The 2nd Conference on Engineered Wood Products based on Poplar/Willow Wood (CEWPPW2)

2ND CONFERENCE ON ENGINEERED WOOD PRODUCTS BASED ON POPLAR/WILLOW WOOD CEWPPW2

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Editor: Joris Van Acker
Ghent University

Conference organised by

Pro Populus

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IPC
INTERNATIONAL POPLAR COMMISSION

PROCEEDINGS

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September 8th – 10th 2016
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Edited by

Joris Van Acker
Ghent University, Belgium

2nd Conference on Engineered Wood Products based on Poplar/Willow Wood CEWPPW2
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Conference is linked to the 25th Session of IPC and with the help of the local organiser Garnica plywood taking place in León in Spain. The management of the conference is in the hands of the organisation Pro-Populus.

Editor:

Prof. Joris VAN ACKER (chairman IPC WP harvesting and utilization)

Proceedings of the
2nd Conference on Engineered Wood Products based on Poplar/Willow Wood CEWPPW2

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PREFACE

Under the structure of the International Poplar Commission (IPC) the "Working party (WP) on harvesting and utilization of poplar & willow wood" initiated a first conference on Engineered Wood Products Based on Poplar/Willow Wood at the Nanjing Forestry University - PRChina, October 21st-24th 2008. The 2nd conference is again linked to the IPC meeting, now the 25th meeting in Berlin (http://www.fao.org/forestry/ipc/en/). Since the first conference (proceedings available on http://foris.fao.org/static/pdf/ipc/IPCProceedingsNanjing2008.pdf) a lot of innovation and increased attention can be seen in the sector of engineered wood products, in particular related to poplar, aspen and willow.

The 2nd Conference on Engineered Wood Products based on Poplar/Willow Wood is organised the 9th – 10th September, 2016 in at the Conference centre of the Parador de León, Plaza de San Marcos, 7 – León, Spain. For IPC a field trip to Garnica Plywood at Valencia de Don Juan is organised prior to the scientific sessions on 8th September, 2016.

The president of the company Garnica Plywood, Mr. Pedro Garnica is also the president of Pro-Populus. This European association was created in 2008 and is considered the "European poplar association", as it is unique in the sense that, for the first time, it gathers growers, promoters and industrial users of poplar for the variety of uses it offers (panels, packaging, energy, etc.). Both the company Garnica Plywood and the organisation Pro-Populus have been key in organizing this conference.

The **International Poplar Commission (IPC)**, an FAO technical statutory body on forestry, aims to promote the cultivation, conservation and utilization of members of the family Salicaceae, which includes poplars and willows. The Working Party on Harvesting and Utilization of Poplar and Willow Wood is specifically dedicated to the poplar/willow forestry-wood industry chain and has taken the initiative to organize this conference in León, Spain organized back to back immediately prior to the 25th IPC meeting in Berlin.

The organisers and editor would like to thank the speakers for their papers because without them there is no conference. I am sure that everyone involved in the conference from organiser to participant would like to thank the local organisers of Garnica Plywood and Pro-Populus.

We hope that you enjoy the conference and find the papers useful in your future work.

Prof. Joris VAN ACKER
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Phenotypic and genotypic correlations for wood properties of hybrid poplar clones of Southern Quebec

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Keywords: Hybrid poplar, phenotypic correlations, genotypic correlations, wood anatomical, physical and mechanical properties

ABSTRACT

This study aims to understand the phenotypic and genotypic correlations among wood anatomical, physical, and mechanical properties of hybrid poplar clones. Samples were taken from seven clones grown in three sites in Southern Quebec, Canada. Five trees per clone were randomly sampled from each site to measure anatomical, physical, and mechanical wood properties. The observed phenotypic and genotypic correlations between these wood properties were moderate to strong, except fiber length and vessel proportion. Genotypic correlations for all wood properties were higher than corresponding phenotypic correlations. Furthermore, fiber length showed weak correlations, whereas, vessel proportion showed strongly negative correlations with all other properties. Strong correlations were also found among fiber proportion, wall thickness, basic density, and mechanical properties. Results from this study further show close genotypic and phenotypic correlations between fiber proportion, wall thickness, and wood density and consequently on the mechanical performance of wood products. These findings indicate that there is a substantial opportunity to improve wood quality by selecting several wood properties for different end uses.

INTRODUCTION

The Canadian forests are among the most extensive in the world and represent one of Canada’s most valuable natural resources. Poplar is one of the top components of this resource, particularly the stands located in the boreal region of the country. In Québec, Quebec’s ministry of natural resources has been actively breeding and selecting hybrid poplar clones for growth, adaptability to the climatic conditions, and wood quality. The program of genetic improvement of poplars started in 1969 to produce improved hybridized poplar populations using five main parental species: *P. balsamifera*, P. *deltoides, P. maximowiczii, P. nigra*, and *P. trichocarpa* (Périnet *et al*. 2007). In Quebec, the anticipated yields were 14 m^3/ha.yr on average sites, 20 m^3/ha·yr on the best sites and 10 m^3/ha·yr in boreal sites (Messier *et al*. 2003).

Poplars are important species for forest products industries, particularly for the establishment of fiber for pulp and paper, engineered wood products such as oriented strand board, laminated veneer lumber, and structural composite lumber. Poplar wood is well suited for particle, flake, and strand-based composite boards due to its low density, ease of cutting, low processing cost and availability.
The introduction of wood quality traits selection criteria is considered as an important objective for the breeding program. However, wood quality can only be defined in terms of specific end-uses and may involve several wood properties, such as fiber morphology, and wood density (Downes *et al*. 1997). Poplars show substantial variation in many important wood properties, such as fiber dimensions (Zhang *et al.* 2003; Pliura *et al*. 2007), and wood density (Zhang *et al*. 2012). Wood density is a commonly used quality indicator that is related to other wood properties such as mechanical strength and shrinkage as well as pulp yield and properties (Panshin and de Zeeuw 1980). Despite its key importance, density is not the only basic property involved in wood mechanical strength development. Jacobsen et al. (2005) stated that high mechanical strength is associated with thick fiber walls. Moreover, the thickness of poplar cell walls in turn is positively correlated with wood density (Pliura *et al*. 2007).
In a breeding program, knowledge of genetic correlation plays a vital role in the prediction of correlated responses and the development of effective selection indexes. Several studies have focused on the fiber morphology, density, and growth properties of poplars (Beaudoin *et al*. 1992; Koubaa *et al*. 1998 a, b; Zhang *et al*. 2003; Pliura *et al*. 2005, 2007; Zhang et al. 2012). However, there is no available study on the phenotypic and genotypic correlations among anatomical, physical, and mechanical properties of hybrid poplar clones. Therefore, the main objectives of this study were: 1) to estimate the genotypic and the phenotypic correlations among wood anatomical, physical, and mechanical properties, and 2) to evaluate the implication of these relationships in hybrid poplar breeding programs for wood quality.

EXPERIMENTAL

Plant material

The materials used in this study were collected from three hybrid poplar clonal trials established by the Department of forest research at Quebec's ministry of natural resources between 1991 and 1995. The trial sites are located in Pointe-Platon (46°40'N 71°51'W), Saint-Ours (45°54'N 73°09'W), and Windsor (45°42'N 71°57'W) in southern Quebec, Canada. Trees for hybrid clone trials were planted at the Saint-Ours and Windsor sites in 1993, and in 1991 at the Pointe-Platon site. Site characteristics and details on the hybrid poplar clones are described in Huda *et al*. 2012; 2014.

Sampling and measurement

Five trees of each clone were randomly sampled at each site, for a total of 105 trees. A disc of 800 mm in length with its base at a height of 0.5 m above the ground was collected from each tree stem after felling for physical and mechanical properties measurements. Disc edges were coated with wax to maintain wood moisture content (MC) and to prevent decay. A 2.5 cm wide slab was cut horizontally along the diameter of each disc (bark to bark passing through pith) and then conditioned at 20°C and 60% relative humidity for several weeks until an equilibrium MC of 12% was reached.

For the anatomical analysis, cross sections of 20 μm were cut using a sliding microtome with a disposable blade. Sections were then double stained with 1% safranin stain for 5 minutes and 0.1% astrablue stain for 15 minutes. Stain in excess was removed by washing sections successively using 50, 80, and 100% ethanol solutions. Safranin stains all tissues, and astrablue replaces safranin in purely cellulosic G-layers of tension wood. Sections were then permanently mounted on microscope slides with cover slips using Permount mounting medium. Samples were left for two weeks to allow the mounting medium to dry thoroughly. Sample images were taken at ×50 magnification with a Leica compound microscope (DM 1000) equipped with a PL-A686 high-resolution microscopy camera. Black and white images at 1200 × 1600 resolution were captured using a green filter to maximize contrast. The WinCELL Pro 2004a program (Regent Instruments Inc.), an image analysis system specifically designed for wood cell analysis, was used to measure fiber wall thickness and tension wood proportion. Tissue proportion in different cell types was estimated from 2 sections from each block. Vessel tissue was distinguished from fiber and ray tissue by defining a 570 μm^2 four-square area for every grid examined, and tissue types that fell within this area were noted. Fiber proportion was measured by the same method. A Fiber Quality Analyzer (FQA) (OpTest Equipment Inc., LDA02) was used to measure fiber length.
For physical and mechanical properties, specimens were cut into 20 mm (T) x 20 mm (R) x 100 mm (L) pieces for basic density, shrinkage, and compression tests, and 20 mm (T) x 20 mm (R) x 330 mm (L) pieces for bending tests. Sample preparation and measurement of physical and mechanical properties were conducted according to ASTM D143 except for dimension of samples. Physical properties measured were basic density (oven-dry mass to green volume ratio), total volumetric, longitudinal, tangential and radial shrinkages. Mechanical properties were modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending, and the ultimate crushing strength (CS) parallel to the grain. The specimens were weighed in an analytical balance and a digital micrometer was used to determine their T, R, and L dimensions. Longitudinal, radial, and tangential shrinkages were calculated as the ratio of the dimensional variation in each direction between saturated and oven-dry states on the dimension in the saturated state. Volumetric shrinkage was calculated from direct volume measurement. Three-point static bending tests were carried out using a universal testing machine with a span length of 300 mm and maximum load of 20 kN. Compression parallel to the grain tests were performed on a universal testing machine with a maximum load of 100 kN.

