Drewno 2016, Vol. 59, No. 198
DOI: 10.12841/wood.1644-3985.156.14

RESEARCH PAPERS

Jānis Iejavs, Uldis Spulle

CELLULAR WOOD MATERIAL PROPERTIES – REVIEW

The invention of cellular wood material and lightweight furniture panels with the trade mark of Dendrolight® is just one of the wood industry's innovations in the last decade. During the manufacturing process due to the sawn longitudinal grooves, solid timber becomes 40% lighter. Timber with grooves is a raw material for the cellular wood material production and furthermore is used for various sandwich panel designs. Since 2007 when cellular wood material production technology and furniture panels were patented, several researchers worked with experimental, analytical and numerical analysis of the cellular wood material properties for structural applications. This paper summarizes the main knowledge about the physical and mechanical properties of cellular wood materials and the possibilities for their potential improvement.

Keywords: cellular wood material; physical-mechanical properties, physical--chemical properties

Introduction

The reduction of manufacturing, transporting, assembling and exploitation costs of structural building elements are important issues due to both ecological and economical aspects. Several researchers [Skuratov 2010; Voth 2009] are looking for new lightweight constructions for wooden house manufacturing and cost effectiveness of sandwich materials [Pflug et al. 2003]. One way that we can reduce the weight of structural elements during the manufacturing process is to modify their structure by replacing high density material of the members with lower density material.

The invention of lightweight panels with the trade mark of Dendrolight in Austria in 2005 by the inventor Johann Berger is one of the latest wood industry innovations of the last decade. At the initial stage of the material development due to the patent issue and cellular wood material (CWM) production

Jānis Iejavs✉ (*janis.iejavs@e-koks.lv*), Uldis Spulle (*uldis.spulle@llu.lv*), Latvia University of Agriculture, Jelgava, Latvia

technology development, there was limited information about the manufacturing process and material properties.

At present three-layer cellular wood panels have a wide, non-structural application in the furniture industry, with a small amount in door production and transportation within the manufacturing industry. Due to the sawn longitudinal grooves, solid timber becomes 40% lighter and it is possible to produce CWM with a lower density and with a higher form stability compared to solid timber. Cellular wood material in two directions of three has the identical structure, therefore, two different direction properties were evaluated and compared. These directions were defined as parallel and perpendicular to the gluing press run.

Nonstructural CWM initial research [Jakovļevs 2011] and the start-up of the world's first industrial plant in Latvia in 2010 with a manufacturing capacity of 65 thousand m^3 cellular wood panel material per year made it necessary to develop Johann Berger's idea [Follrich et al. 2006] to use CWM in buildings as a structural element. Since CWM with its current structure was patented only in 2007, there was a lack of information about CWM properties for structural applications. This paper summarizes 10 years of experience of the main physical and mechanical properties of CWM, which were partially obtained during the process of writing the PhD thesis by Jānis Iejavs. In addition, some possibilities for improvement of the materials' properties are presented.

The significant variation in raw materials (wood species, timber quality and geometry), manufacturing technology (board width and thickness, adhesive type, etc.) and lay-ups of the sandwich panels made of CWM makes it difficult to find analytical and numerical models to predict CWM properties. Therefore, mainly experimental analysis methods were used to determine the properties of the material and sandwich panels.

Cellular wood material

As a raw material for CWM production mainly finger jointed Scots pine (*Pinus sylvestris* L.) timber was used in the research projects. Spruce (*Picea abies* L.) and aspen (*Populus tremula* L.) timber was mentioned as alternatives for CWM production. CWM was manufactured industrially on a unique automatic production line, especially designed and produced for CWM production for the company Dendrolight Latvija Ltd. The illustration of the complex CWM production process is shown in figure 1.

The structure and the manufacturing technology of CWM significantly influence both the physical and mechanical properties of CWM and products.

CWM is mainly produced from finger jointed lamellas, with cross section dimensions of 28 × 106 mm. In some studies lamellas with a thickness of 25 mm or 18 mm were used. During the manufacturing process due to the sawn longitudinal grooves, finger jointed lamellas lose weight.

