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WATER VAPOUR PERMEABILITY PROPERTIES OF CELLULAR WOOD MATERIAL AND CONDENSATION RISK OF COMPOSITE PANEL WALLS

Janis IEJAVS
PhD student – Latvia University of Agriculture
Address: Dobeles str. 41, Jelgava, Latvia, LV-3001
E-mail: janis.iejavs@e-koks.lv

Rihards ROZINS
PhD student – Latvia University of agriculture
Address: Dobeles str. 41, Jelgava, Latvia, LV-3001
E-mail: rihardsrozins@inbox.lv

Abstract:

Invention of light weight cellular wood material (CWM) with a trade mark of Dendrolight is one of innovations in wood industry of the last decade. The aim of the research was to define the water vapour permeability properties of CWM and to analyse the condensation risk of various wall envelopes where solid wood cellular material is used. To determine the water vapour permeability of CWM, test samples were produced in the factory using routine production technology and tested according to the standard EN 12086:2014. Water vapour permeability factor (µ) and other properties of six different configurations of CWM samples were determined. Using the experimental data the indicative influence of geometrical parameters such as lamella thickness, number of lamellas and material direction were investigated and evaluated. To study the condensation risk within the wall envelope containing CWM calculation method given in LVS EN ISO 13788:2012 was used. To ease the calculation process previously developed JavaScript calculation software that had only capability to calculate thermal transmittance was extended so that condensation risk in multi-layer composite walls can be analysed. Water vapour permeability factor in CWM is highly direction dependant. If parallel and perpendicular direction of CWM is compared the value of water vapour permeability factor can differentiate more than two times. Another significant factor for condensation risk analysis is overall thickness of CWM since it directly influences the equivalent air layer thickness. The influence of other factors such as lamella thickness, or groove depth is minor when water vapour permeability properties are compared. From the analysis of CWM performance in building envelope it can be concluded that uninsulated CWM panels used during winter months will pose the risk of condensation damage to structure, but the risk can be reduced or prevented if insulation layer is applied to the CWM panel wall.

Key words: *light weight panels; cellular wood material; water vapour permeability; wall constructions; condensation risk.*

INTRODUCTION

The efficiency of building material is question that should be evaluated through various aspects of its lifecycle. The material should be energy, resource and labour efficient in production, transportation, assembling, exploitation and recycling processes. Several researchers (Voth 2009, Skuratov 2010) are looking for new construction materials and light - weight structural panels for efficient wood buildings. One possibility to utilize full potential of structural material is to create a sandwich panel. Efficiency studies and guidelines for effective sandwich panel structural design are outlined by J. Pflug *et al*. (2003). With rising demand for energy efficient homes, thermal properties of building materials and structures are those that are investigated most when the choices between the alternative construction materials are made. To properly develop the wall, floor or roof structure layer by layer it is very important to evaluate the moisture permeability properties of each material and stack them properly to avoid the moisture damage to structures and to avoid the illnesses created by mould. Therefore it is very important to know the water vapour permeability properties of each material used in the building envelope.

The aim of the research was to evaluate the water vapour permeability properties of three layer cellular wood panel walls. Industrially produced Scots pine (*Pinus sylvestris* L.) cellular wood material was used to made test specimens and to determine water vapour permeability properties. There are several structural materials (fibreboard, chipboard, strand board, plywood and solid timber panels) that can be combined with cellular material core to produce structural sandwich panels. In this research only Scots pine cellular wood Material samples with diameters from 74-140mm were tested.

In the literature review no data of pine wood cellular wood material (CWM) water vapour permeability properties were found. Therefore to achieve the goal this research was divided in two parts where first part focuses on investigating the CWM as lone material and the second part analyses CWM within a system with another materials. Water vapour permeability factor for six different types of cellular wood material was determined, and the influence of the material structure (lamellas and material thickness) variation was investigated. When the water vapour permeability factor (μ) based on experimental data were obtained the research proceeded with analysing the CWM in system with another materials.

OBJECTIVES

The objective of the research was to determine the water vapour permeability properties of cellular wood material and analytically analyse condensation risk of various wall envelopes where cellular wood material as raw material was used.