Statistical analysis

SAS® version 9.3 (SAS 2010) was used for statistical analyses. Residuals were tested for normality and homogeneity of variance using statistics provided by the UNIVARIATE procedure. Tree effects were not considered in the analysis, as preliminary testing showed negligible contribution to the total variance. In many cases, the variance component for these terms could not be estimated or was not significant. The mixed linear model was used to estimate variance components:

$$X_{ijk} = \mu + S_i + C_j + (S \times C)_{ij} + \varepsilon_{ijk} \qquad [1]$$

where X_{ijk} is an observation on the the *jth* clone from the *ith* site; μ is the overall mean; S_i is the fixed effect due to the *ith* site; C_j is the fixed effect due to the *jth* clone; $(S \times C)_{ij}$ is the interaction between site and clone and ε_{ijk} is the random error. The Pearson's correlation coefficients for the phenotypic interrelationships were computed using the

SAS CORR procedure. Significance levels were calculated with respect to the null hypothesis r=0. The genotypic correlation (r_A) of two traits x and y were obtained with,

$$r_A = \frac{\sigma_{c(xy)}}{\sqrt{\sigma^2_{c(x)} \times \sigma^2_{c(y)}}} \quad [2]$$

$$\sigma_{c(xy)} = \left(\sigma^2_{c(x+y)} - \sigma^2_{c(x)} - \sigma^2_{c(y)}\right) \quad [3]$$

Where $\sigma^2_{c(x)}$ is the clone variance component for the trait x, $\sigma^2_{c(y)}$ is the clone variance component for the trait y and $\sigma_{c(xy)}$ is the clone covariance component. The method is described in detail by Williams et al. (2002). Because of sampling errors and mathematical approximation, some genotypic correlations exceeded ±1. In these cases, we considered them equal to ±1, considering the asymptotic nature of distribution of the correlation coefficients. The estimation of genotypic correlation was performed with MANOVA option using the GLM procedure in SAS. Standard errors associated with the genotypic correlations were estimated according to Robertson (1959).

$$\sigma(r_A) = \frac{1-r_A^2}{\sqrt{2}} \text{ x } \sqrt{\left[\frac{\sigma(h_x^2) \text{ x } \sigma(h_y^2)}{h_x^2 \text{ x } h_y^2}\right]} \quad [4]$$

Where h_x^2 and h_y^2 are the heritability estimates for traits x and y; $\sigma(h_x^2)$ and $\sigma(h_x^2)$ are the associated standard errors for heritability estimates.

RESULTS AND DISCUSSION

Phenotypic correlations between wood properties

Correlations between all studied properties are shown (Table 1). In good agreement with previous findings (Zhang *et al*. 2003, Porth *et al*. 2013), the correlations between fiber length and all other properties were not significant at both tree and clone levels. A close negative relationship was found between fiber and vessel proportions. Increasing the proportion of one element will lead to a decrease in the other. A positive relationship between fiber proportion and wall thickness was observed (Table 1). Clones with higher fiber proportion tend to develop thicker cell walls. Similarly, the negative relationship between fiber wall thickness and vessel proportion suggests that clones with higher vessel proportion have thinner cell walls. These findings explain the positive correlation between density and fiber wall thickness and the negative correlation between vessel proportion and density. Indeed, wood density was correlated to all anatomical features, except fiber length. These results are explained by the fact that the fiber morphological properties of wood largely determine its density (Panshin and de Zeeuw 1980). Higher fiber proportion and fiber wall thickness are associated with higher wood density (Ziemińska *et al*. 2013). However, high vessel proportion will yield hydraulic conductivity, which could cause higher shrinkage, and disruption in wood structure.

Positive correlations between tension wood proportion and fiber wall thickness were found (Table 1). Thus, higher tension wood proportion is associated with smaller fiber lumen area and thicker walls. On the other hand, vessel proportion was negatively

correlated to tension wood proportion. These findings are in good agreement with previous findings for eastern cottonwood (Kaeiser and Boyce 1965). The correlation between wood density and tension wood proportion was positive and significant. This result could be explained by the higher fiber proportion and greater fiber wall thickness of tension wood. In addition, the formation of tension wood was associated with the presence of a gelatinous layer that increases the amount of cellulosic material in the fiber. Increased wall thickness for tension wood fibers is due to thicker G-layers.

The correlation between tension wood proportion and volumetric shrinkage was not significant (Table 1). The volumetric shrinkage of wood is influenced by the higher content of tension wood. The samples of the present study might have variable contents of tension wood, which hereby explains the insignificant variation of volumetric shrinkage values among the tested clones, although, this result is difficult to explain. However, Gorisek and Straze (2006) reported that the chemical composition and cell wall organization such as, high crystallinity of cellulose in G-layer, small amount of matrix substance, smaller micro voids in cell walls, are probable reason of non-significance relationship between wood shrinkage and tension wood. On the other hand, the presence of tension wood was positively correlated to the longitudinal, radial, and tangential shrinkages. Many authors also confirmed the existence of this positive correlation between tension wood and longitudinal shrinkage in poplar wood (Clair and Thibaut 2001). Axial shrinkage of tension wood is more than 5 times higher than that of normal wood (Sassus 1998).

The correlations between tension wood and mechanical properties were also significant (Table 1). This result is in good agreement with Pilate et al. (2004), which suggested that the presence of the G-layer contributes, in a significant way, to specific mechanical properties of wood. The results of the present study indicate that tension wood will not negatively affect the mechanical performance of the wood. Similarly, in a parallel study Hernández *et al*. (2011) found that tension wood did not affect the machining properties of these hybrid poplar clones. Clair *et al*. (2003) also found similar results for chestnut. In tension wood of poplar, the secondary wall is replaced by a poorly lignified or purely cellulosic layer that is generally thick (Okumura *et al*. 1977). Besides, tension wood is characterized by a higher proportion of fibers and a lower proportion of vessels (Jourez *et al*. 2001). As a result, the increase of fiber proportion implies more walls by volume of wood tissue, thus, a higher density and mechanical properties. The correlation between volumetric shrinkage and wood density is positive and significant at the clone and tree levels. For radial shrinkage, the correlation with wood density was significant but those of longitudinal and tangential shrinkage were not. A similar result was reported in *P. x euramericana* hybrid clones by Koubaa *et al*. (1998a). Volumetric shrinkage had no significant relationship with anatomical or mechanical properties in the present study. Volumetric shrinkage and swelling properties are affected by several wood properties, such as the heartwood to sapwood ratio and the microfibril angle in the S2 layer (Bektaş and Güler 2001). However, our results showed that among the properties studied, wood density has the greatest effect on wood shrinkage. Hence, the direct measurement of shrinkage values of tested poplar clones gives some degree of confidence on their dimensional stability.

Mechanical properties improved with increased fiber proportion. However, no relationship with other anatomical properties was found except tension wood (Table 1). In good agreement with previous reports (Hernández *et al*. 1998, De Boever *et al*. 2007), a positive relationship between mechanical properties and density. At the individual tree level, density showed a highly significant correlation with flexural MOR

and ultimate crushing strength and moderate but significant correlation with flexural MOE.
At the clonal level, density affected all mechanical properties. Similarly, the correlations between mechanical properties and wood density ranged from moderate to high and could be explained by the fact that the density used for the correlation analysis was the overall tree density of clones and not the density of the tested samples. In addition, the tested poplar clones were only 15 years of age, thus, the wood was mainly juvenile.

Genotypic correlations between wood properties

Genotypic correlations among traits were moderate to strong, depending on traits at individual sites (Table 2). Significant negative genetic or genotypic correlations between density and growth properties were reported for poplars (Beaudoin *et al*. 1992, Hernández *et al*. 1998, Pliura *et al*. 2007).

However, no study addressed the genotypic correlations among different wood properties in hybrid poplars. Genotypic correlation between fiber length and other wood properties were weak and negative, except for vessel proportion and flexural MOR. The genotypic correlation between fiber length and density of the present study are in good agreement with the study of Porth *et al*. (2013) *on P. trichocarpa*. In both phenotypic and genotypic correlations, we observed weak correlations between fiber length and other wood properties, which make fiber length an independent trait for wood breeding. However, these correlations could be an indication of properties that are functionally or developmentally less related, and are therefore phenotypically and genetically less integrated. Thus, it is difficult to improve both fiber length and density simultaneously.
The genotypic correlations between fiber proportion and other wood properties were strong and positive, while the genotypic correlation with vessel proportion was negative (r = -0.97). As expected, the genotypic correlations were strong and negative for vessel proportion and other properties (Table 2). Fiber and vessel proportions showed opposite correlation with the other wood properties especially at the genetic level. The genotypic correlations between fiber wall thickness and other wood properties were strong. At the genetic level, fiber wall thickness was associated with higher fiber proportion, indicating a tendency for higher mechanical properties. All correlations with tension wood were positive, with the exception of vessel proportion where strong negative genotypic correlation was detected, due to the fact that the gelatinous fiber layer formed in tension wood has narrower vessels and a lower vessel area. This result could be explained by the fact that the S3 layer of secondary wall was replaced by the thick cellulosic layer known as gelatinous fiber layer inside the lumen of the fiber. Kaeiser and Boyce (1965) described that gravitational stimulus generally induce the formation of gelatinous fibres, which modify the anatomical characteristics of other elements of wood, such as modifications of the size of rays, vessels, and fibers in *Populus* deltoides.
Strong genotypic correlations were observed between tension wood and shrinkage properties. Tension wood consists of hydrophilic substance within the G-layers (Mellerowicz and Gorshkova 2012). As a result, when tension wood is dried and water removed rapidly, it causes a greater level of shrinkage and it impacts on wood mechanical properties and, consequently, wood quality. The strong genotypic correlations between density and these properties indicated that selection of any one of these properties would result in a highly correlated response to selection in the others. However, breeding program based on density may lead to severe reduction in fiber length. The latter has a strong genotypic correlation with growth properties whereas

significant negative genetic correlations were found between density and growth (Hernández *et al*. 1998, Pliura *et al*. 2007). The genotypic correlations among density and different shrinkage properties were moderate. Moreover, the genotypic correlation between wood density and mechanical properties were positive and strong (Table 2).
This study further found strong genotypic correlations between the wood mechanical properties and wood anatomical properties except for fiber length. On the other hand, the strong positive relationships between mechanical properties and anatomical properties at genetic level present a possible strategy for wood quality improvement.
Breeding strategies that would aim to improve fiber proportion and wall thickness, would have negligible influence on fiber length. The genotypic correlations among mechanical properties and density were very strong. As a result, the inclusion of wood density into tree breeding programs can lead to an improvement of mechanical strength properties. Moreover, these high genotypic correlations with MOE and MOR make density a strong candidate for direct genetic improvement of general wood quality.

Nevertheless, the use of this property can ultimately benefit solid wood and fiber-based wood products. For example, selection for increased wood density for industrial implications would at the same time increase pulp yield and solid wood product value, and decrease the production cost. However, the choice of the properties to be included in the improvement program often depends on their ease of assessment or determination. Therefore, wood properties such as fiber proportion, fiber wall thickness and easily measurable wood density can be used for the improvement of mechanical wood properties as a selection strategy.
Broad surveys of literature suggested that genetic and phenotypic correlations have the same sign and even the magnitude (Falconer and Mackey 1996). Our finding also confirmed the relationships of phenotypic and genetic correlations reported in the literature. For example, phenotypic and approximate genetic correlations of vessel proportion with all properties were all negative. However, in the present study, the genotypic correlations were found stronger than phenotypic correlations for all wood properties. These results might be explained by the environmental influences that weaken the phenotypic correlation between wood properties in comparison to genotypic correlation. This is consistent with findings from an earlier study showing environmental influence on phenotypic coefficient of variation and genotypic coefficient of variation of wood anatomical properties (Huda *et al*. 2012).