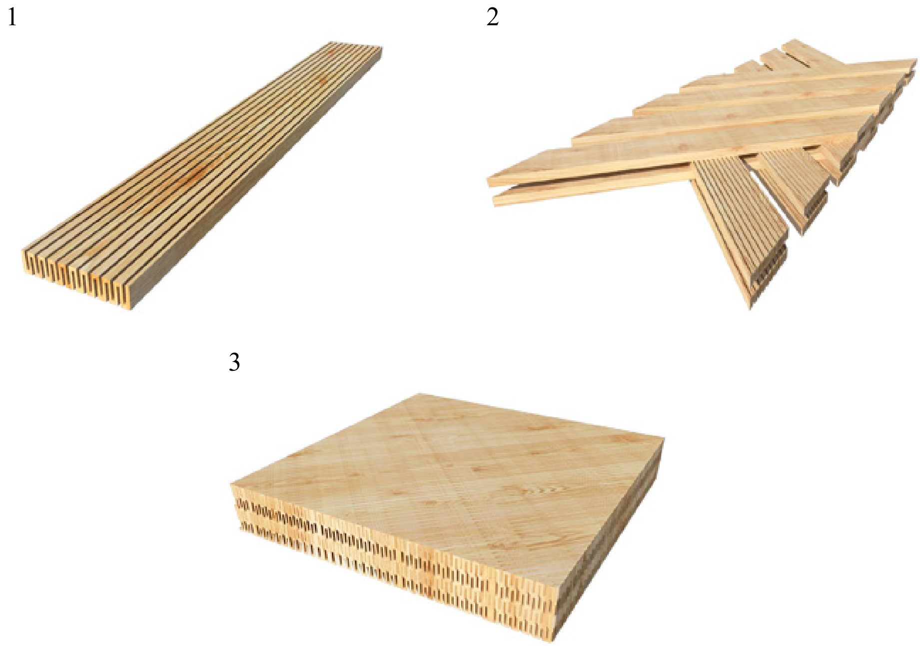

Fig. 1. Cellular wood material production process: 1 – lamella with grooves; 2 – gluing of lamellas; 3 – cellular wood material block

When these lamellas are glued crosswise with several layers together a CWM block is obtained, which is the raw material for non-structural and structural sandwich panel design. A two and four-layer CWM was mainly used in the studies. Due to the limits of the industrial production technology of CWM only polyvinyl acetate Cascol 3353 (PVA) adhesive was applied in CWM gluing. For the real structural product manufacturing, PVA adhesive should be replaced with suitable certified structural adhesive.

The three layer composite CWM sandwich panel is obtained when the CWM block (defined as a material in a parallel direction) or sawn slices of the CWM (defined as in a perpendicular direction) are covered with different types of top layer materials (fibreboard, chipboard, solid wood panels, plywood, etc.).

Examples of CWM directions and three-layer composite structural sandwich panels are presented in figure 2.

Properties

Moisture content

Moisture content influences the main physical and mechanical properties of wood and wood products significantly. Since CWM is made of solid timber and

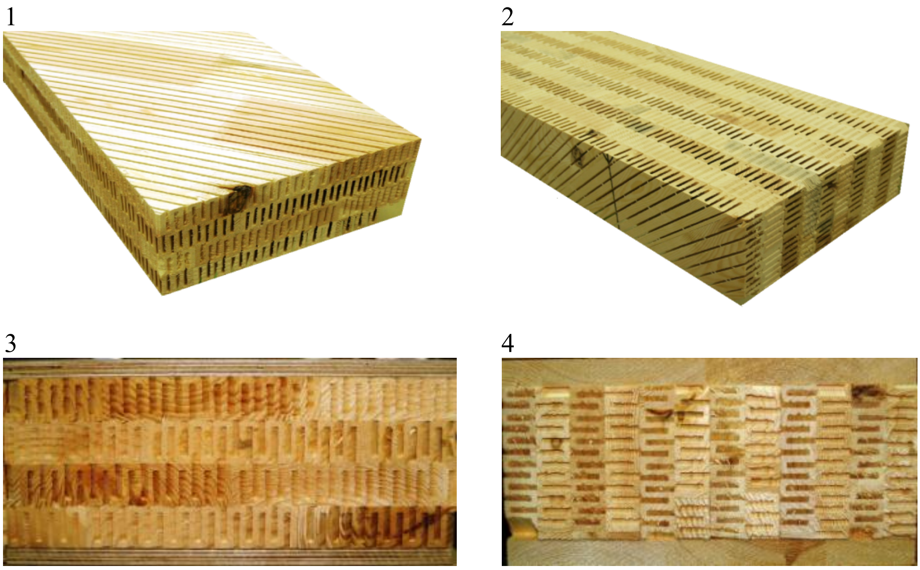

Fig. 2. Directions of cellular wood material and example of three-layer composite sandwich panels for structural application: 1 – parallel direction, 2 – perpendicular direction, 3 – CWM in a parallel direction covered with birch plywood and 2 – CWM in a perpendicular direction covered with solid pine timber

