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STRAW PULP AS A SECONDARY LIGNOCELLULOSIC RAW MATERIAL AND ITS IMPACT ON PROPERTIES OF INSULATING FIBERBOARDS PART II. PREPARATION OF INSULATED FIBERBOARDS WITH STRAW FIBER CONTENT

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ABSTRACT

The paper describes the effect of an addition of straw pulp as a partial refund of softwood pulp in the preparation of insulating fibreboard (IFB) on its properties. A preparation of straw pulp from wheat straw and its characterization with the subsequent laboratory preparation of straw insulation fibre board's (SIFB) has been described in Part I. A preparation of mixed pulp prepared by jointly grinding and mixing of straw and wood pulp for required percentage content is described in Part II. The pulp is characterized by fractional composition of fiber length, determining the water retention value (WRV), dewatering rate and defibering degrees (DD). Uncompressed wood – straw insulating fiberboards with various content of straw pulp were prepared from thus characterized pulp. Strength properties - flexural strength and tensile strength perpendicular to the face (internal bond strength) and physical properties - swelling and water absorption were determined for prepared plates. A coefficient of thermal conductivity to characterize the thermal properties of the insulation boards was determined as well.

KEYWORDS: Wood- straw insulating fiberboards, characteristic of pulp, fiber distribution according Brecht-Holl, properties of insulating boards, coefficient of thermal conductivity.

INTRODUCTION

A replacing of fiber from coniferous wood used in the manufacture of insulating fiberboards by secondary raw materials can be an important factor for enhancing the competitiveness of the production. The possibility to replace wood by other material in the manufacture of fiberboards must arise from a similarity of some properties and chemical composition (Han, 1998; Youngquist et al. 1994; Felby et al. 2004).

Board's creating processes during the uncompressed IFB production are based on utilise of physic-chemical and chemical bonds and not least the mechanical forces of interlocking fibers (Lübke et al. 2014). An ability of the replacement fiber of entering into a contact with the wood fibers and forming the same or similar chemical bonds is therefore important. From this point of view monocots plants (family *Poaceae*), belonging to cereals, appear as proper replacement.

Agglomerated materials based on flax, hemp and bagasse are produce worldwide from stalks of plants of the family *Poaceae*. Also insulating materials from the entire wheat straw are manufactured under the different trade names, e.g. Stramit (Lübke et al. 2014). Research of a wood particles substitution by particles of these residues was provided. The effort to create a medium-density particleboard (Mo et al. 2003), respectively a low density particleboard (Wang and Sun 2002) or to find a suitable use of this material, for example sound absorbing construction (Yang et al. 2003) was made. The plants had not been defibered in above mentioned cases. Fiber boards are also produced from rice straw. Cereal straw after chemical treatment is used for a paper production (Youngquist et al. 1994). It can be stated that the stalks of cereals (wheat straw) in terms of tissue and chemical composition are similar to timber. As reported by Reddy and Yang (2005) lignocellulosic agricultural by-products are a copious and cheap source for cellulose fibers.

In addition to that similarity an availability of the secondary material for the production is important. It is obvious that the use of wheat straw, which is produced in amount of 800.000 tons annually in Slovakia, has a real potential for a successful application in the manufacture of uncompressed IFB as a partial compensation of pulp made of coniferous wood. The amount of replaced wood pulp depends on its physic-mechanical and thermal properties of the resulting SIFB.

To determine the properties of a pulp obtained by common milling of wood chips and the chopped straw in a ratio of 1:1 and a pulp where the ratio of straw fiber is in range 0-50 % and also to determine the properties of insulation plates prepared from it is the aim of the work.

MATERIAL AND METHODS

Mixed defibrated pulp was taken from the IFB production line in Smrečina Hofatex, Inc. Banská Bystrica (Slovakia). The pulp was refined under pilot treatment line at Slovak Forest Products Research Institute in Bratislava. Refined wood fiber was removed from the production line DVDN. The following chemicals were used to prepare the pulp: Paraffin emulsion - 1.5 %, starch emulsion – 4 % and aluminum sulphate - 0.7 % measured on a dry substance of wood fiber.