Table 1: Pearson coefficients of correlation between the anatomical, physical, and mechanical properties of hybrid poplar clones. Upper right part (in italic) of the table presents the correlations between tree averages (n=105) and the lower left part indicates the correlations between clone averages within sites (n=21)

	FL [mm]	**FP [%]**	**VP [%]**	**FWT [µm]**	**TW [%]**	**BD [kg/m³]**	**VSH [%]**	**LSH [%]**	**TSH [%]**	**RSH [%]**	**MOE [MPa]**	**MOR [MPa]**	**CS [MPa]**
FL [mm]	1	-0.16^{ns}	0.29^{**}	-0.15^{ns}	-0.02^{ns}	0.07^{ns}	-0.04^{ns}	-0.14^{ns}	0.16^{ns}	-0.12^{ns}	0.06^{ns}	0.08^{ns}	0.05^{ns}
FP [%]	-0.21^{ns}	1	-0.70^{**}	0.53^{**}	0.30^{**}	0.44^{**}	0.19^{ns}	0.04^{ns}	-0.03^{ns}	0.35^{**}	0.31^{**}	0.53^{**}	0.41^{**}
VP [%]	0.36^{ns}	-0.75^{**}	1	-0.38^{**}	-0.39^{**}	-0.41^{**}	-0.27^{**}	-0.26^{**}	-0.08^{ns}	-0.27^{**}	-0.17^{ns}	-0.47^{**}	-0.38^{**}
FWT [µm]	-0.24^{ns}	0.55^{**}	-0.47^{*}	1	0.30^{**}	0.34^{**}	0.17^{ns}	0.04^{ns}	0.06^{ns}	0.21^{*}	0.15^{ns}	0.37^{**}	0.33^{*}
TW [%]	0.04^{ns}	0.43^{ns}	-0.51^{*}	0.47^{*}	1	0.35^{**}	0.19^{ns}	0.56^{**}	0.41^{**}	0.30^{*}	0.23^{*}	0.53^{**}	0.38^{**}
BD [kg/m³]	0.08^{ns}	0.57^{**}	-0.52^{*}	0.48^{*}	0.78^{**}	1	0.36^{**}	0.19^{ns}	0.12^{ns}	0.24^{*}	0.42^{**}	0.61^{**}	0.80^{**}
VSH [%]	-0.02^{ns}	0.32^{ns}	-0.39^{ns}	0.33^{ns}	0.41^{ns}	0.45^{*}	1	0.25^{*}	0.44^{*}	0.09^{ns}	-0.08^{ns}	0.24^{**}	0.30^{**}
LSH [%]	-0.19^{ns}	0.06^{ns}	-0.37^{ns}	0.12^{ns}	0.56^{**}	0.38^{ns}	0.51^{*}	1	0.35^{**}	0.04^{ns}	-0.08^{ns}	0.21^{ns}	0.27^{**}
TSH [%]	-0.09^{ns}	0.63^{**}	-0.44^{*}	0.43^{*}	0.44^{*}	0.39^{ns}	0.10^{ns}	-0.19^{ns}	1	0.03^{ns}	0.27^{**}	0.28^{**}	0.32^{**}
RSH [%]	0.18^{ns}	-0.03^{ns}	-0.08^{ns}	0.18^{ns}	0.51^{*}	0.43^{*}	0.57^{**}	0.39^{ns}	0.16^{ns}	1	0.10^{ns}	0.24^{**}	0.15^{ns}
MOE [MPa]	-0.02^{ns}	0.52^{**}	-0.29^{ns}	0.30^{ns}	0.44^{*}	0.71^{**}	0.06^{ns}	-0.12^{ns}	0.42^{ns}	-0.03^{ns}	1	0.73^{**}	0.51^{**}
MOR [MPa]	-0.01^{ns}	0.66^{**}	-0.57^{**}	0.49^{*}	0.75^{**}	0.90^{**}	0.34^{ns}	0.36^{ns}	0.45^{*}	0.38^{ns}	0.78^{**}	1	0.69^{**}
CS [MPa]	0.05^{ns}	0.57^{**}	-0.43^{*}	0.47^{*}	0.73^{**}	0.88^{**}	0.31^{ns}	0.42^{*}	0.30^{ns}	0.35^{ns}	0.83^{**}	0.90^{**}	1

FL fiber length, FP fiber proportion, VP vessel proportion, FWT fiber wall thickness, TW tension wood proportion, BD basic density, VSH volumetric shrinkage, LSH longitudinal shrinkage, RSH radial shrinkage, TSH tangential shrinkage, MOE flexural modulus of elasticity, MOR flexural modulus of rupture, and CS ultimate crushing strength parallel to the grain.

Table 2: Estimated genotypic correlations (below diagonal) and standard errors (above diagonals, in Italic) for the anatomical, physical, and mechanical properties of hybrid poplar clones

	FL [mm]	FP [%]	VP [%]	FWT [μm]	TW [%]	BD [kg/m³]	VSH [%]	LSH [%]	TSH [%]	RSH [%]	MOE [MPa]	MOR [MPa]	CS [MPa]
FL [mm]	1	*0.15*	*0.23*	*0.14*	*0.15*	*0.18*	*0.24*	*0.25*	*0.24*	*0.27*	*0.12*	*0.15*	*0.22*
FP [%]	-0.10	1	*0.18*	*0.07*	*0.23*	*0.01*	*0.05*	*0.06*	*0.01*	*0.05*	*0.04*	*0.16*	*0.04*
VP [%]	0.24	-0.97	1	*0.18*	*0.15*	*0.01*	*0.36*	*0.26*	*0.10*	*0.19*	*0.23*	*0.13*	*0.20*
FWT	-0.07	0.74	-0.90	1	*0.18*	*0.14*	*0.39*	*0.36*	*0.18*	*0.26*	*0.12*	*0.07*	*0.06*
TW [%]	-0.04	0.87	-0.91	0.88	1	*0.07*	*0.14*	*0.17*	*0.15*	*0.13*	*0.08*	*0.01*	*0.03*
BD	-0.02	0.90	-0.92	0.84	0.86	1	*0.21*	*0.26*	*0.01*	*0.17*	*0.12*	*0.17*	*0.10*
VSH [%]	-0.30	0.62	-0.76	0.69	0.73	0.53	1	*0.22*	*0.01*	*0.01*	*0.36*	*0.21*	*0.28*
LSH [%]	-0.19	0.42	-0.58	0.66	0.77	0.56	0.72	1	*0.38*	*0.14*	*0.04*	*0.10*	*0.11*
TSH [%]	-0.18	0.67	-0.74	0.60	0.82	0.69	1.00	0.93	1	*0.46*	*0.32*	*0.33*	*0.37*
RSH [%]	-0.08	1.00	-0.98	1.00	0.94	1.00	0.99	0.49	0.86	1	*0.24*	*0.11*	*0.12*
MOE [MPa]	-0.23	0.78	-0.77	0.72	0.88	0.97	0.46	0.93	0.72	0.42	1	*0.28*	*0.01*
MOR [MPa]	0.07	0.90	-0.84	0.77	0.76	0.97	0.73	0.64	0.83	0.98	0.68	1	*0.14*
CS [MPa]	-0.01	0.64	-0.74	0.73	0.81	0.93	0.53	0.86	0.67	0.62	1.00	0.83	1

FL fiber length, FP fiber proportion, VP vessel proportion, FWT fiber wall thickness, TW tension wood proportion, BD basic density, VSH volumetric shrinkage, LSH longitudinal shrinkage, RSH radial shrinkage, TSH tangential shrinkage, MOE flexural modulus of elasticity, MOR flexural modulus of rupture, and CS ultimate crushing strength parallel to the grain.

CONCLUSIONS

This study showed that the correlations of fiber properties together with density and strength properties were strong and significant at both phenotypic and genetic levels. Similarly, tension wood proportion was positively correlated to fiber proportion and cell wall thickness. Only the correlations between fiber length and other properties did not follow this trend. The correlations between wood density and mechanical properties were moderate at the phenotypic level and strong at the genotypic level. It is therefore apparent that, apart from wood density, other attributes of clones could be involved in mechanical performance. Therefore, caution should be taken when selecting clones for mechanical properties based on density.
This study further showed that genotypic correlations for all wood components were higher and more stable than the corresponding phenotypic correlations. Several strong genotypic relationships were found which indicates a good indicator for detection of genetic effects, thus, lead to significant improvement in selection process of these properties. Considerable variation in wood properties within trees and clones were of sufficient magnitude and could provide an opportunity to select clones for utilization in different applications.

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Early assessment of poplar and willow wood properties: selection of parameters and their predictability

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ABSTRACT

Assessing the potential of poplar and willow wood as construction material, requires detailed characterization of their properties and the variability thereon. Both growth features as well as density and dimensional stability were assessed here. Although poplar and willow are categorized as fast growing, still a broad range of growth vigour is displayed. More important than growth rate, however, is stem form and ovality, more clearly indicating the potential of high processing yields for the respective clones.

First, tension wood is insufficiently described by standard surface or volume weighted averages per clone. Variability of this growth feature has to be further detailed by parameters characterizing the spatial distribution. The Tension wood index (TWI20) and the Tension wood diffusion coefficient (TWDC100) were introduced. Both parameters quantify the degree of diffuse distribution of tension wood and have to be considered together with the total amount of tension wood when classifying clones.

Second, density is considered as the most important material characteristic. Variability in density is not adequately described with mean values and standard deviation. Poplar or willow clones displaying the same mean density, can differ significantly in how density values are distributed in the stem volume. Therefore, the Density uniformity index (DUI) and Density variability coefficient (DVC) were introduced to assess variation in density more accurately and to allow correlating density differences to end product performances.

Third, dimensional stability is significantly related to density. Clones with higher density will display a lower degree of dimensional stability. However, this also implies that clones with high DUI (and low DVC) will have lower variability in shrinkage and swelling along longer wooden elements (beams or veneer sheets) and as such display lower differential tension in changing climate conditions.

Some parameters offer possibilities for early assessment. For the wood basic properties only the possibility of ranking clones on their variation in density (DUI) is possible. DUI values based on the core wood samples (juvenile wood) deliver the same ranking of clones as the DUI based on the sapwood samples. Absolute values of density, however, cannot be predicted. The latter also applies for dimensional stability of poplar and willow clones, given its close correlation with density. In this study, no indications could be found that variation in tension wood, and especially the spatial distribution of the gelatinous fibres could be predicted in an early growing stage.