adhesive, the equilibrium moisture content of the material is the same as for wood species from which CWM is made. After Scots pine CWM conditioning in a standard atmosphere of 20 ±2°C and relative humidity of 65 ±5%, the average moisture content of 60 specimens was 12.5% (varying from 11.9 to 13.6%) [Jakovļevs 2013]. It was determined with a drying and weighing method according to the standard EN 13183-1.

No significant difference ($p > 0.05$) was found between the equilibrium moisture content of pine CWM and the solid pine equilibrium moisture content 12.0% according to the standard DIN 68100-07. The coherence between the moisture content of CWM and the relative air humidity at a temperature of 20 ±2°C is given below [Iejavs 2016]:

$$W = 0.0011\,RH^2 + 0.0838\,RH + 1.61 \tag{1}$$

where: W – moisture content of CWM, %,
RH – relative humidity of the air, %.

The given coherence is positive and strong (r = 1.00), valid for the relative air humidity range from 30% to 85%.

Density

Density specimens before testing, were conditioned in the standard atmosphere to reach a constant mass. The apparent density of the pine CWM was determined from 60 cubic specimens, by measuring and dividing the specimen mass by its dimensions. The obtained apparent density of pine CWM varied from 277 to 332 kg·m^{-3} and the average value was 308 kg·m^{-3}.

The coherence between the density of CWM and moisture content at a temperature of 20 ±2°C is given below [Iejavs 2016]:

$$\rho = 2.55\,W + 277.86 \qquad (2)$$

where: ρ – density of CWM, kg·m^{-3},
W – moisture content of CWM, %.

The given coherence is moderately strong (r = 0.53) and valid for CWM moisture content range from 6% to 17%.

The characteristic value calculated according to the standard EN 14358 was 285 kg·m^{-3}. The increase of the lamella width and thickness in CWM production decreases the material density significantly. The cellular wood materials' apparent density compared to the solid pine timber density of 510 kg·m^{-3} was 38% less on average [Wagenführ 1996]. CWM density is 35% to 65% less compared to typical wood based panel density values (birch plywood, oriented strand board, particle board, etc.) figure 3 [Iejavs 2016].

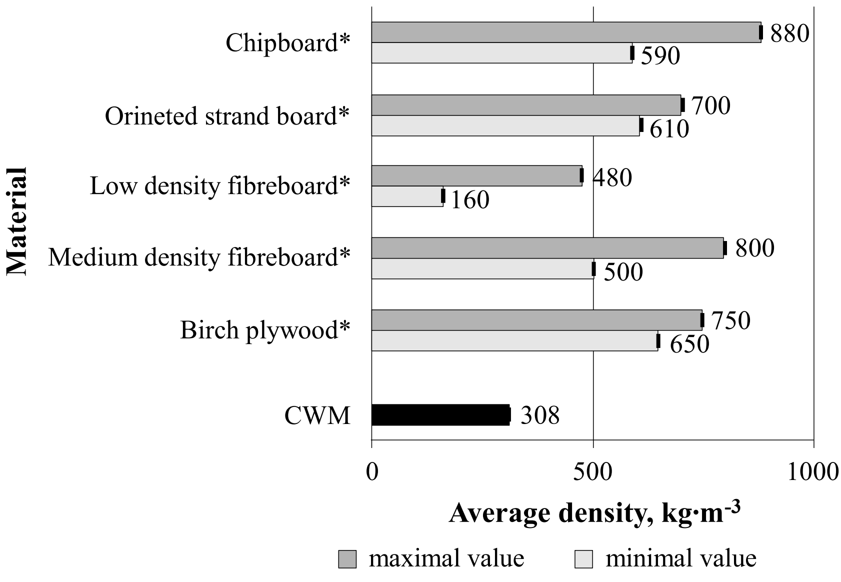

Fig. 3. Comparison of CWM and wood based panel average density values [*Bowyear et al. 2003]

The mean value of the apparent density can be used to calculate the weight of CWM and CWM sandwich panels. When a sandwich panel is made from CWM covered with wood based panels, a significant increase of the apparent density was observed.