Straw was chopped by a cutter mill MN 300/400 to the size 30- 50 mm. The chopped straw was mixed with the wood chips (50/50) and co-defibered under thermomechanical conditions by the disk devices VP-L-S24. It is fitted with a milling equipment with a 26° cutting angle, a load of the cutting edges of 4.5-7.5 $J.m^{-1}$ and the effective energy consumption of 200-245 $kWh.t^{-1}$. Refining of the mix pulp was provided by the mill Jylhä 0 with KU blades (14° cutting angle) and with the second length of cutting edges of Ls=13.53 $km.s^{-1}$ at 950 RPM. The Asplund pulp was milled using of 30 kW motor under the specific load of cutting edges Bs=1.3 J.m^{-1}.

The wood pulp and the mixed pulp were characterized by a fractionation. The fiber fractionation was performed on a fractional device by Brecht Holl according to STN 500289 (1984). The fibers were also characterized by a dewatering rate, the amount of retained water (WRV) and defibering degrees (DD). Defibering degrees reflect the dewatering time of 128 g fiber in 10 litters of water. The fiber distribution for various values of DD was measured three times.

IFB made of the pulp above described were prepared with a density of 250 kg.m^{-3} at a pilot line Defibrator AB. Preparation of SIFB with the various content of the straw pulp was carried out. The calculated amount of the wet refined wood fiber and the calculated amount of the refined mixed pulp is soaked in water to form water substance with 1.5 % content of the dry matter and allowed to stand with occasional stirring for 2 hours. Calculated amounts of the starch glue, paraffin emulsions and aluminum sulfate was added into the water solution under a permanent stirring in Valley holander. The aqueous suspension is transferred to a dewatering machine. The board is cold-pressed after the dewatering. Drying is carried out in a convection oven at 160°C for 3 to 5 hours depending on the specific weight of the board.

Physic and mechanical properties- a density, flexural strength, tensile strength perpendicular to the board, swelling, water absorption were tested according to the relevant standards STN EN - 622-4 (2000), 310 (1998), 319 (1995), 317 (1995) at prepared boards under laboratory conditions (t=20°C, φ=65 %).

Thermal properties of the insulation boards were determined on a coefficient of thermal conductivity base. The coefficient of thermal conductivity (λ) was measured using ISOMET. The measured samples with dimensions 100x100x thickness (mm^3) were tested under laboratory conditions (t=20°C, φ=65 %) as well with an accuracy of ± 0.001W.m^{-1}.K^{-1}.

RESULTS AND DISCUSSION

Analysis of the properties of the mixed pulp

The mixed pulp with 50 % representation of the straw fiber was characterized above mentioned assays (Tab. 1). The obtained fiber had before the refining a high percentage of particles and also the residual fine fiber less than 240 Mesh determined according Brecht-Holl. To reduce particles and not substantially increase the percentage of residual fine fibers was the aim of the refining. A method of the refining was tested in the laboratory conditions at the pilot plant. The samples were ground on Valley holander for 5, 10, 15 and 25 minutes.

Tab. 1: Parameters measured during a laboratory refining of mixed pulp- wood/straw 50/50.

Measured value		Mixed pulp before the refining	Mixed pulp after 5 min of the refining	Mixed pulp after 10 min of the refining
Brecht- Holl (%)	chips	24.8	19.9	16.9
	40 Mesh	45.6	48.1	50.2
	120 Mesh	10.0	9.7	8.1
	240 Mesh	7.3	6.3	5.7
	residue	12.3	16.0	19.1
Dewatering rate (s) (6 g/1000 g H_2O)	500 ml	5.1	5.2	7.1
	700 ml	13	14.7	19.3
	800 ml	20	24.0	31.2

Measured value		Mixed pulp after 15 min of the refining	Mixed pulp after 25 min of the refining	Refined wood pulp
Brecht- Holl (%)	chips	13.5	8.0	9.3
	40 Mesh	51.1	49.5	54.5
	120 Mesh	10.5	11.5	15.0
	240 Mesh	4.5	6.3	6.9
	residue	20.4	24.7	14.3
Dewatering rate (s) (6 g/1000 g H_2O)	500 ml	11.2	22.0	7.1
	700 ml	29.8	56.4	14.8
	800 ml	48.6	89.7	28.1

The most appropriate milling time resulted from obtained values is between 15 and 25 min, when the percentage of the particles is reduced from the original value of 24.8 % into 13.5-8.0 % and the percentage of long fibers is increased to 49.5-51.1 %. The percentage of residual fine fiber increases at 20.4 % after a 15 min milling. The optimal milling time of 18 min influences from the graph of a dependence of percentage of chips on fine fibers (Fig. 1). The residual fraction should be within 24 % and chips should fall to 12 % on this level of milling.