INTRODUCTION

As a fast-growing species, poplar offers opportunities to cover increasing wood demands.
Since 1948, research performed at the former Institute for Poplar Cultivation (currently the Institute for Nature and Forest Research - INBO, Geraardsbergen, Belgium), has played a leading role in selection and breeding of poplar and more recently also of willow, not only for vigour, but also in terms of adaptation to climate conditions as well as disease resistance. Due to recent shifts in resistance to rust disease and changing industrial demands, new selected poplar hybrids had to be introduced. This necessitates continuous monitoring of wood quality with respect to possible end-uses.
Wood quality is to a large extent genetically determined (Zobel and Jett 1995). Moreover, wood is formed by a living individual with cyclic activity, resulting in an annually fluctuating growth in width and height, which is dependent on site conditions and influenced by age. Consequently, wood properties can show a certain variation between and within individuals of the same poplar or willow clone. This may affect the overall wood quality and its final utilisation.
The produced poplar wood is usually light, with a density between 360 and 540 kg/m³, and quite strong resulting in a favourable strength-density ratio. This is an important feature with regard to construction purposes.
To allow poplar wood to be used in higher value-added products (e.g. laminated timber, plywood or other construction materials), an additional emphasis is necessary with regard to improving certain physical and mechanical properties.
The study focuses on defining and understanding the variability of the basic wood properties (density and dimensional stability) of poplars and willows and their interrelations.
A first part describes the growth related features of the selected poplar and willow clones. As both members of the Salicaceae are fast-growing, figures are given concerning mean growth vigour (mean radial increment and yield time). However, the effectiveness of transformation processes is also influenced by stem form, e.g. round stems for peeling, stems with limited taper furthermore relevant for sawn wood production. As such, eccentricity or ovality and tree shape factor are discussed for the selected clones. Poplar and willow trees are characterized by the formation of a 'false heart wood'. The often irregular greyish poplar to brown-reddish willow wood does not show high natural durability. In some applications it is depreciated due to aesthetic reasons. Finally, the rapid growth and the short rotation periods, mostly 15 to 25 years, results in high proportions of juvenile wood.
Tension wood is also a growth related feature, hence its influence on basic wood properties and transformation processes is treated in a separate part. An effective parameter is sought after to explain product variability in terms of tension wood quantification.
Furthermore, another part is dedicated to the most distinct physical property, density. Again, variability and its impact on processing strategy is the main research angle. Therefore, a new parameter, the Density Uniformity Index (DUI), is introduced.
Finally, all these parameters are assessed in terms of their early prediction potential, i.e. predicting final poplar wood quality based on the characteristics at an early stage of growth (6-8 years).

MATERIALS, METHODS, RESULTS AND DISCUSSION

The study considered 24 poplar clones. An overview of the clones and their growth features is given in Table 1.

Table 1 Mean dendrometrical features (mean annual radial increment (cm/year), commercial harvesting time in which clones total 250 m³/ha (year)) and mean stem characteristics (tree shape factor for the whole commercial stem (15 meter) as well as the lower and upper stem part separately (-), mean eccentricity at breast height (-) and mean heartwood proportion (%)) for the selected poplar clones. Standard deviations are between brackets.

Clone		MAI [cm/year]	Yield time [year]	Tree shape factor $\lambda_{0.9}$ Total tree	Lower stem part	Upper stem part	Ovality	Heartwood proportion [%]
'Robusta'	DN	0.94 (0.09)	27	0.51 (0.02)	0.60	0.53	0.92 (0.02)	48 (9)
'Gaver'	DN	1.14 (0.13)	25	0.42 (0.06)	0.61	0.43	0.88 (0.01)	43 (5)
'Gibecq'	DN	1.03 (0.09)	24	0.55 (0.05)	0.68	0.33	0.95 (0.05)	49 (7)
'Ghoy'	DN	1.38 (0.15)	18	0.55 (0.02)	0.60	0.52	0.95 (0.04)	52 (9)
'Ogy'	DN	0.91 (0.12)	29	0.49 (0.02)	0.63	0.56	0.85 (0.02)	46 (13)
'Primo'	DN	1.13 (0.09)	23	0.51 (0.03)	0.55	0.51	0.84 (0.02)	48 (14)
'Tardif'	DN	0.93 (0.09)	27	0.52 (0.05)	0.51	0.49	0.79 (0.03)	46 (7)
'Muur'	DN	1.26 (0.13)	21	0.49 (0.03)	0.53	0.52	0.85 (0.02)	31 (5)
'Vesten'	DN	1.43 (0.17)	18	0.49 (0.05)	0.53	0.58	0.85 (0.06)	42 (5)
'Oudenberg'	DN	1.15 (0.12)	23	0.49 (0.02)	0.52	0.58	0.85 (0.05)	40 (5)
'Hoogvorst'	TD	1.44 (0.23)	17	0.58 (0.02)	0.63	0.65	0.90 (0.02)	32 (6)
'Hazendans'	TD	1.05 (0.14)	26	0.45 (0.03)	0.57	0.52	0.90 (0.03)	42 (7)
'Beaupré'	TD	1.47 (0.14)	17	0.52 (0.01)	0.63	0.40	0.90 (0.01)	31 (5)
'Trichobel'	T	1.20 (0.14)	23	0.45 (0.05)	0.51	0.44	0.82 (0.05)	36 (7)
'Fritzi Pauley'	T	0.80 (0.07)	33	0.48 (0.02)	0.56	0.40	0.89 (0.02)	24 (7)
'Grimminge'	D(TD)	0.93 (0.09)	29	0.48 (0.03)	0.62	0.45	0.76 (0.05)	33 (7)
'Bakan'	TM	1.24 (0.15)	19	0.60 (0.03)	0.71	0.59	0.85 (0.02)	24 (5)
'Skado'	TM	1.25 (0.17)	20	0.55 (0.03)	0.59	0.56	0.85 (0.03)	24 (6)
DTM1	DTM	1.27 (0.14)	19	0.57 (0.03)	0.63	0.63	0.91 (0.01)	30 (7)
DTM2	DTM	1.49 (0.21)	17	0.56 (0.05)	0.61	0.59	0.85 (0.05)	40 (8)
DTM3	DTM	1.29 (0.14)	19	0.55 (0.04)	0.63	0.65	0.78 (0.04)	40 (10)
DM1	DM	1.13 (0.14)	21	0.59 (0.03)	0.64	0.69	0.83 (0.07)	51 (8)
DM2	DM	1.28 (0.12)	19	0.55 (0.04)	0.61	0.57	0.84 (0.04)	50 (7)
'grey poplar'		0.85 (0.69)	27	0.65 (0.05)	0.66	0.58	0.68 (0.05)	27 (10)

Also 19 willow clones (16 S*alix alba* and 3 S*alix x rubens*) were included in the study. As this paper represents an extensive amount of data and experimental design, a selection was made of parameters to discuss in terms of early assessment potential.

Growth features

The mean radial increment varies between 0.80 and 1.47 cm/year for poplar and between 0.60 and 1.30 cm/year for the selected willow clones. Figure 3.1 displays the Box whisker plot for this growth parameter. The average growth vigour of poplar (1.16 cm/year) is significantly (p=0.05) higher than for willow (0.96 cm/year), though both species have potential for selecting clones with increased growing capacity. However, the poplar distribution is skewed to the left (skewness = -0.13), resulting in a lower

mean value than the median value. In willow the mean radial increment distribution displays an opposite skewness (= 0.11). Furthermore, for both poplar and willow growth distribution a considerable excess kurtosis is noticed (-0.96 and -1.16 respectively), outlining the wide variety of growth rate for these members of the Salicaceae. The highest mean radial increment is found for the clones from the hybrid classes DTM, DM and TM, followed by 'Hoogvorst' and 'Hazendans' from the hybrid group TD. In general, the clones from the hybrid group DN tend to grow slower, except the clones 'Ghoy', 'Muur' and 'Vesten'. These high mean annual radial increments (>1.20 cm/year) are only met by the willow clones 'Sem_5', 'Bon_3', 'Bon_5' and 'Bon_8'. The poplar clones with slower growth rate are 'Robusta' and 'Tardif' from the hybrid group DN, 'Fritzi Pauley' (T) and the 'Grey poplar'. For the selected willow clones no significant differences in growth rate were found between *Salix alba* and *Salix x rubens* clones. Growth rate as such is not sufficient to evaluate the potential processing yield, as tree shape and ovality will also influence the effectiveness in processing poplar and willow logs.
A weak, but statistically significant positive correlation was found between the tree shape factor of the upper stem part and the growth rate (R^2=0.34 for poplar and R^2=0.40 for willow). The same is true for the relationship between growth rate and ovality.

Tension wood

To identify the tension wood zones, the surfaces of the cross sections were stained with a zinc-chloride-iodine solution, a stain used to detect the presence of cellulose named after Ernst Schultze (1860–1912). The reader is referred to Badia *et al*. (2005, 2006) for more details.
Analysis of tension wood occurrence within the poplar clones revealed two separate groups. The overall volume weighted tension wood proportion of 25% seems to be a separating value. Only the clones 'Hoogvorst', 'Hazendans', 'Beaupré' and 'Trichobel' display low numbers of tension wood fibres. For all the other poplar clones tension wood ranges from 25 to 40 % and they were not statistically separated. Some clones that were omitted from the analysis because there was insufficient data ('Skado', 'Bakan', 'Muur', 'Vesten' and 'Oudenberg'), seem to belong to the first group with low tension wood occurrence. The willow clones could also be divided into two groups based on a tension wood percentage of approximately 35%.
From the processing point of view, a low amount of tension wood fibres is preferable. However, processing companies clearly stated that these clones do show larger differences in processing behaviour than expected from the small differences in tension. Moreover, the tension wood distribution and the possibility of having heavily clumped zones of tension wood, could influence the outcome of the veneer process more than the absolute proportion of gelatinous fibres.
Therefore, parameters are evaluated for the assessment of the spatial distribution of tension wood (Isebrands *et al.* 2014). In order to evaluate the spatial distribution of the individual tension wood areas, a three-parameter Weibull probability density function (pdf) was fitted to the data. In this case, each clone was evaluated in terms of the occurrence of large tension wood zones. The probability of having individual tension wood zones that surpass 20% of the surface of an evaluated stem disc (f>20%) is defined as the Tension Wood Index (TWI_{20}). Using the distribution of the individual tension wood zones reveals more information on different spatial patterns between clones (TWI_{20}). However, this does not include the relative position of these smaller or

larger zones within the stem disc. As such, a lot of small tension wood zones can still be aggregated within one quadrant of a cross section or at one side of the tree. Therefore, an additional parameter is introduced, namely the Tension Wood Diffusion Coefficient (TWDC). A vector is rotated counter clockwise from 0 to 360 ° (blue vector in Figure 1). For each position the ratio of the length of the vector within tension wood zones to the total vector length is calculated and plotted. The range (maximum – minimum) for this vector length ratio is calculated per quadrant. The Tension Wood Diffusion Coefficient (TWDC) is defined as the standard deviation of the four quadrant ranges. The lower this standard deviation, the more diffuse the tension wood fibres are distributed along the four quadrants.