Swelling and shrinkage

Shrinkage and swelling properties of wood based materials play an important role, when different types of wood materials need to be connected together. If shrinkage and swelling properties of the materials are not taken into account it may lead to the destruction of the joint or the whole structure. To evaluate the swelling and shrinkage coefficients of pine CWM as a function of air relative humidity and wood moisture content, a study was carried out. All three directions of CWM were investigated in the air relative humidity range from 30% to 85% with a corresponding wood moisture content range from 6% to 18%. In total 60 specimens were produced, 20 for each direction with the cross section of 56 × 56 mm and length of 300 mm. The test method of material shrinkage and swelling coefficients was based on the standard EN 318 requirements.

Essential conclusions: the structure of CWM provides a higher structural stability of the material compared to solid pine wood; the dimensional changes of CWM are similar in the longitudinal direction and in width, and the average shrinkage and swelling coefficient of 0.021 can be used for structural calculations and product design; a dimensional change of CWM in material thickness is comparable with that of the solid pine tangential and radial direction average shrinkage coefficient value of 0.22 [Wagenführ 1996; DIN 68100-07:2010]. For calculation purposes the average value of 0.25 of shrinkage and swelling coefficients is recommended. In the longitudinal and in width direction the average shrinkage and swelling coefficient of 0.021 is significantly lower compared with wood based panel coefficients in the thickness direction [Jakovļevs 2013].

Thermal conductivity and thermal transmittance

The efficiency of a building material is a topic that should be evaluated through various aspects of its life cycle. The material should be energy, resource and labour efficient in production, transportation, assembling, exploitation and recycling processes. With the rising demand for energy efficient homes, thermal properties of building materials and structures are mostly investigated when a choice between alternative construction materials should be made. The thermal conductivity of the material in most cases is related to the density of the material. One way in which the density of a material can be reduced and the thermal resistance can be increased is to create a series of cavities in the material. Research was conducted to evaluate the thermal properties of three-layer cellular wood panels for applications in construction. Industrially produced Scots pine CWM was used to create the test specimens and to determine the coefficient of thermal conductivity according to the standard EN 12667. Thermal conductivity of CWM is considerably directionally dependent, therefore the thermal conductivity in the parallel direction

λ_0 0.0977 W·m^{-1}·K^{-1} is up to 34% better than the thermal conductivity measured in the perpendicular direction λ_{90} 0.148 W·m^{-1}·K^{-1}.

The thermal resistance of CWM is not sufficient to be able to provide acceptable levels of thermal transmittance of a whole structure, therefore, to achieve the requirements of the building standard, it is strongly recommended using CWM sandwich panels in combination with an appropriate insulation material. For example a wall panel with CWM in a parallel direction with a thickness of 56 mm and top layers with 25 mm solid timber in combination with 125 mm mineral wool (λ 0.04 W·m^{-1}·K^{-1}) is an optimal building envelope that meets the requirements of the Latvian building standard LBN 002-01 and reaches a thermal transmittance value of 0.23 W·m^{-2}·K^{-1} [Iejavs 2016].

For CWM sandwich panels a numerically acquired heat flux model in the commercial computer code ANSYS and experimental test results, good agreement was found [Labans et. al. 2012].

Sound insulation

Due to the reduced mass, the decreased material thickness and holes in the CWM parallel and perpendicular directions, significant decrease of sound insulation properties were predicted compared to the solid wood and cross laminated timber panel properties. No information about CWM sound insulation properties in literature analysis was found. Therefore, initial research was made to evaluate CWM as a core material for structural door and wall panel design from the sound insulation point of view. Two large dimension specimens with a thickness of 25 mm and 60 mm respectively, were produced with CWM in a perpendicular direction covered with 4 mm thick high density fibre board top layers as door panels. Three structural wall panels with a thicknesses of 92 mm 108 mm and 148 mm respectively, were produced. CWM in a parallel direction covered with 18 mm thick pine solid timber top layers was used. A sound reduction index was determined for all five panels according to the standards EN ISO 10140-2 (1 to 5) and EN ISO 717-1 as the sound insulation property.