MATERIALS AND METHODS

Cellular wood material for experimental test samples was produced using various thickness Scots pine (*Pinus sylvestris* L.) lamellas. Precise dimensions of profiles can be found in Table 1. The profiles are produced by several planning procedures - first board is planed from all four sides. After planning, 8 double faced grooves, which releases all inner tensions and reduces the weight of wood board, were cut into longitudinal direction in the flat faces of board. The dimensions of grooves are as follows: pitch 6.4mm and width 3.2mm, depth of groove is 4mm less than the thickness of whole lamella. The thickness of the lamella used to produce tested material can be found in Table 1. The average moisture content of the profiles in production process was 12%, measured by Greisinger GMH 3830 Moisture Meter. One component polivinilacetate (PVA) adhesive Cascol 3353 was used for all gluing operations in cellular wood material and panel production. Each layer was aligned horizontally in 90 degree direction to the previous layer.

Water vapour permeability properties were determined according to standard EN 12086:2014 test principles. The water vapour resistance factor μ is a measure of the material's relative reluctance to let water vapour pass through, and is measured in comparison to the properties of air. The μ-value is a property of the bulk material and needs to be multiplied by the material's thickness when used in a particular construction.

The analyses of the specimens were carried out according to scheme A. For testing purpose cylindrical CWM samples were produced- to one of the flat faces glass container was attached. The glass container is filled with absorbent ($CaCl_2$) and sustains relative air humidity (RH) 0% in the container (dry climate). Then the samples with attached containers are placed in conditioned environment with temperature 23±1ºC and RH 50±3% that is assumed to be wet climate. To create conditioned environment Emmerson S04OA device was used. The mass of the specimens were determined by scales with accuracy 0.01g.

To experimentally determine water vapour permeability of CWM and to evaluate the influence of factors that might have effect on water vapour permeability several test samples were created. Test samples can be divided in six unique groups. Half of the samples had the material orientation with CWM layers aligned parallel (Table 1 - material orientation 0) to the flat face of sample, but another half with perpendicular orientation. The samples were produced using three currently most commonly used lamella thickness. Markings, dimensions, orientation of the material for tests presented are in the Table 1.

The diameter of the test specimens for groups with perpendicularly oriented material was increased provide free air flow through the CWM in perpendicular direction. The diameter of the specimens was increased from 74 to 140mm.

Table 1

Water vapour permeability test specimen description

Specimen markings	Material orientation	Material type marking	No. of lamellas, pcs.	Thickness of lamella, mm	Total thickness of CWM, mm	Diameter of the specimen, mm
1-1 to 1-3	0	2-25	2	25	50	74
1-4 to 1-6	0	4-18	4	18	72	74
1-7 to 1-9	0	4-28	4	28	112	74
2-1 to 2-3	90	2-25	2	25	50	140
2-4 to 2-6	90	4-18	4	18	72	140
2-7 to 2-9	90	4-28	4	28	112	140

All specimens before the test to ensure that they are with same moisture content were conditioned to constant mass in the standard atmosphere with temperature 23±1ºC and relative air humidity 50±3%. As extra parameter material density was determined according to standard ISO 13061-2 dividing specimen mass by volume. The differences between the test specimens can be observed in the Fig. 1.

a. ***b.***

Fig. 1.
Samples for determination water vapour permeability properties of cellular wood material: a - in parallel direction; b – in perpendicular direction.

To assess the possibilities to use CWM as building material, it was analysed thru 6 different key case studies of various wall envelopes. The thermal properties that are needed to carry out the condensation risk analysis were obtained from the previous research stage (Rozins and Iejavs 2014). By combining the thermal properties from previous research and water vapour permeability properties determined in this research, it is possible to analyse the CWM behaviour and condensation risks in the building envelope where it is combined with another materials. The cases that were analysed together with explanation why each case is special are listed starting from lowest thermal resistance to more effective solutions in Table 2.

Table 2

Thermal transmittance of six different wall structures where Cellular wood material (CWM) in parallel direction is used

Case	Wall structure	Thickness of layer t, mm	Thermal conductivity l,W·m^{-1}·K^{-1}	Wall weight kg·m^{-2}	Thermal transmittance U,W·m^{-2}·K^{-1}	Comments
1	Wood boards	25	0.13	37	0.94	Thinnest standard panel for construction based on production technology
	CWM_0	50	0.098			
	Wood boards	25	0.13			
2	Wood boards	25	0.13	56	0.59	Thickest standard panel for construction based on production technology
	CWM_0	112	0.098			
	Wood boards	25	0.13			
3	Wood boards	25	0.13	104	0.30	Theoretical panel to meet LBN 002-01 requirements
	CWM_0	270	0.098			
	Wood boards	25	0.13			
4	Wood boards	25	0.13	200	0.15	Theoretical panel to meet passive standard requirements
	CWM_0	590	0.098			
	Wood boards	25	0.13			
5	Wood boards	25	0.13	57	0.23	Optimal building envelope that meets the requirements of LBN 002-01
	CWM_0	56	0.098			
	Wood boards	25	0.13			
	Insulation material	125	0.04			
6	Wood boards	25	0.13	82	0.15	Optimal building envelope that meets the requirements of passive standard
	CWM_0	56	0.098			
	Wood boards	25	0.13			
	Insulation material	225	0.04			