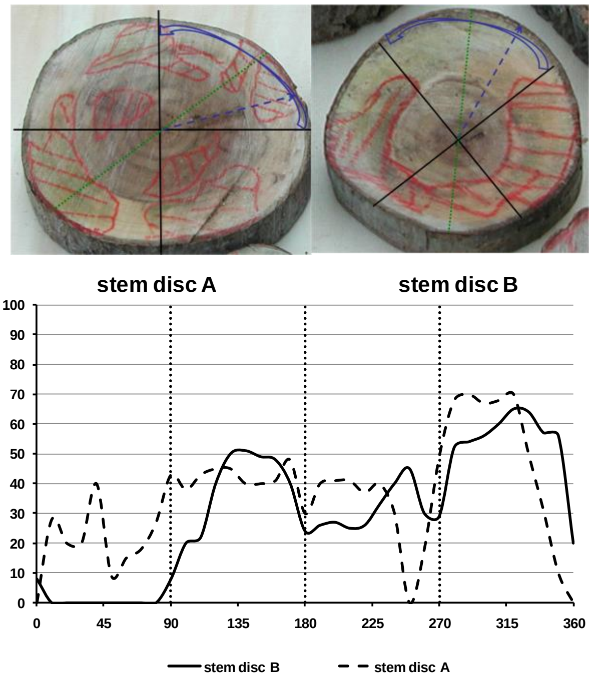

Figure 1: Schematic presentation of the determination of the Tension Wood Diffusion Coefficient (TWDC) for two sample discs (disc A with TWDC= 26% and disc B with TWDC= 36%).

A cluster analysis (Ward's method) was conducted on all clones including TWI20, TWDC100 and total tension wood occurrence. As such three spatial groups of poplar clones could be discerned. The first cluster ('Grey poplar', 'Ogy' and 'Gaver') contains the clones which display preferential small individual tension wood zones with a rather diffuse distribution pattern, irrespective of the total amount of tension wood. A second cluster groups the clones 'Gibecq', 'Robusta', 'DTM1', 'Ghoy' and both DM clones. These clones show similar aggregated tension wood zones. The limit seems to be at a TWDC of 30%. The final group contains the poplar clones having medium to large average individual tension wood zones more evenly distributed over the stem cross section.

However, this analysis can only be conducted on stem discs of fully grown trees (harvested between 25-35 years). No evidence was found that this could also be determined on smaller stems (sampling at 6-8 years).

Density

The overall density is evaluated for the entire dataset and is firstly based on an assumed underlying normal distribution. In addition to the average density, a volume weighted density value for the whole stem is calculated based on the means of each radial-height combination. First a weighted density per height level was calculated with weighing factors in relation to the square of the radius of each subsample (midpoint of the sample in relation to the pith of the stem disc). The total tree weighted density was then based on a lengthwise weighing of the latter averages.
However, it is more important to consider the variation in density that is to be expected within a wooden volume during processing or within an end-product (e.g. wooden beam or veneer sheet) (De Boever *et al*. 2007). Differences in density are linked to different swelling and shrinkage behaviour and can as such lead to differential tensions during drying. Large density variations can also complicate vibration analysis for stiffness quantification.
It could be significantly ($p = 0.05$) proven that density increases with height for all the observed poplar and willow clones, except for grey poplar. The latter shows a limited but significant decrease in density with height. This is in accordance with the findings of Yanchuk *et al.* (1983) who reported a decrease in density towards mid-height and a further increase toward the end of the commercial stem for the related trembling aspen. Other literature references mention an increase with height without specifying the pattern within the stem volume for similar poplar hybrid classes as tested in this research (Beaudoin *et al*. 1992, Clausen and Kaufert 1952, Debell *et al.* 2002, Pezlen 1998).
In low density diffuse-porous hardwoods, such as poplar and willow, density is slightly higher near the pith, then decreases substantially a short distance from the pith to increase again in the mature wood at about growth ring 15 (Yanchuk *et al.* 1983, 1984). However, some clones do not display any radial variation in density. Zobel and Van Buijtenen (1999), demonstrated that the major portion of radial variation in density depends on the distance from the pith. Wood close to the cambium was denser than near the pith, but the correlation between juvenile (core wood) and mature wood (sapwood) was weak, making early prediction of density unreliable (Farmer and Wilcox 1966). Blankenhorn *et al.* (1988) in turn reported a decrease of density with age.
The final step in the density analysis, is to transform the observed and statistically proven differences in density, both radial and longitudinal, into one parameter to assess its influence on poplar and willow wood processing. In most applications, the variation in the longitudinal direction is by far the most important, e.g. in a sawn wood beam or a veneer sheet (L >> R or T). In both product types the radial dimension is significant smaller than the longitudinal direction (length). In products it is likely that sometimes within the same wooden element two radial and two height positional variations are present.
The overlap is studied between all combinations of probability density functions (based on Weibull distributions) at a certain radial-height combination (f1) with a pdf at a distance of one height and/or radial level (f2). The difference between both probabilities is introduced as the Density Uniformity Index (DUI) and expresses the probability that in a certain direction of the tree (radial and/or longitudinal) the same range of density values is found. This number is, per definition, always between 0 and 1. The more uniform density is distributed along the radial or longitudinal axis, the higher the DUI. Figure 2 visualizes this definition for the clones 'Robusta' and 'Beaupré' by comparing

the pdf for total height level 2 with the pdf for total height level 1. Both clones show similar mean density but the difference in DUI is more indicative than the difference in standard deviation.

$$Density\ Uniformity\ Index = f_1(y_1 = x_{1,\bar{x}-n\sigma}) - f_1(y_2 = x_{2,\bar{x}+n\sigma})$$

With: f1(y) = probability density function at certain radial-height level;
f2(x) = probability density function of the level f1(y) is compared to;
n = the number of times the standard deviation (σ) is used

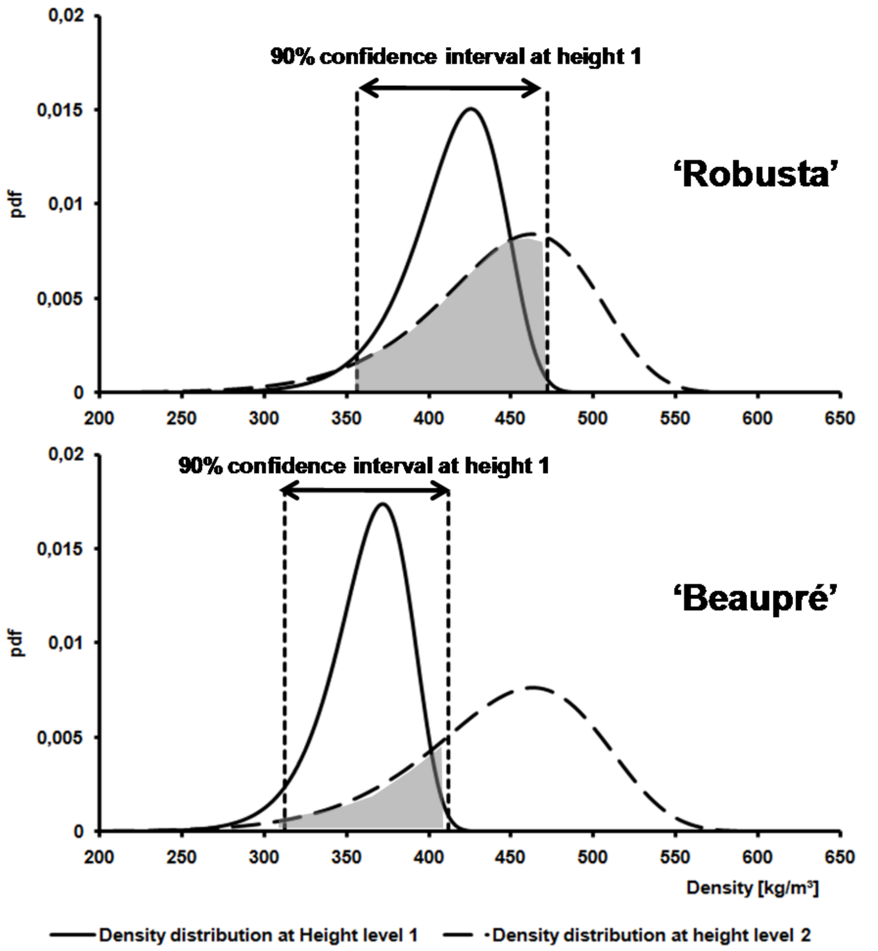

Figure 2: Visual representation of the calculation of the Density Uniformity Index (DUIH2H12σ) for the clone 'Robusta'(DUI=0.62) and 'Beaupré (DUI=0.23).

A correlation is found between the shape parameter and the standard deviation from the overall Weibull distributions from both radial position 1 (core samples) and radial position 3 (sapwood). This finding opens perspectives of ranking clones at an early selection stadium. Hence, the variability within the core of the stem volume over the total tree height is correlated with the way density variations will be distributed in the entire mature stem. However, since no correlation is found (except a weak correlation with the average weighted density) it will remain difficult to predict the absolute density of the mature wood. Tables 2 and 3 give the values of the DUI and related parameters for all poplar and willow clones.

These tables also contain a value for the Density Variability Coefficient (DVC) which expresses the amount of added variability (%) to a wooden element (beam, veneer sheet, …) per meter in the length direction. The DVC is as such based on the DUI but normalised to the length of the considered stem part and expressed as a percentage.

Table 2. Density Uniformity Index (DUI) and Density Variability Coefficient (DVC) for the selected poplar clones as well as the correlated features of underlying Normal (Volume weighted density, standard deviation) and three-parameter Weibull distributions (standard deviation, density range, shape factors of overall radial distributions).

		Normal distribution		Weibull distribution		Radial position shape factor (β)			
Clone		Volume weighted density [kg/m³]	Standard deviation	Standard deviation	Density range [kg/m³]	Core wood	Sap wood	$DUI_{H2,H1,2\sigma}$	DVC [%]
‘Robusta’	DN	443	44	45	146	8.85	15.69	0.62	5
‘Gaver’	DN	432	54	46	150	9.07	7.36	0.77	3
‘Gibecq’	DN	487	79	77	254	6.08	6.55	0.08	12
‘Ghoy’	DN	405	45	44	143	7.91	13.06	0.37	8
‘Ogy’	DN	419	45	47	154	9.19	9.31	0.37	8
‘Primo’	DN	455	52	78	257	7.13	13.78	0.54	6
‘Tardif’	DN	434	39	43	141	10.91	11.93	0.59	5
‘Muur’	DN	341	41	-	-	-	-	0.57*	6
‘Vesten’	DN	459	47	-	-	-	-	0.50*	7
‘Oudenberg’	DN	366	54	-	-	-	-	0.43*	8
‘Hoogvorst’	TD	393	34	33	111	13.21	16.34	0.82	2
‘hazendans’	TD	451	34	44	143	12.54	10.44	0.34	9
‘Beauprez’	TD	423	63	62	209	8.48	7.29	0.23	10
‘Trichobel’	T	403	27	29	109	12.30	13.10	0.63	5
‘Fritzi Pauley’	T	436	32	35	115	11.60	13.20	0.62	5
‘Grimminge’	D(TD)	452	71	68	209	8.20	9.80	0.31	9
‘Bakan’	TM	414	43	-	-	-	-	0.55*	6
‘Skado’	TM	403	47	-	-	-	-	0.50*	7
DTM1	DTM	405	41	42	141	11.30	11.90	0.55	6
DTM2	DTM	390	32	31	105	12.40	15.40	0.62	5
DTM3	DTM	391	27	29	103	12.40	13.60	0.67	4
DM1	DM	365	54	51	169	9.60	10.90	0.53	6
DM2	DM	362	57	56	182	9.40	10.60	0.42	8
‘grey poplar’		498	52	53	172	15.03	10.44	0.86	2

Table 3. Density Uniformity Index (DUI) and Density Variability Coefficient (DVC) for the selected willow clones as well as the correlated features of underlying Normal (Volume weighted density, standard deviation) and three-parameter Weibull distributions (standard deviation, density range).