The obtained sound reduction index R_w values for the door panels were from 26 dB (for the 25 mm panel) to 31 dB (for the 60 mm panel). Only the 60 mm thick CWM sandwich panel without improvement can be used as a separating door leaf construction since R_w limit values (27 dB) given by the construction standard LBN 016-11 were exceeded. The three-layer CWM wall panel sound reduction index increases when the panel thickness and mass were increased. The obtained R_w values were as follows: 33 dB for the 92 mm thick panel, 35dB for the 108 mm panel and 37 dB for the 148 mm panel. The 92 mm and 108 mm thick wall panels provide similar sound reduction index values compared with the four layers of 100 mm thick cross laminated timber with R_w value 34 dB. None of the three panels can be used as wall panels without sound insulation improvement, since R_w limit value 45 dB was not reached. These panels can be used as a layer in a multi-layer wall panel design. The same structural improvement methods as for the cross laminated timber panels can be used to increase the CWM wall panel sound insulation property.

Reaction to fire

The reaction to fire performance is a key parameter for any building product on the market. Since CWM is a new product on the market, its properties were not known. A lot of research was done in the field of fire safety. A very similar wood product well known in the market, is cross laminated timber (CLT) which has shown excellent fire resistance performance in the case of fire. Reaction to fire performance of a standard CLT panel is the same as that of solid wood D-s2-d0. In some cases fire retardants are used to improve reaction to fire performance to Euroclass B-s1-d0, which is the highest possible class for wood based products.

CWM has the same chemical composition as CLT panels, but it is structurally different due to the air channels inside the structure of the panel. These channels are too narrow to make a chimney effect in the case of fire. It has been checked experimentally. However, heat transfer with hot pyrolysis gases happens and some kind of faster fire spread takes place in larger scale testing. It is important to understand the material's performance in a fire to take the relevant measures for ensuring a certain fire safety level. CWM reaction to fire performance was different in the parallel direction and in the perpendicular direction. CWM in a parallel direction fits within the requirements of a reaction to fire class D-s2-d0, however, the reaction to fire the parameters – fire growth rate index (FIGRA) and total heat release (THR_{600s}) were twice as high as for solid wood boards with a thickness of at least 25 mm. [Buksans et al. 2013]. CWM in a perpendicular direction showed the worst performance due to rapid fire development promoted by the convection effect. Formally CWM in a perpendicular direction can be classified in Euroclass E, but in reality the uncovered product in a perpendicular orientation does not exist. Usually CWM is covered by some other kind of wood based products, for example – solid wood boards, plywood, medium density fiberboard and others. A combination with different covering materials completely changes the performance of cellular wood products. Cellular core panels become dimensionally stable not only in the case of moisture change, but also in the case of fire. The product showed good potential to be a core material for fire resistant doors due to the high dimensional stability of the door leaf. The reaction to fire class for three-layer cellular panels depends on the reaction to the fire performance of the top layer, however, good synergy between two wood based products connected still exist. Gluing the cellular core together with a 4 mm thin MDF board facing will give the performance of a thicker product. In the case of a three-layer cellular wood based panel reaction to fire class of at least D-s2-d0 can be achieved. A combination of cellular wood core and magnesite board facing showed the best performance in the reaction to fire and gave a good prognosis for fire resistance.

The cellular wood structure is also a good challenge for the improvement of fire performance of the product, due to an easy fire retardant treatment with a high uptake capacity. Different treatment methods were used and at least a two times better reaction to fire performance was achieved by different product variations. A large potential of reaction to fire performance improvement exists, however larger problems exist in the case of the gluing process after fire retardant treatment. Most of the fire retardants change the surface energy and adhesion between the core and the facing is too weak. A serious investigation between the combinations of fire retardants along with the gluing process should be done in order to retain the mechanical properties of the three-layers of CWM.

Fire resistance properties of cellular wood material were not investigated, but some hypothesis arise from the medium scale reaction to the fire tests. The charring rate of CWM is about twice as high as for solid wood members. The fuel load of CWM is smaller compared to CLT but it gives a higher heat emission in the same time unit due to a faster combustion process.

Mechanical properties

Bending, compression and tension are common stress types for structural load bearing panels. Therefore, to use CWM in a structural element design, the eight most significant mechanical properties should be determined: ultimate strength and moduli of elasticity in bending, compression, tension and shear. All eight parameters were determined with test methods based on the standard EN 408 requirements. Characteristic values for all the properties were calculated according to the standard EN 14358.