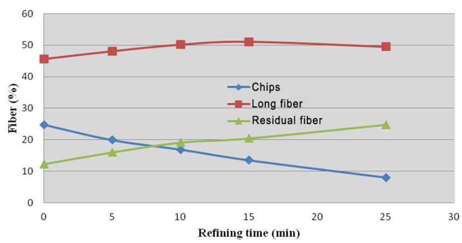

Fig. 1: Analysis of mixture pulp- wood/ straw (50/50) at different time of refining at Valley holander at laboratory conditions.

Analysis of fibers obtained after 18 min refining shows an improved value of a fiber percentage than the mixed pulp obtained from the factory. Content of chips decreased from 24.8 to 11.9 % and content of long fibers collected on Mesh 40 positively increased. Also increased the proportion of short fibers collected on the site of the Mesh 120. The proportion of fine fibers slightly decreased and the proportion of short fibers was not changed. Negative changed occurred by the increase of the residue fine fiber content from 12.3 to 24.8 %. Comparing the mixture pulp (wood/ straw fiber = 50/50) with the wood pulp after refining at the factory, we find significant differences in the percentage of residual fine fibers – 14.3 % for wood pulp and 24.8 % for the mixture (Tab. 2).

A significant difference in fibers collected on the 40 Mesh and also a significant difference in the residual proportion of fine fibers is obvious when comparing the defibered mixture pulp and wood pulp. The above analysis shows that during a common defibering of the mixed pulp with a 50 % share of straw an increasing destruction of straw versus wood occurs. Milling of straw causes a reduced proportion of long fibers and an increased proportion of fine fiber. A portion of fine fibre which formed during the defibering cannot be significantly reduced in the next processing. If straw is refined on pulp with DD 45 seconds, the proportion of fine fibre is only 13.7 % (Lübke et al. 2014).

Tab. 2: Parameters of mixture pulp- wood/straw (50/50) refined at a pilot plant installed in Bratislava and wood pulp refined at the production line of Smrečina Hofatex, Inc.

Measured value		Refined wood pulp from producer	Defibered wood pulp from producer	Defibered mixture pulp 50/50 from producer	Mixture pulp 50/50 refined 18 min at a pilot plant
Brecht-Holl (%)	chips	9.3	31.3	24.8	14.9
	40 Mesh	64.5	70.6	55.6	59.6
	120 Mesh	22.0	11.7	14.8	19.2
	240 Mesh	6.9	8.7	7.3	3.3
	residue	6.6	9.1	22.3	19.8
Dewatering rate (s) (6 g/1000 g H_2O)	500 ml	7.1	2.5	5.1	30.4
	700 ml	14.8	6.4	13.0	75.1
	800 ml	28.1	8.7	20.0	116.9
Defibering degrees (s)		35.0	14.5	39.5	130.0

These facts are reflected on the dewatering time. The dewatering rate is increased to 200 % at defibered mixed pulp (wood / straw = 50/50) in comparing to defibered wood pulp. It is increased to 400 % when the mixed pulp is refined also. Dewatering rate is directly related to defibering degrees (DD). The DD is equals to 39.5 for defibered mixed pulp, while DD is 14.5 for defibered wood pulp. DD= 35 for refined wood pulp taken from the production line and DD=130 for refined mixture pulp (50/50) taken from the pilot plan. The above mentioned composition of fiber size with about 3x higher concentration of the remaining fine fibers increases the value of DD almost 4 times.

The high values of the residual fine fibers result in processing problems in dewatering the fiber mat. An increased percentage of fine fibers causes an increased density of insulation boards, which improves their mechanical properties but crucially influences a coefficient of thermal conductivity.