		Normal distribution		Weibull distribution			
Clone		Volume weighted density [kg/m³]	Standard deviation	Standard deviation	Density range [kg/m³]	$DUI_{H2,H1,2\sigma}$	DVC [%]
Sem_1	A	394	14	16	51	0.76	4
Sem_2	R	447	21	19	61	0.47	9
Sem_3	A	414	21	23	62	0.59	7
Sem_4	A	421	15	18	42	0.73	5
Sem_5	A	443	17	15	42	0.51	8
Sem_6	A	458	17	19	51	0.63	6
Sem_7	A	460	13	15	49	0.82	3
Sem_8	A	397	20	18	68	0.61	7
Sem_9	R	421	21	18	59	0.48	9
Sem_10	R	427	18	21	51	0.59	7
Bon_1	A	426	20	21	66	0.43	10
Bon_2	A	381	10	11	41	0.82	3
Bon_3	A	416	11	12	43	0.59	7
Bon_4	A	397	12	11	53	0.71	5
Bon_5	A	425	10	14	37	0.76	4
Bon_6	A	402	15	16	57	0.64	6
Bon_7	A	428	13	11	48	0.71	5
Bon_8	A	388	12	15	51	0.81	3
Bree	A	433	19	16	53	0.81	3

CONCLUSIONS

Some parameters have potential for early assessment. For the basic wood properties ranking clones on their variation in density (DUI) is the only possibility: DUI values based on core wood samples (juvenile wood) result in the same ranking of clones as the DUI based on the sapwood samples. However, absolute values of density cannot be predicted. The latter also applies for dimensional stability of poplar and willow clones, since its close correlation with density. In this study, no proof could be found that also variation in tension wood, and especially the spatial distribution of the gelatinous fibres could be predicted at an early growing stage.

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Demonstration of the low risk of transferring microorganisms from artificially contaminated poplar crates to foodstuffs

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ABSTRACT

Poplar is the wood most used to make light wood packaging and commonly used in contact with foodstuffs, for example for packaging fruits or vegetables. During storage, transport, handling, wooden crates can come into contact with different kinds of micro-organisms (bacteria and fungal spores) which can potentially be a risk for human health if transferred to foodstuffs. The aim of this study was to demonstrate if poplar wood used for manufacturing crates, artificially contaminated under laboratory conditions, is able to transfer pathogen microorganisms to fruits. Moreover, because the analysis of microbial contamination is standardized only for paper and cardboard materials but not for wood packaging, another aims were to set up a methods allowing 1) high yield removal of microorganisms from wooden surface and 2) the assessment of the transfer of microorganisms from wood to foodstuffs.

The model selected for this study was, as follows: poplar crates / apple packaging / contamination with the two microorganisms *Escherichia coli* and *Penicillium expansum*. First, the survival rate of the microorganisms inoculated to poplar wood at different concentrations was assessed after 1h and 1 week. Then, the transfer rate of microorganisms from poplar to both sound and wounded apples was quantified after 1h and 1 week of contact. Finally, a model was established in order to determine a transfer threshold for both microorganisms from wooden packaging to apples. Both the survival of the two test microorganisms on poplar wood and their transfer from wood to apples were found to be extremely low, contributing to demonstrate that wood is a safe material with regards to microbial contamination of foodstuffs.

INTRODUCTION

Wood is widely used in contact with foodstuffs to make crates for vegetables or fruits. Aromatic wood properties are used in wine barrels (Husson 1996, Miserey 1997, Barthelemy 1998), and wooden boards are used for the maturation of surface ripened cheeses (Richard 1997).
As is the case of other packaging materials, wooden packages have to keep the food in good condition until it is purchased and consumed. The most common species used for food packaging are poplar, pine, beech, and spruce. Poplar is particularly used for manufacturing light packaging.

Because it is a porous and absorbent material, wood is commonly considered as less safe and secure than plastic or stainless steel packaging (Jacobson 1979, Lapping and Connor 1991). However, several studies have demonstrated that microorganisms do not survive easily on wood (Schönwälder *et al.* 2002, Milling *et al.* 2005, Revol-Junelles *et al.* 2005, DeVere and Purchase 2007). The European regulation n° 1935/2004 of the 27th of October 2004 indicates that materials intended for safe food contact must not modify foodstuffs characteristics. National recommendations for harvesting and packaging fruits require the use of clean wooden, plastic or cardboard boxes (Lurol *et al.* 2007).
In France, more than 20 wood species are authorized by the French decree of November, 1945 for direct contact with solid or liquid food products.

The French standardised method NFQ 03-070-1 (AFNOR 1998), which is a grinding based method, is suitable for analysing microbial contamination of paper and cardboard. Currently, no standard yet exists for wood. A comparative analysis was managed to remove microorganisms from wooden surfaces used in the food industry. A grinding technique was developed on poplar (Ismaïl *et al.* 2014).
On the basis of this method, the transfer of microorganisms from wood to foodstuffs has been analyzed. The model “poplar packaging/apple” was chosen.

We chose two relevant hygienic risk models: *Escherichia coli* and *Penicillium expansum*. *E. coli* is a gram negative bacterium, commonly used as an indicator of hygienic practice in food industry. Several studies have demonstrated that *E. coli* could grow on several fruits as well as on vegetables (Janisiewicz *et al.* 1999, Leverentz *et al.* 2004, Sivapalasingam *et al.* 2004, Alegre *et al.* 2010). *P. expansum* is an ascomycete, responsible of postharvest decay of several fruits (Xiao *et al.* 2011, Chatterton *et al.* 2012, Yu *et al.*, 2012, Wang *et al.* 2015). It is an substantial spoilage fungi for the fruit sector, in particular for pears and apples (Giraud *et al.* 2001, Amiri *et al.* 2005).

In this study, the survival rate of the microorganisms on poplar specimens was assessed, after 1h and 1 week. Secondly, the transfer rate of microorganisms from poplar to apple was quantified, after 1h or 1 week of contact. Finally, a model has been finalized using our results to describe a transfer threshold for both microorganisms from wooden packaging to apples. Analysis on wounded apples was also carried out.

EXPERIMENTAL

Biological materials

Wood samples and apples

Poplar sapwood slats of *Populus euramericana*, freshly cut, were 0.4 cm thick (Bois Diffusion, Valanjou, France). Wood samples measuring 60x40 mm were cut within these slats (surface of 24 cm²). Specimens were sterilized by ionization prior to use (Ionisos, Dagneux, France).
Golden delicious apples from French suppliers were used in this study. Organic apples were stored at 4°C and disinfected with ethanol 70% prior to use. As a control, contact plates of PCA medium (tryptone 5g/L, yeast extract 2.5g/L, glucose 1g/L) were applied 10 seconds at the surface of apples and incubated at 22°C for 48h to ensure that disinfection was fully carried out.

Microorganism strains and inoculum preparation

Escherichia coli strain (ATCC-700926) was stored in cryotubes containing beads at -80°C. Two beads of a cryotube were suspended in 10 mL of PCA medium for 24h at 37°C and 180 rpm. 1 mL of this sub-cultured was then inoculated in 100 mL of PCA for 24h at 37°C and 180 rpm. The concentration of this culture was expected to be at $1x10^8$ CFU/mL. This solution was used to inoculate wood specimens and to prepare dilutions in sterile water with 0.9% NaCl.
Penicillium expansum strain (ATCC-7861) was propagated on malt/agar medium (Malt 40g/l; agar 20g/L). Spores suspension was generated by culturing *P. expansum* on 4 malt/agar plates for 2 weeks at 22°C. 10 mL of water with 0.9% NaCl and Tween® 0.05% was added to each plate and spores were then collected. After filtration through sterile gauze, spores suspension was rinsed three times in 10 mL of sterile water by centrifuging 20 min at 2000 g. Spores were then counted on a Malassez cell. This solution was used to inoculate wood specimens after dilutions in sterile water with NaCl 0.9%. Concentrations of the inocula of $8x10^7$, $8x10^6$ and $8x10^5$cells/mL were chosen.

Methods

Wood moisture content

A moisture content of 37% was used in this study as it represents wet packaging storage conditions. The moisture content was then determine as already described in Ismail et al, 2014 to ensure that specimens were at 37% of moisture content.

Viability control of inocula

A viability control was carried out to determine the concentration of viable microorganisms in tested solutions.
For *P. expansum*, inoculum viability was assessed by sowing 100 µL of serial dilutions on malt/agar plates. After incubation 48h at 22°C, enumeration of colonies was undertaken to determine strain viability.
For *E. coli*, inoculum viability was assessed by sowing 1 mL of serial dilutions on PCA plates. After incubation 24h at 37°C, enumeration of colonies was undertaken to determine strain viability.

Inoculation of wood specimens

Sterile wood specimens were inoculated with 300 µL of inocula, at several concentrations. After 15 minutes of inoculum static impregnation, specimens were grinded, incubated alone or in contact with an apple for 1h at room temperature, 1 week or 3 weeks at 10°C and 85% RH. These conditions correspond to optimum storage conditions in cold room.

Microbial enumeration

After incubation, microorganisms from wood specimens were recovered by grinding as already described (Ismail et al, 2014). After incubation, apples were peeled fruitlessly using a stainless steel potato peeler to extract microorganisms. 5 cm² of peel corresponding to the surface contact with boards were blend using a Stomacher® 80 (Seward, United-Kingdom) in 6 mL of sterile water with NaCl 0.9% for 2 min.
The recovery solutions were inoculated sowing 1 mL of serial dilutions on PCA (for *E. coli*) or 100µL of serial dilutions on malt/agar (for *P. expansum*). After incubation at 22°C for *P. expansum* or 37°C for *E. coli*, enumeration of colonies was undertaken.

Analysis on wounded apples

Wood specimens were inoculated with inoculum of *P. expansum* at $8x10^7$ and $8x10^5$ cells/mL. To mimic wounds on apples and associated necrosis linked to *P. expansum*, apples were wounded with 4 nails prior to contact with wood specimens. Controls on uninoculated wood and on plates covered with *P. expansum* cultures (positive control) were carried out. Necroses on apples were measured after 12 days of incubation at 10°C and 85% RH. Microbial enumeration was also performed on wood specimens, and on necrotized peels in contact with wood.

Statistical analysis

The experiments, described above, were performed in triplicates, except for wounded apples, where 30 replicates were used. Results of microbial enumeration, expressed in CFU/cm² and transformed in log10 scale, correspond to the mean value ± standard deviation. Results were analyzed using a Student t-test ($p<0.05$) with the Minitab® statistical software 16 (Minitab® Inc.). A transfer rate (%) was expressed as follow: (CFU/cm² recovered on apples after incubation) x 100 / (CFU/cm² inoculated on wood specimens at T0).