According to LBN 002-01.25. Structure that is composed of homogenous layers is acceptable for exploitation and extra water vapour analysis doesn't need to be carried out if the warm side of structure has at least five times greater water vapour resistance than the cold side. Looking on the given cases the structures are made of symmetric sandwich panels and only cases 5 and 6 might comply with this requirement therefore in further analysis all six cases will be assessed.

As the requirement stated in LBN 002-01.25. is not for filled- the further actions that needs to be carried out are described in LBN 002-01.31. According to this standard it is required to prove with calculation that net volume of accumulated condensate within the structure is negative (greater amount of moisture must be able to evaporate from structure than the amount of water that can go in), also it must be confirmed that short term accumulated moisture during air temperature or humidity extremes doesn't damage the structure. And for construction elements made of wood there is an extra requirement that states- it is unacceptable if there is condensate in wood structures.

The evaluation of condensation risk according to LVS EN ISO 13788 method was performed. This method also has similar restriction that allows for condensate to be present in structures for short durations, but during the period of 1 year moisture must evaporate. Another thing that must be considered is fact that if relative moisture content within structure exceeds 80% the mould growth risk arises. Therefore to assure that evaluated structures are sufficient for use the border was drawn and requirement of relative humidity lower than 80% was set.

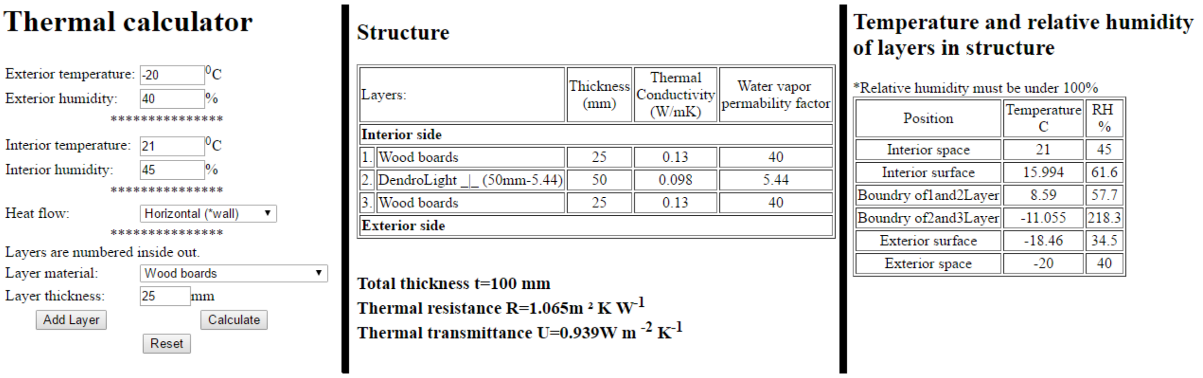
For the calculation the Average monthly temperature and humidity values were used. The environment conditions were obtained from LBN 003-01 "Būvklimatoloģija", but the place of the "test" house was assumed to be in Riga (Latvia). The interior climate of the assumed building is constant-conditioned air with temperature 21°C and relative humidity 45% thru whole year. Exterior climate input data for condensation risk analysis are presented in Table 3.

Table 3

Exterior climate input data for condensation risk analysis

Parameter	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature $T_{e,}$ ^{o}C	-4.7	-4.3	-0.6	5.1	11.4	15.4	16.9	16.2	11.9	7.2	2.1	-2.3
Relative humidity RH_e, %	85	82	79	73	69	72	76	78	81	83	86	86

In previous research (Rozins and Iejavs 2014) calculation software was developed. This software had a capability to calculate thermal transmittance of building envelopes containing CWM, during the current research the capabilities of the calculation software was extended and condensation risk analysis module was created. Using this software it is possible to check if in given conditions condensation risk in is present. Illustration of the layout of calculation software can be seen in Fig. 2.