Physical and mechanical properties of the prepared IFB containing a straw pulp

An evaluation of the physic-mechanical properties of fiber natural materials is based on the molecular composition and structure of the fibers. Straw is considered as itself composite material, comprising cellulose microfibrils bound within an amorphous matrix of lignin and hemicellulose (Hornsby et al. 1997). Many authors attach an important role in strength to lignin. Lignin is a highly crosslinked molecular complex with amorphous structure and acts as glue between individual cells and between the fibrils forming the cell wall (Mohanty et al. 2000). Lignin is first formed between neighbouring cells in a "middle lamella," bonding them tightly into a tissue, and then spreads into the cell wall penetrating the hemicelluloses and bonding the cellulose fibrils (Majumdar and Chanda 2001). Lignin provides plant tissue and individual fibers with compressive strength and stiffens the cell wall of the fibers to protect the carbohydrates from chemical and physical damage (Saheb and Jog 1999). The lignin content of the fibers influences the structure, properties, morphology, flexibility and rate of hydrolysis. The elasticity of the fiber is important property for physic-mechanical properties as well. Fibers with higher lignin content appear finer and will be more flexible (Sukumaran et al. 2001). Generally, fibers with a lower amount of cellulose have higher lignin content.

Boards with a various content of mixture pulp were prepared to determine the effect of the different treatment of a mixed fiber on properties of SIFB. The resulting refined mixed fiber containing 50 % of straw pulp was added to the refined wood fiber produced in the factory, so that the resulting fibers contained 5, 10, 15, 20, 30 and 50 % of the straw pulp. Properties of such prepared board are shown in Tab. 3.

Tab. 3: Basic physic- mechanical properties of IFB with a content of the refined straw.

Percentage of straw (%)	Density ($g.cm^{-3}$)	Flexural strength (MPa)	Tensile strength perpendicular to the face (kPa)	Swelling after 2 hours (%)	Water absorption after 2 hours (%)
0	0.287	3.78	34	2.91	12.60
5	0.282	3.93	36	3.12	12.65
10	0.286	4.66	42	3.21	13.10
15	0.298	5.71	42	3.25	13.31
20	0.327	6.53	54	3.16	13.90
30	0.357	7.90	58	3.01	14.71
50	0.411	11.57	79	2.85	15.81

Percentage of refined mixed pulp with high content of fine fibers has an impact of the increased density of the IFB (Fig. 2). Fibreboard prepared as a board with a density of 0.282 $g.cm^{-3}$ gradually increases its density up to 0.411 $g.cm^{-3}$ at 5 % of straw pulp. At 50 % level it increases to 143 %. Varying the straw content does not affect the swelling of fibreboards after 2 hour (Fig. 3). Some increasing occurs at 10 and 15 % of straw pulp content and a decreasing at 30 and 50 %. Water absorption gradually increased with the increased content of straw fibers. It is about 15.8 at 50 % of the straw content, means an increasing to 125 %. A reason of the higher values of water absorption of SIFB comparing to IFB is caused by differences in the anatomical structure of coniferous wood and stubble of straw. Conifers include tracheas with thick cell walls arranged in regular rows. The cross section contains only a small lumen (Požgaj et al. 1997).

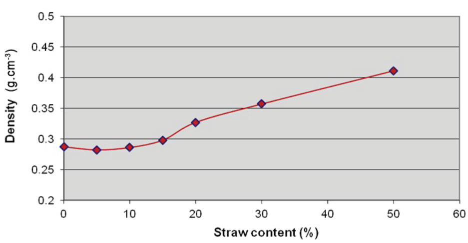

Fig. 2: Density of IFB with refined straw content.

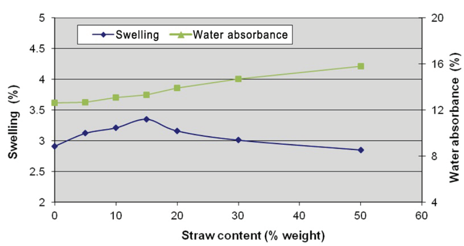

Fig. 3: Water absorption and swelling of IFB with a refined straw content.