RESULTS AND DISCUSSION

Viability on wood

To assess the viability of the two microorganisms on wood, suspensions of 4.14 log CFU/cm² for *E. coli* and 5.57 log CFU/cm² for *P. expansum* were inoculated on wood specimens at 37% of moisture content. Immediately after inoculation (T0), after 1h of incubation at room temperature or 1 week at 10°C and 85%, microbial enumerations were performed. Results are presented in Table 1.

Table 1: Viability of E. coli or P. expansum on wood after 1 h or 1 week of incubation. Results correspond to Mean (standard deviation).* means significantly different from result obtained at T0 ($p<0.05$, Student t-test).

Incubation time	*E. coli*	*P. expansum*
T0	3.95 (0.23)	5.36 (0.15)
1 hour	1.85 (0.23) *	5.00 (0.02)
1 week	0.02 (0) *	4.94 (0.63)

Our results demonstrate that *P. expansum* conidia can survive on wood specimens even after 1 week, as from 4.94 to 5.36 log CFU/cm² are recovered whatever the incubation time. However, they do not grow. For *E. coli*, results after 1 hour and 1 week are significantly different from results obtained at T0 and demonstrate that *E. coli* do not seem to survive on poplar specimens.

We can observe a different behavior between *E. coli* and *P. expansum*. Poplar contains phenolic compounds able to inactivate microbial adhesins and too complex with microbial cell wall (Cowan 1999). *E. coli* is a gram negative bacterium, with a peptidoglycan layer whereas conidia of *P. expansum* are resistance shape, with a thick cell wall. These phenolic compounds could complex with the cell wall of *E. coli* leading to a lower viability.
Physiological differences exist between *E. coli* cells and *P. expansum* conidia. *E. coli* is a gram negative bacterium whereas *P. expansum* conidia are resistant cells. *E. coli* requires a temperature range of 7°C to 37°C a minimum water activity (aw) of 0.95 and a pH optimum of 6 to 7 (Anonymous 1996, Presser *et al.* 1997) . *P. expansum* is more tolerant as its conidia require a temperature range of 0°C to 35°C, a minimum aw of 0.82 and a pH of 2 to 10 (Piit and Hocking 2009, Anonymous 2011).

A hypothesis could be that poplar exhibits unfavorable conditions for *E. coli* survival such as a low water activity, a pH of 5.8 to 6.4 (Balatinecz *et al.* 2014). Revol-Junelles *et al*. (2005) results indicated that the decrease of *E. coli* survival was probably linked to the desiccation of bacterial cells on poplar surfaces because of its hygroscopic properties and of its wood natural extractives (Revol-Junelles *et al.* 2005).
P. expansum conidia survival on poplar is constant whatever the incubation time at 10°C and 85% RH. These results suggest that the conditions on poplar such as surface moisture content and pH allowed *P. expansum* conidia to survive but not to grow on wood (Piit and Hocking 2009, Anonymous 2011).

Transfer rates from poplar to apples

To assess transfer rates of *E. coli* and *P. expansum* from wood to apples, suspensions of 4.14 log CFU/cm² and 5.57 log CFU/cm² respectively, were inoculated in sterile conditions on wood specimens at 37% of moisture content. An apple was then put in contact with wood samples. After incubation 1h at room temperature or 1 week at 10°C and 85% RH, microbial enumerations were performed on wood samples and on apples. Results are presented in Figure 1.

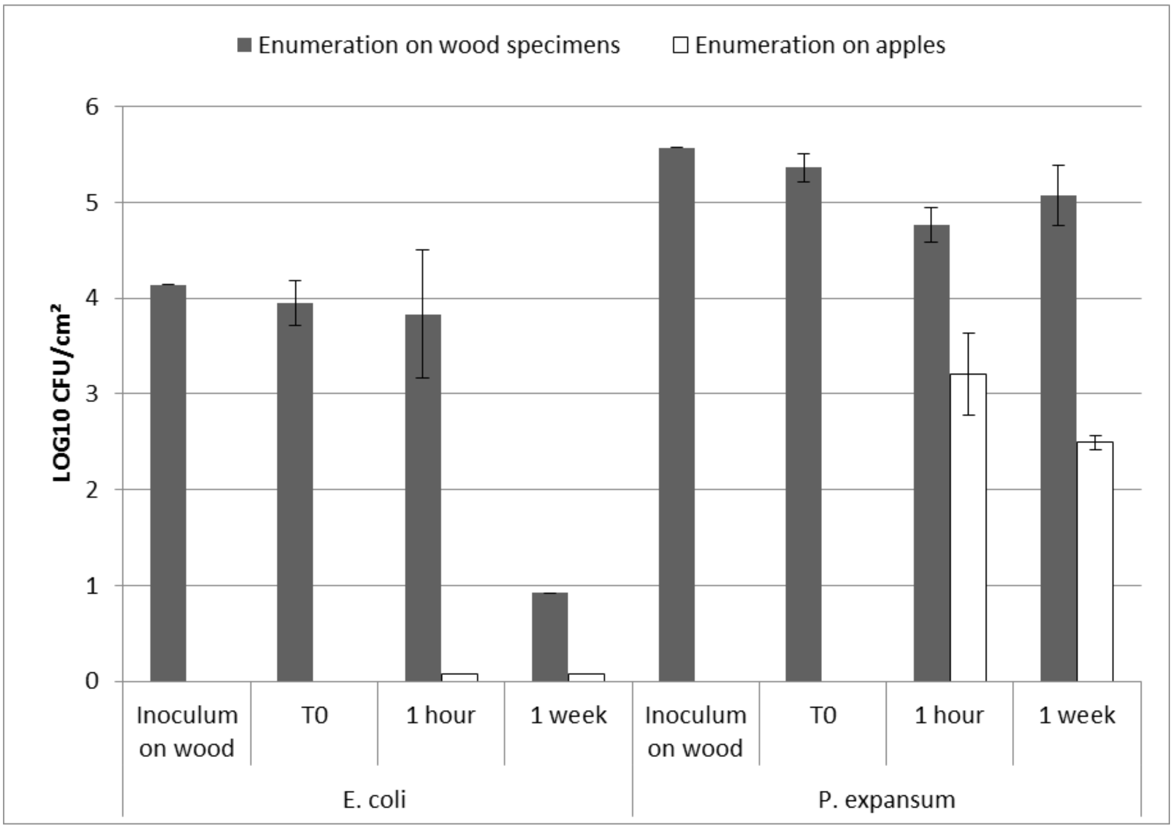

Figure 1: Enumeration of E. coli (on the left) or P. expansum (on the right) on wood samples and apples after 1 hour or 1 week.

Analyses were first performed on wood specimens. For *E. coli*, only 0.92 log_{10} CFU/cm² are recovered after 1 week. For *P. expansum*, more than 4 log_{10} CFU/cm² are recovered on wood specimens, whatever the incubation time. These results, coupled with results of Table 1 strongly suggest that recovery of these two microorganisms on wood specimens is not affected by contact with apples.

Analyses were then performed on apples. For *E. coli*, obtained recoveries were lower than the detection level of the method, suggesting that *E. coli* is not transferred from wood to apples. Calculated corresponding transfer rates (0.008%) after 1 hour or 1 week confirm this hypothesis. For *P. expansum,* 3.21 log_{10} CFU/cm² are recovered after 1 hour and 2.49 after 1 week. Corresponding transfer rates after 1 hour or 1 week are equal to or lower than 0.25%. These results demonstrate that *E. coli* is not transferred from wood to apples and that the transfer rate of *P. expansum* from poplar to apples is very low.

This study, leading to low transfer rates, was carried out using very high contamination levels of both microorganisms on wood. Such levels are higher than possible contaminations of wooden packages. Thus, taking into consideration both a lower package contamination and a low transfer rate, the apple contamination would be considered to be insignificant.

In our study, transfer rates are very low, whatever the considered microorganism. This result is fully in accordance with several studies, dealing with the transfer of *Listeria*

monocytogenes from wood specimens to chicken meat or cheeses (Goh *et al.* 2014; Ismaïl *et al.* 2014), of several foodborne pathogens from stainless steel surfaces to food (Kusumaningrum 2003). However, transfer rates of microorganisms could vary according to considered foodstuffs (Silagyi *et al.* 2009, Abadias *et al.* 2012, Jensen *et al.* 2013, Goh *et al.* 2014). Materials, depending on their topography and properties, could also influence transfer rates and recovery (Gough and Dodd 1998, Midelet and Carpentier 2002, Amiri *et al.* 2005, Dawson *et al.* 2007, Knobben *et al.* 2007). In this sense, one perspective could be to assess transfer rates of *E. coli* and *P. expansum* from wood to several fruits or vegetables and also from several materials (with different properties) to apple.

Impact of inoculum concentration

As only transfer rate of *P. expansum* was above detection level of our method, analysis with several inoculum concentrations was carried out with this microorganism. Wood samples were inoculated with $8x10^7$, $8x10^6$ or $8x10^5$ cells/mL, incubated in contact with an apple for 1 hour, 1 week or 3 weeks. Enumeration on apples was then performed. Results are presented in Figure 2.

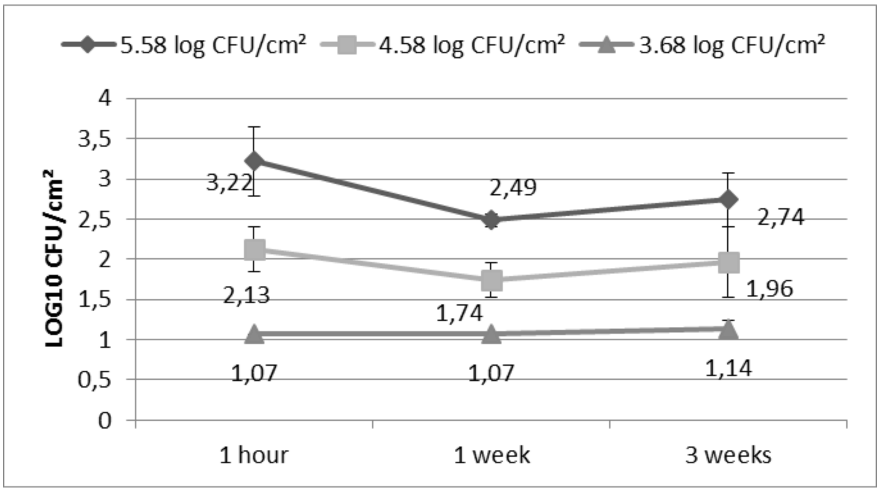

Figure 2: Enumeration of P. expansum on apples after 1 hour, 1 week or 3 weeks of incubation, according to inoculum concentration dropped off on wood samples at T0.

Three concentrations corresponding to 5.58, 4.58 and 3.68 $\log_{10}$ CFU/cm² were inoculated on wood specimens at T0. For the highest concentration, results obtained after 1 hour to 3 weeks are steady, with values ranging from 2.49 to 3.22 $\log_{10}$ CFU/cm². For the median concentration, results are steady again, ranging from 1.74 to 2.13. For the lowest concentration, results are at the detection level (1.07 log). Our results demonstrate that a relationship exists between inoculated concentration and recovered concentration on apples. This correlation is independent of incubation time. A log loss of approximatively 3 is observable between inoculation on wood samples and recovery on apples, whatever the tested concentration. Transfer of *P. expansum* from wood to apple peel is very low ($\leq$ 0.25%) and proportional to inoculum concentration on wood.

