR with change in direction.

The specific stiffness than provide correlations of stiffness per unit of weight. The better performance was presented by OSB, whereas specific stiffness in longitudinal direction was observed at the level of 8.56 GPa/g·cm^{-2}, which is by 30% higher than other tested materials.

CONCLUSION

In off-site manufacturing technology, prefabricated materials play a major role in construction industry. Products have been developed with improved moisture, fire and acoustic resistance as well as light weight and improved mechanical properties. As the range of material widens, so does the need of characterization parameters. Traditionally, a prefabricated material comes with specifications like bending properties, swelling factor, density etc. whereas highly informative parameters like vertical density profile still needs to be adopted by industries. In this study we measured basic mechanical properties and vertical density profile of four commercial products viz. cement board, oriented strand board, gypsum board and gypsum fiber board. On the basis of these measured quantities, we used density profile ratio and specific stiffness as derived parameters. Idea of using density profile ratio is based on its widely reported relationship with MOR. As shown in Fig. 2. Graph between MOR and density, represented for different materials and their orientation in the Ashby-like plot. Value of density profile ratios are also shown in Ashby-like plot, for tested materials of different thicknesses, which is certainly more informative for utilization purpose. The two different correlations in two directions were considered in case of OSB and in Fig. 3, values of specific modulus, also follow the similar trend. Considering the Figs. 2 and 3, it can be said that density profile ratio and specific modulus provides insight into thickness and orientation related properties of materials along with basic mechanical properties. They can be highly useful for optimal utilization of these materials. These parameters may offer more sophisticated and informative alternate to classical parameters as shown in various figures. Nevertheless, more research is required to ascertain replacement and adaption of these quantities into standards.

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