Straw contains two large vessels and one or two vessels of smaller size which appear as holes in the cross-section holes. The vessels figure as transpiration stream lines and they also have a mechanical function. They are surrounded by a sclerenchymatic mesh (Han 1998). It means that straw has a larger internal volume than wood for equal weight unit. The amount of water collected by straw is 1.6 times higher than by wood (Lübke 2014). If value of WRV is divided by value of water absorption of SIFB with DD = 45 sec than obtained value of 13.75 % is the value of water absorption achieved by wood base IFB. Despite the increased value of water absorption of SIFB the swelling is the same or lower than IFB with 13 % absorbability.

Flexural strength increases with an increasing content of straw very much. It increases from 3.78 MPa at 0 % straw content to the value of 11.57 MPa at 50 % straw content; it means an increasing to 306 % (Fig. 4). The increase is partly due to the growth of specific weight of SIFB. Stronger growth in strength properties of SIFB occurs with an increasing rate of a straw pulp.

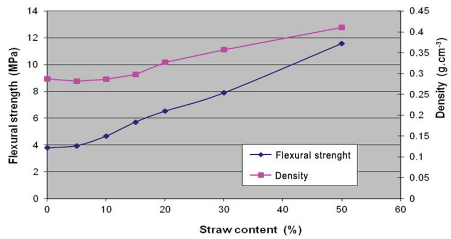

Fig. 4: Flexural strength and density in the dependence on a straw content of SIFB.

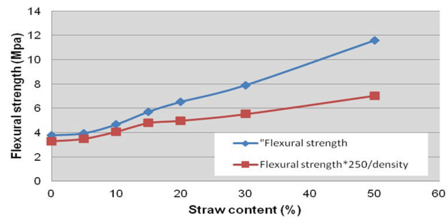

Fig. 5: Flexural strength of IFB depending on the content of refined straw and strength converted on the density of 250 kg.m^{-3}.

Fig. 5 shows a growing tendency of the ratio of the bending strength to density. Strength properties are increased up to 306 % for boards with 50 % content of straw pulp. By comparing the values obtained it is obvious that an increase to 143 % of specific weight caused an increase of the bending strength at 306 %. Remarkably, even at a lower content of straw fiber, when the specific weight is at the same level as it is for the comparative sample containing 0 % of straw pulp, the flexural strength increased up to 151 %.

This indicates that the increase of flexural strength of SIFB due to increasing representation of the straw pulp is due to the increase of the specific weight and the presence of the straw fibers.

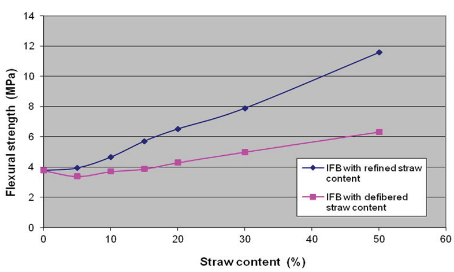

Fig. 6: Flexural strength of IFB with a refined/ defibered straw content.

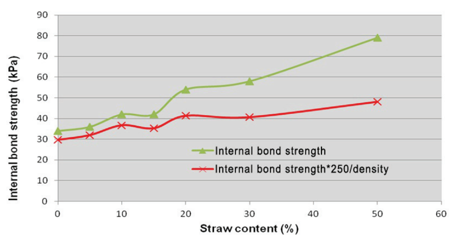

Fig. 7: Strength perpendicular to the face of IFB depending on the content of refined straw and strength converted on the density of 250 kg.m^{-3}.

Effect of the straw pulp will affect the flexural stiffness of boards made of the refined mixed pulp versus the wood pulp. Similarly, in boards with the addition of the defibered mixed pulp versus mixed wood pulp. The finer fibers are involved in the increase in flexural strength after refining of the mixed pulp (Fig. 6). The dependence of tensile strength perpendicular to the face (internal bond strength) on the straw content in a board (Fig. 7) has a similar behaviour – its value increases with the increasing content of the straw pulp.

Increase of the content of a straw pulp from 0 to 50 % causes the strength increase from 34 to 79 kPa, it is to 230 %. This increase exceeded the increase of internal bond strength. Curve of ratio of strength to density increases. It represents an increase to 162 at 50 % of the straw fibre content. Increase the density to 143 % caused increase of the bending strength to 230 %. The values of internal bonding strength for samples with a low percentage of straw increased to 123 % similar as for the bending strength.