The average strength properties of CWM range from 0.217 MPa for shear strength in a parallel direction to 2.15 MPa for bending strength in a perpendicular direction. The average stiffness properties of the CWM range from 5.87 MPa for the shear modulus in a parallel direction to 179 MPa for a local modulus of elasticity (MOE) in bending in a parallel direction. The characteristic compressive strength values of 1.05 MPa and 1.20 MPa were obtained when the material was loaded in a perpendicular and parallel direction accordingly. The obtained compressive strength properties can be compared with solid timber when loaded in compression in a perpendicular direction to the grain (2.5 MPa). For comparison, the characteristic compressive strength perpendicular to the grain of cross laminated timber panels range from 2.85 MPa [Bogensperger et al. 2011] to 3.3 MPa [Serrano and Enquist 2010]. The obtained pine CWM properties can be used for a new lightweight structural element and product design.

Research on the specimen size effect on CWM properties in a parallel direction was carried out to evaluate dimensional change influence on CWM main mechanical properties. The essential conclusions were listed as follows: an increase of specimen dimensions significantly increases the CWM bending strength and local modulus of elasticity in bending, an increase of CWM thickness significantly decreases the compressive strength of the material and an increase of the CWM compressed area did not influence the compressive strength. A significant influence of the CWM dimension changes in shear strength and shear was not observed [Ješauskis 2014].

Due to both the loss of the material and change of the structure of the material a significant decrease in the strength and the stiffness properties was observed if CWM is compared to solid timber. A decrease of approximately 14 times from 24 MPa to 2.11 MPa of characteristic bending strength and a decrease of 54 times from 7400 MPa to 136 MPa of characteristic MOE in bending on average were observed. According to the previous study on the three--layer CWM panels for structural application, a CWM covering with 20 mm solid timber can increase the average bending strength property up to 32.2 MPa, average MOE in bending up to 10900 MPa and a compression strength up to 17.5 MPa [Iejavs 2016].

According to Labans and Kalnins, CWM and CWM sandwich panels between numerically acquired compression and bending deformations in the commercial computer code ANSYS and experimental test results, good agreement was found. The difference did not exceed more than 20% [Labans and Kalnins 2012].

Adhesion with wood based materials

Three-layer cellular wood panels consist of a CWM core layer and two top layers made of solid wood or wood based panels. The initial research on non--structural CWM panels made of aspen (*Populus tremula* L.) wood shows that the tension strength perpendicular to the plain of the three layer CWM panels varies from 0.46 MPa to 0.86 MPa when PVA was used as a binder between CWM in a perpendicular direction and wood based materials [Jakovļevs 2013].

To evaluate the adhesion and bonding quality between Scots pine CWM and solid wood (pine, ash and thermally and mechanically treated grey alder) and wood based panels (oriented strand board, high density fibreboard and birch plywood) a study was carried out. The thermoplastic PVA adhesives are typical for the three-layer cellular panel gluing. To increase the thermal and moisture resistance of these products, emulsion polymer isocyanate Kleiberit EPI 304.4 and polyurethane Kleiberit PUR 501 (PUR) adhesives were evaluated as binders for three-layer cellular wood panel production. There were 15 specimens manufactured for each of the twelve CWM, adhesives and top layer material combinations. To evaluate the bonding quality of the panel's the internal bond (IB) was evaluated according to the standard EN 319. The fracture mode of the glued joint as an extra parameter was also evaluated. The initial research shows that emulsion polymer isocyanate and PUR adhesives, with good results, can be used for three layer CWM productions for both solid timber and wood based panels since the fracture mode occurs mainly between CWM and the top layer material. The average IB of the panels varies from 0.31 MPa (panels with oriented strand board top layers) up to 1.00 MPa (panels with pine or plywood top layers) when CWM was used in a perpendicular direction. The top layer significantly influences the fracture mode of the three-layer cellular wood panels, especially when the IB of top layer is lower compared to the IB of the CWM and the bonded joint between the CWM and the top layer material.

When CWM in a parallel direction was used as core material for sandwich panel production the IB of the panel was equal to the CWM structural tension strength 0.43 MPa, since specimens broke in the CWM. Only the CWM covered with oriented strand board shows a significantly lower average tension strength value 0.31 MPa since the specimen breaks in the oriented strand board layer [Jakovļevs 2013].