Thermal calculator

Exterior temperature: -20 ^{0}C
Exterior humidity: 40 %
****
Interior temperature: 21 ^{0}C
Interior humidity: 45 %
****
Heat flow: Horizontal (*wall)
****
Layers are numbered inside out.
Layer material: Wood boards
Layer thickness: 25 mm

Structure

	Layers:	Thickness (mm)	Thermal Conductivity (W/mK)	Water vapor permability factor
Interior side				
1.	Wood boards	25	0.13	40
2.	DendroLight _|_ (50mm-5.44)	50	0.098	5.44
3.	Wood boards	25	0.13	40
Exterior side				

Total thickness t=100 mm
Thermal resistance R=1.065m ² K W^{-1}
Thermal transmittance U=0.939W m $^{-2}$ K^{-1}

Temperature and relative humidity of layers in structure

*Relative humidity must be under 100%

Position	Temperature C	RH %
Interior space	21	45
Interior surface	15.994	61.6
Boundry of1and2Layer	8.59	57.7
Boundry of2and3Layer	-11.055	218.3
Exterior surface	-18.46	34.5
Exterior space	-20	40

Fig. 2.
Illustration of the layout of thermal calculation software.

Thermal calculator can be used to calculate heat flows in three different directions: horizontal, vertical up, and vertical down. Eight different predefined construction materials and three types of air gaps are available to define the layers of structure. Each individual layer is defined by choosing the layer material from dropdown menu and typing the layer thickness in text box. When the material and thickness is set each layer needs to be added to the wall structure by clicking on the add layer button. If layer is added successfully it can be seen as a row in the structure Table. When all layers are defined to calculate the thermal transmittance, temperature in each boundary layer between the two layers and to check relative humidity on each of boundaries between layers the button “Calculate” should be pressed.

The calculation process in the thermal calculator is carried out by calculating the temperature on each of the boundaries between the layers including the interior and exterior face. For each of these temperatures air saturation pressure is calculated. Then using the water vapour permeability factor for each of the defined layers equivalent air layer thickness is determined. Using this parameter and combining it with interior and exterior air water vapour partial pressure the partial pressure values on each of the boundary layers can be determined. Then from saturation pressure and partial pressure the relative humidity on each of boundary layers are calculated. The calculated results are displayed as illustrated above. If the relative humidity within the structure exceeds 80% the risk of mould growth and structural damage increases but if the relative humidity increases or exceeds 100% condensation occurs, therefore it’s strongly advised to redesign or at least recheck the structure with ISO 13788 method checking if during the time period of one year all moisture that is accumulated during “wet” months are evaporated and in the end of year the structure is in dry state.

RESULTS AND DISCUSSION

For all three types of cellular wood material following average density values were determined: for 112mm thick specimens 311kg·m^{-3}; for 72mm thick specimens 304kg·m^{-3} and for 50mm thick specimen 335kg·m^{-3}.

Water vapour permeability properties were experimentally determined for three different CWM types. Each of the material type was tested both in parallel and perpendicular direction. Water vapour permeability was determined according to standard LVS EN 12086:2014 and the results are presented in the Table 4.

Table 4

Water vapour permeability properties of cellular wood material

Property	**Specimen type**					
	Material in parallel direction			**Material in perpendicular direction**		
	2-25	**4-18**	**4-28**	**2-25**	**4-18**	**4-28**
Average value of water vapour resistance factor *μ*	14.4	21.1	15.5	5.44	4.31	6.53
Standard deviation	2.10	6.07	2.20	0.617	0.255	0.762
Confidence interval of mean	9.18-19.6	6.02-36.2	10.0-21.0	2.78-8.09	3.21-5.40	3.25-9.8
Average equivalent air layer thickness S_d, m	0.697	1.53	1.71	0.280	0.311	0.734
Standard deviation	0.102	0.441	0.240	0.033	0.019	0.0845
Confidence interval of mean	0.444-0.950	0.434-2.63	1.11-2.31	0.135-0.416	0.229-0.392	0.370-1.10

According to Table 4 CWM in parallel direction is characterized with water vapour resistance factor µ 14.4 for material made of two 25mm thick lamellas; 15.5 for material made of four 18mm thick lamellas and 21.1 for material made of four 28mm thick lamellas and total thickness of 112mm of the material. Since the average water vapour resistance factor values for all 3 types of CWM has their confidence interval borders overlapping, it’s possible to assume that the material structure does not influence CWM water vapour resistance factor significantly.