Thermal properties

Coefficient of thermal conductivity (λ) as the characteristic value of the material for insulation panels was determined for the prepared plates with varying percentages of straw pulp (Tab. 4).

Tab. 4: Thermal properties of IFB prepared with refined straw content.

Straw content (%)	**0**	**5**	**10**	**15**	**20**	**30**	**50**
λ ($W.m^{-1}.K^{-1}$)	0.055	0.056	0.055	0.057	0.058	0.060	0.064

Thermal properties are worsened with the increased density. The heat conductivity increases from 0.055 $W.m^{-1}.K^{-1}$ at 0 % content of a straw pulp to 0064 $W.m^{-1}.K^{-1}$ for 50 % content of a straw pulp (Fig. 8). A curve of the ratio of the coefficient of thermal conductivity to the density is approximately constant at low concentrations of straw (until 15 %). Higher concentrations of straw reduce the ratio markedly. The improvement is 21 at 50 % of straw content. This fact is due to the larger diameter of straw vessel compared to wood, thus increasing the internal volume of the pulp. In case of recalculating of the determined value of the coefficient of thermal conductivity on density of 250 $kg.m^{-3}$ the value of 0.049 $W.m^{-1}.K^{-1}$ will be improved at 0.0383 $W.m^{-1}.K^{-1}$. The reached value could significantly improve the competitive position of insulation boards based on wood and straw on the market.

The problem is that the addition of refined or even defibered straw pulp, which is grounded together with wood, causes enlargement of the density of the insulation boards highly above a desired value. It is therefore necessary to prepare IFB containing a straw pulp by a separate straw grinding. This should avoid a breaking the straw fiber on fine fibers already during defibering process as happened in the joint grinding of wood chips and chopped straw. This way will be possible to prepare IFB with a straw content fiber in a density of 250 $kg.m^{-3}$.

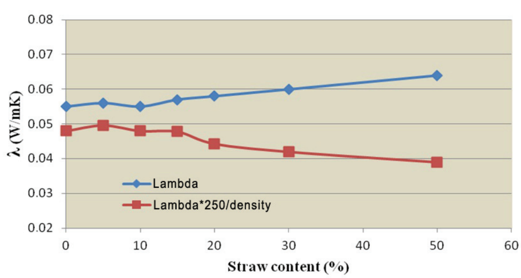

Fig. 8: Coefficient of thermal conductivity (λ) of IFB with straw content.

CONCLUSIONS

It can be concluded that the addition of straw pulp influences the physic-mechanical and thermal properties of the insulation boards. The bulk density of insulating boards increases with a growth of the straw pulp content, which improves mechanical properties and deteriorates the water absorption of boards. The growth of the flexural strength is very significant with increase of the straw content. It increases from the value of 3.78 at 11.57 MPa at 50 % of straw pulp. The tensile strength perpendicular to the face increases from 34 kPa at 0 % content of the straw pulp to 79 kPa at 50 % of the straw pulp. The increase is partly due to the growth of density of SIFB and partly by the presence of straw fibers.

The swelling of IFB after 2 hours does not change significantly with a change of the straw content. Water absorption gradually increases from 12.6 to 15.8 % at the 50 % of the straw with a proportion of straw pulp, which is an increase of 25 %. The increase is due to the larger vessel diameter of the straw compared to the wood, thus increasing the internal volume of the fibers.

Thermal properties of insulation boards are improved with increasing content of straw pulp after conversion per unit volume weight, respectively at the bulk density of 250 $kg.m^{-3}$. The attainable value of 0.0383 $W.m^{-1}.K^{-1}$ is at the level of other insulating materials. Straw pulp needs to be prepared separately, so that when added to the wood fibers reach the necessary specific weight of 250 $kg.m^{-3}$. The separate grinding of straw prevents a formation of high residual fiber resulting in a poor dewatering fiber and a high density of insulation boards. Overall, the addition of a proper crushed straw pulp is likely to be beneficial for strength and insulation properties of IFB with the straw content.

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