Resistance to withdrawal of screws

To evaluate the influence of a screw's depth on the force required to withdraw a screw from CWM, a study was carried out. In total 120 square specimens with the dimensions of 75 mm were used to determine the average withdrawal force for the length and thickness direction of the material. The standard wood screws of 6 × 120 mm, with a thread length of 70 mm were used with a thread depth of 14, 42 mm and 70 mm in the material. The study test methodology was based on the standard EN 320 test principles. The main conclusions are as follows: with an increase of thread depth, the force required to withdraw a screw from the CWM significantly increases. If the thread depth is increased from 14 mm to 70 mm, it is possible to increase the force about three times from 902 N to 2811 N on average when the screws are inserted in a parallel direction. In a perpendicular direction the increase is more significant – from 869 N to 4311 N on average. A pre drilling operation or the use of wood screws with self--tapping tips is recommended to avoid cracks in the CWM. A significant increase in the withdrawal of screw resistance from 330 N to 905 N was observed when the CWM was covered with top layers of a 4 mm thick high density fibreboard [Jakovļevs 2013].

Summary of the CWM properties

General average CWM structural properties obtained in the studies are shown in table 1.

Table 1. General properties of CWM

No.	Parameter	Unit	CWM direction	
			parallel	perpendicular
	Physical properties			
1	Moisture content W	%	12.3	
2	Density ρ	$kg{\cdot}m^{-3}$	308	
3	Shrinkage coefficient k_{sh}	$\%{\cdot}\%^{-1}$	0.248	0.0214
4	Swelling coefficient k_{sw}	$\%{\cdot}\%^{-1}$	0.255	0.0215
5	Volume shrinkage coefficient k_v	$\%{\cdot}\%^{-1}$	0.275	
8	Thermal conductivity λ	$W{\cdot}m^{-1}{\cdot}K^{-1}$	0.0975	0.148
9	Heat release rate FIGRA	$W{\cdot}s^{-1}$	696	1426
10	Total heat release in 600 s THR_{600s}	MJ	58	108
11	Reaction to fire class	–	D-s1, d0	E
	Mechanical properties			
12	Bending strength f_m	MPa	2.07	2.15
14	Compressive strength f_c	MPa	1.27	1.44
16	Tensile strength f_t	MPa	0.427	0.892
18	Shear strength f_v	MPa	0.217	1.73
20	Local modulus of elasticity in bending $E_{m,l}$	MPa	179	140
22	Modulus of elasticity in compression E_c	MPa	155	124
24	Modulus of elasticity in tension E_t	MPa	161	125
26	Shear modulus G	MPa	5.87	94.5
28	Shear strength of CWM glued joint f_{sl}	MPa	0.649	–
29	Withdrawal resistance of screws SPEC 17 when inserted 70 mm deep F_s	N	4311	2811
30	Internal bond of covered CWM $f_{t,cov}$	MPa	0.427	0.311-1.00

Conclusions

A significant number of studies were carried out to determine the physical and mechanical properties of CWM and CWM products to estimate the material for structural applications. Since a significant decrease of mechanical and some physical properties was observed, compared to solid timber and wood based panels properties, CWM covering with a top layer material and supplementation with other building materials was found to be an effective method for CWM property improvement. No information about fire resistance or the water vapour permeability properties of CWM and its products was found. Since both properties are significant for the structural element design they should be determined and evaluated.

References

Bogensperger T., Augustin M., Schikhofer G. [2011]: Properties of CLT-panels exposed to compression perpendicular to their plane. In: International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures, 28 August – 1 September, Alghero, Italy. Karsluhe: 1-15

Bowyer J.L., Shmulsky R., Haygreen J.G. [2003]: Forest products and wood science: an introduction. Forth Edition, Iowa State Press, Iowa: 554 p.