Any CWM consists of multiple lamellas being placed side by side to form the sheets, that are later glued together layer by layer to form CWM. If the CWM is examined, it can be seen that in some samples there are connections between lamellas, but another samples are made with just one lamella covering both sample faces (Fig. 3). The samples that, had connection between lamellas on one or more layers proved to have significantly higher water vapour permeability than samples without the connections. It can be explained with the fact that there are small air gap between the two side by side placed lamellas that allows the air and vapour to flow. The sample top face with connection of two side by side lamellas can be seen left and sample top face without the connection on right side of Fig. 3.

a. ***b.***

Fig. 3.
Structural difference of specimen surface in material parallel direction:
a – with air gap between lamellas; b – without air gap.

Average equivalent air layer thickness of the CWM in parallel direction is approximately from 2.2 to 2.6 times lower for material made of two lamellas compared with material made of four lamellas. Significant difference between both CWM specimen types made of four lamellas was not found.

According to the Table 4 CWM in perpendicular direction is characterized with water vapour resistance factor µ 5.44 for material made of two 25mm thick lamellas; 4.31 for material made of four 18mm thick lamellas and 6.53 for material made of four 28mm thick lamellas and total thickness of 112mm of the material. CWM lamella count and thickness did not influence significantly water vapour resistance factor in CWM perpendicular direction.

If the water vapour permeability factors for CWM in perpendicular direction are compared to values in parallel direction, it can be seen, that the difference is more than 2 times. The reason why the water vapour permeability factor for CWM in perpendicular direction is multiple times smaller than the value for same material in parallel direction can be found by analysing the cavities created by grooves in the lamellas. If the material is placed in perpendicular direction the cavities connect both sides of material allowing air and vapour to flow freely - therefore increasing the possibilities for moisture being transferred thru material.

An average equivalent air layer thickness value between specimens in the material perpendicular direction varies in the range from 0.280 to 0.734m. Since confidence border of mean values overlaps no significant effect of lamella number and thickness were observed.

In the Fig. 4 most common building materials together with CWM has their density and water vapour resistance factors displayed. For the comparison the data of CWM made of 28mm thick lamellas was used. In this comparison the differences between the common construction materials compared to CWM can be observed.

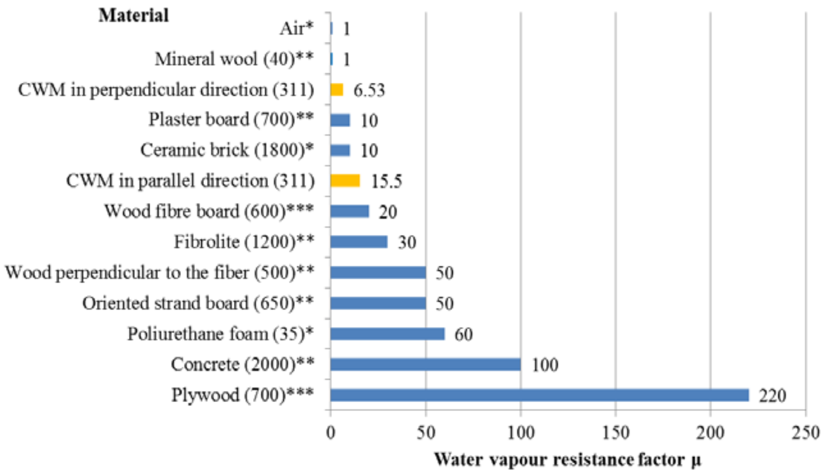


Fig. 4.
Cellular wood material (CWM) and other building material water vapour resistance factor comparison: density ρ in $kg\cdot m^{-3}$ presented in brackets.
(Borodinecs and Kreslins 2007*; LVS EN ISO 10456:2008**; LVS EN 13986:2005***).

As it can be seen in the Fig. 4 water vapour resistance factor µ for CWM in perpendicular direction is 2.4 times lower compared with resistance factor of material in parallel direction. The µ value of 6.53 for CWM in perpendicular direction (Fig. 4) was observed and compared with µ value 1 of air and mineral wool. If CWM is being cut perpendicularly to the water vapour migration direction with plane, the cross-section would consist of about 40% of air cavities that are connecting both faces of material. Therefore theoretical water vapour resistance factor considering cross-section area and fact that cavities are aligned 45° to vapour migration direction is significantly lower at about 3 to 4.5. The difference between the theoretical and measured water vapour resistance factor might be explained by the size of test specimens- possibly if the diameter of the sample would have been increased even further the water vapour resistance factor for CWM (perpendicular) would have dropped closer to theoretical value. The currently measured CWM water vapour resistance factor in perpendicular direction is 15.5 what is 23% less than average density wood fibre board µ value 20. Water vapour resistance factor of CWM in parallel direction is 3.2 times and in perpendicular direction 7.7 times lower compared with µ value of solid timber perpendicular to the fibre. For fibrolite, oriented wood particle board, polyurethane foam and plywood µ value is 1.9 to 14.2 times higher compared to CWM in parallel direction and 4.6 to 33.7 times higher compared with CWM µ value in perpendicular direction.

Obtained CWM water vapour resistance properties are used for internal condensation risk analysis of six different cases of possible wall envelopes. In the Table 5 the maximal relative humidity in given conditions of the six test cases over the period of year can be seen in Table 5.

Table 5

Maximal relative humidity RH within the wall envelope in %

Case	Month											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	100	97	87	74	65	64	65	67	71	76	85	93
2	104	101	90	77	67	66	68	70	74	80	89	98
3	103	100	89	77	69	69	71	73	78	82	90	97
4	102	98	89	78	70	71	74	76	80	85	92	98
5	47	47	47	46	46	55	62	62	52	46	47	47
6	46	46	46	46	46	53	60	60	50	46	46	46

🟥 maximal relative humidity ≥ 100%;
🟨 maximal relative humidity 100% > RH ≥ 80%.

From the data in Table 5 it can be seen that first 4 cases (Table 2) – walls made of simple 3 layer sandwich panel construction where core is CWM will poses risk of being damaged by condensation or mould (RH>80%). Also it must be noted that according to LBN thermal transmittance of wall described in case 1 and 2 is insufficient therefore walls with such structure can only be used in summer houses, hobby houses, or temporary housing.

Cases 3 and 4 (Table 5, Table 2) represent extreme instances that were used to prove the concept. In these cases CWM material layer thickness in sandwich panel is extended to point where wall envelope can for fill the requirements of thermal transmittance outlined in LBN or passive standard. Therefore Cases 3 and 4 clearly reach the standard requirements for thermal transmittance, but when condensation risk is analysed, it can be seen, that such structures will be damaged by moisture.

Cases 5 and 6 (Table 5, Table 2) illustrate insulated CWM sandwich panel walls. For these two cases maximum relative humidity within the wall is 60-62%. Therefore it can be concluded that CWM sandwich panel walls can be insulated to avoid the risk of condensation within the structure.

CONCLUSIONS

1. Water vapour permeability of cellular wood material is highly direction dependant. In the research it was determined that water vapour resistance factor of CWM if compared between its parallel and perpendicular direction can vary for more than two times.

2. Water vapour permeability factor average values of CWM in parallel direction range from 14.4 to 21.1, but in perpendicular direction the values are in range between 4.3 and 6.5.

3. Significant variation of water vapour permeability properties between material directions can be explained by clear differences of cross-sections in each direction. Material in perpendicular direction has cavities that goes through the whole material and connects both sides of material. CWM

in parallel direction however has these cavities aligned in a way that they are not connecting both sides of material therefore it can be said that material is “closed”.

4. Significant influence of lamella and material total thickness changes on the water vapour permeability factor value was not observed. The parameter called “equivalent air layer thickness” (Sd) varies significantly if two CWM samples with different thickness are compared since it depends on material thickness directly.

5. CWM vapour permeability is significantly higher compared to most structural wood based panels and solid timber.

6. Obtained CWM water vapour resistance properties can be used for internal condensation risk analysis of structures made of cellular wood material, for example for external wall and ceiling multi layers composite panel design. Obtained data lets constructor correctly design external separation constructions putting low water vapour permeability material in warm side of the construction, but with high water vapour permeability in the cold side of the structure.

7. The uninsulated CWM panels can only be used for buildings that don’t need to comply with the rules of energy efficiency regulations. Such wall envelope if the building is continuously used during winter months will poses the risk of condensation damage to structure, therefore the main use for such walls could be seasonal buildings and cabins.

8. The insulated CWM panel walls can be used as building block for any building- the thermal requirements of LBN and passive standard can be met, and such composition of wall prevents the risk of water condensation in the wall. The positive thing of such wall structure is that it can be built without plastic foil within the building envelope what means the natural benefits of using wood in building stays intact.

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