Buksans E., Morozovs A., Rudzitis E. [2013]: Improvement of the reaction to fire performance of cellular wood material. In: International journal in the field of wood engeneering ProLigno. Part 2. Universităţii "Transilvania", Braşov, Romania 9, 4: 203--210

Follrich J., Berger J., Frybort S., Teischinger A., Müller U. [2006]: DendroLight (R) – an innovative wood based light weight panel. In: Wood resources and panel properties. COST Action E44-E49, Valencia

Iejavs J. [2016]: Priedes (*Pinus sylvestris* L.) koksnes šūnveida materiāla īpašības un to uzlabošanas iespējas. (Properties and the possibilities for improving of pine (*Pinus sylvestris* L.) cellular wood material performance). Latvia University of Agriculture, Jelgava [Doctoral theses, unpublished]

Jakovļevs V. [2011]: Šūnveida plātnes no apses (*Populus tremula* L.) koksnes fizikāli – mehāniskās īpašības (Physical-mechanical properties of aspen (*Populus tremula* L.) cellular wood material). Latvia University of Agriculture, Jelgava [Diploma theses]

Jakovļevs V. [2013]: Physical and mechanical properties of solid wood cellular material of pine (*Pinus sylvestris* L.). Latvia University of Agriculture, Jelgava [Master theses]

Ješauskis E. [2014]: Ģeometrisko izmēru ietekme uz koksnes šūnveida materiāla mehāniskajām īpašībām (Geometric parameters influence on the mechanical properties of the cellular wood material). Latvia University of Agriculture, Jelgava [Diploma theses]

Labans E., Kalnins K., Bikovs A. [2012]: Simulation of mechanical and thermal properties for sandwich panels with cellular wood cores. Scotland. [accessed 11. November 2015]. Available: http://webapp.tudelft.nl/proceedings/ect2012/pdf/labans.pdf

Labans E., Kalnins K. [2012]: Numerical modelling and experimental validation of dendrolight cellular wood material. In: Proceedings of the 8th Meeting "Northern European Network for Wood Science and Engineering (WSE)". Lithuania, Kaunas: 177--184

Pflug J., Vangrimde B., Verpoest I. [2003]: Material efficiency and cost effectiveness of sandwich materials. In: Sampe Conference. Longbeach: 1925-1937

Serrano E., Enquist B. [2010]: Compression strength perpendicular to grain in cross--laminated timber (CLT). In: World Conference on Timber Engineering, 20-24 June 2010 Riva del Garda, Trentino, Italy, Linnaeus University, Faculty of Science and Engineering, School of Engineering: 1-8

Skuratov N. [2010]: New lightweight solid wood panels for green building. In: International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee, Paper IW-4, October (pp. 1-7), Geneva: 11-14

Wagenführ R. [1996]: Holzatlas, Vol 4, Leipzig, Germany, Fachbuchverl

Voth C.R. [2009]: Lightweight sandwich panels using small-diameter timber wood-strands and recycled newsprint cores. PhD thesis. [accessed 12. November 2015] Available: http://www.dissertations.wsu.edu/Thesis/Fall2009/c_voth_120609.pdf

List of standards

DIN 68100-07:2010 Tolerance system for wood working and wood processing – Concepts, series of tolerances, shrinkage and swelling

EN 319:1993 Particleboards and fibreboards – Determination of tensile strength perpendicular to the plane of the board

EN 12667:2001 Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance

EN 13183-1:2002 Moisture content of a piece of sawn timber – Part 1: Determination by oven dry method

EN 318:2002 Wood based panels – Determination of dimensional changes associated with changes in relative humidity

EN 14358:2006 Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample

EN 320:2011 Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws

EN 408+A1:2012 Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties

EN ISO 717-1:1996 Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation

EN ISO 10140-2:2010 Acoustics – Laboratory measurement of sound insulation of building elements - Part 2: Measurement of airborne sound insulation

LBN 002-01 Ministru kabineta noteikumi nr. 495, Ēku norobežojošo konstrukciju siltumtehnika (The Latvian Construction Standard LBN 002-01 Cabinet of Ministers reg. no. 495, Thermotechnics of Building Envelopes). Rīga. 27.11.2001

LBN 016-11 Ministru kabineta noteikumi nr. 499, Būvakustika (Latvian Construction Standard LBN 016-11 Cabinet of Ministers reg. no. 499 Building Acoustics) Rīga. 28.06.2011

Acknowledgements

Review and studies [Ješauskis 2013; Iejavs 2016] mentioned in the manuscript were written with the financial support of Latvia National Research Program "Forest and earth entrails resources: research and sustainable utilization – new products and technologies" (ResProd) 2014-2017.

RESPROD

Submission date: 8.01.2016

Online publication date: 9.12.2016