Analysis of wounded apples

P. expansum is an important spoilage ascomycete for the fruit sector, and in particular pears and apples. To mimic wounds on apples and analyse necrosis linked to *P. expansum*, apples were wounded with 4 nails. Wood specimens were inoculated with 5.67 or 3.66 log CFU/cm². After incubation at 10°C and 85% RH for 12 days, necrosis analysis was performed. Negative and positive controls (apples put in contact with plates invaded with *P. expansum*) were also carried out. Number of apples with necrosis, and number of wounds having necrotized have been estimated. Results are presented in Table 2.

Table 2: Percentage of apples with necrosis and percentage of wounds having necrotized after 12 days of incubation, according to inoculum concentration.

Condition	Apples with necrosis (%)	Wounds having necrotized (%)
Uninoculated wood	0	0
5.67 log CFU/cm² on wood	30	14.17
3.66 log CFU/cm² on wood	33.33	17.65
Positive control	59.26	37.04

Analyses were first performed on apples in contact with non-inoculated wood. No necrosis was observed, confirming that *P. expansum* is necessary for necrosis development. When wood was inoculated with conidia, around 30 % of apples had necroses and between 14 and 17% of wounds had necrotized. Results were identical for both concentrations. On agar plates covered with *P. expansum* mycelia (positive control), 59 % of apples had necroses and between 37% of wounds had necrotized. These results demonstrate that contact with wood reduces percentages of necrosis, compared to the positive control on agar plates. Inoculum concentration does not affect necrosis.

CONCLUSIONS

Our results demonstrate that:

- *P. expansum* conidia can survive on wood specimens even after 1 week but do not grow, whereas *E. coli* do not survive on poplar specimens;
- *E. coli* does not seem to be transferred from poplar specimens to apple peels whereas transfer rates for *P. expansum* after 1 hour or 1 week are equal to or lower than 0.25%;

This study contributes to demonstrate that wood is a safe material with regards to microbial contamination of foodstuffs.

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Thermal insulating materials made up of poplar wood fibres

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Keywords: Composite nonwovens, fibrous insulating materials, pine maritime, poplar.

ABSTRACT

Wood fibre-based materials are obtained from very different manufacturing processes which govern the final density of products and their applications. Among them, a nonwoven process allows to produce a 3-D entangled structure, thick with low density. Nowadays, these materials are made up of maritime pine fibres in southwest of France. In the framework of a French industrial research project, the optimization of the manufacturing process and manufactured materials is an ongoing work. In this article, the focus is on studying the influence of raw materials morphology and bulk density on the apparent thermal properties of the fibrous insulating materials. A design of experiments taking into account these properties is established to evaluate the possibility of valorising poplar use in wood fibre-based insulating materials, by comparing its performance to the maritime pine. Results highlight the overriding impact of the bulk density and the morphology of fibres on the apparent thermal conductivity, and show the potential of using poplar in the manufacturing of wood fibre-based insulating materials.

INTRODUCTION

Industrial processes derived from the nonwovens industry have recently led to the development of wood-based products with thermal insulation properties. The main stages of the manufacturing process are composed of the defibering of wood chips into fibres and fibre bundles, web forming by air-laying and its consolidation by heat through-air bonding. The market of wood fibre-based insulation materials has a projected annual growth of over 10% on European markets until 2020 (Alcimed 2013). Therefore, it is important with the growth of market share, to secure customers with a better knowledge and better technical and environmental performances of these products. Coordinated by the *FINSA* group and financed by *ADEME*, the aim of the French *ECOMATFIB* project [(1)] is to optimize the properties of wood fibre-based insulating materials so that they become more competitive, especially through the optimization of the manufacturing process. An innovative method of multi-objective

optimization will be used to simultaneously satisfy these conflicting goals (Hobbaallah *et al*. 2016).

Identified as one of the weak points of the product, the first objective in the preliminary design of wood fibre-based insulating composites is to minimize thermal conductivity. In the case of fibrous insulating materials, minimizing the thermal conductivity is done by lowering bulk density, which results in lowering the conduction by solid matters, until finding a critical value of bulk density. Below this critical value, there is no longer enough solid matter to prevent heat transfer by radiation. Moreover, natural convection is blocked by trapping air in the structure (Figure 1).

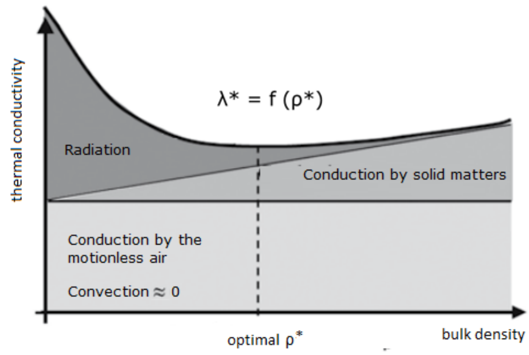


Figure 1: Evolution of the thermal conductivity of insulants depending on their bulk densities (Coquard et al. 2012)

Thereby the thermal properties are closely related to the microstructure of the fibrous networks and more specifically to the solid volume fraction, its degree of division and the distribution of fibre orientation (Bankvall 1973, Klarsfled 1985, Langlais and Klarsfled 2004). Note that thermal properties measured on hygroscopic materials are highly dependent on their hygrothermic state (Traore 2011, Vololonirina *et al*. 2014). Under the effect of various potential gradients (vapour pressure / temperature), hygrothermal transfers, as well as phase changes induced by these transfers, have to be considered. This leads to define an apparent thermal conductivity to describe the physics of transfer modes in this type of medium.

Nowadays, these materials are made up of maritime pine fibres in southwest of France. A design of experiments taking into account poplar wood fibres, their respective energy consumption during the defibering and compression ratio of the batts during their bonding was carried out. Then, the bulk densities and the apparent thermal properties of the poplar fibre-based materials are evaluated and compared to maritime pine fibre-based materials.

MATERIALS AND METHODS

Raw materials

The wood fibre-based insulation materials are elaborated by mixing wood fibres and synthetic fibres. The renewable resources used for this design of experiments are maritime pine and poplar. Maritime pine is delivered as wood chips from the FINSA France factory in Morcenx, France. Poplar is delivered as trees from Alès, France. The synthetic fibres are polyolefin of a length of 6mm and a diameter of about 20µm.

Manufacturing process

The process is based on 3 steps: defibering of wood chips into fibres and fibre bundles (Figure 2a), 3-D fibrous web formation by air-laying (Figure 2b) and its consolidation by heat through-air bonding thanks to thermoplastic fibres previously added (Figure 2c). The first one is specific for all kind of wood fibre-based materials. The two followings are common to the production of nonwoven materials.

Defibering

This operation was carried out at FCBA, Grenoble France with a pressurized 12” refiner from Andritz (Figure 2a). The system consists of a pre-steaming digester for heating wood chips at 150°C. Once time elapsed, chips are conveyed by a screw feeder to the defibering zone. The softened chips are further forced through a narrow gap between two profiled discs which transform the chips into fibres and fibre bundles (Irle and Barbu 2010). Fibres are collected after a blow valve. Plate gap is adjusted manually affecting fibres morphology. Corresponding energy consumption is calculated based on fibre flow and motor load acquired continuously by the relation (1).

energy consumption (kWh/t) = average power (kW) / masse flow (t/h) [1]

3-D web formation

3-D fibrous web formation was carried out at I2M, Talence France using an airlaid machine *(2)* from Laroche (Figure 2b). Firstly, raw materials are opened by means of a card (rotating spiked roller) to separate fibres from fibre tufts. Then, they are introduced and transported to an air stream before being deposited over a perforated drum by air suction pressure. Thereby in air-lay technology, the air performs two functions: it acts as a dispersing medium and as a transportation medium for the fibres towards the rotating perforated forming surface (Albretch 2006, Das *et al*. 2012). The fibres in the air-laid webs tends to be isotropically oriented in the horizontal plane, hence they are sometimes called random-laid webs. Air-laid fabrics are claimed to have a voluminous and a highly porous fibrous structure (highloft). The uniformity of air-laid webs depends on the degree of opening of the fibres and the airflow profile, hence these settings machine are adapted in order to have to a homogeneous webs in mass and thickness. Main settings are proportions of wood and synthetic fibres, feeding speed, spiked roller speed and air stream speed. The webs formed are then superimposed to form a batt. At this point, the cohesion is only assured by the interlocking of fibres with each other’s.

3-D fibrous batt consolidation

3-D fibrous batt consolidation was carried out at I2M, Talence France using a hot-air oven (2) from Strahm (Figure 2c). It is a dry bonding process taking advantage of the thermoplastic properties of synthetic fibres previously added. Through controlled heating, thermoplastic fibres form adhesive and cohesive bonds. These bonding regions are fixed by subsequent cooling and hold the fibrous medium. Main settings are temperature and speed of hot air, dwelling time of the batt in the oven and compression ratio of the batt *(CR)* defined by space between conveyor belts and input thickness of the batt.

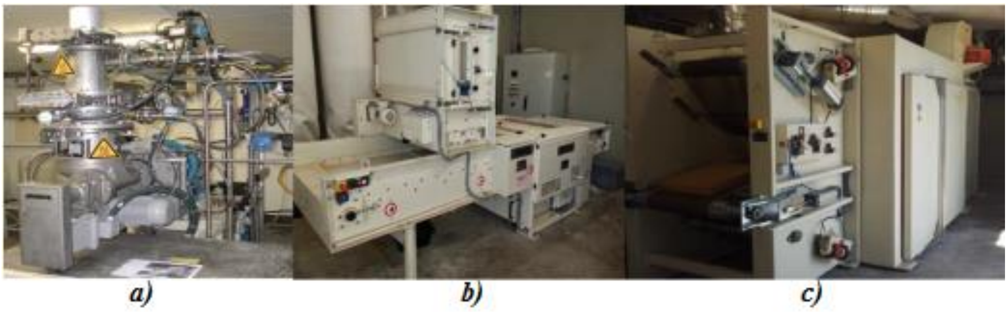


Figure 2: process equipment's used for wood-fibre insulation panels a) refiner b) napper opener c) hot air oven

Input variables used for the experimental design of panels production

Two different fibres populations of maritime pine and one of poplar were produced. The plate gate of the refiner was adjusted manually in order to have a population of maritime pine fibres close to the ones used for insulating materials (PM1), and another population traditionally used for MDF (PM2). The plate gap for the refining of poplar chips was adjusted to obtain a population (PR) close to that used for MDF, while ensuring not having too much thin elements specific to hardwoods. All of these populations were blended with the same proportion of synthetic fibres (S). Each one of these blends was compressed at 3 compression rates (CR) in the oven: 20%, 50% and 75%. The complete design of experiments considering wood fibres morphology and compression ratio during the bonding process is presented in (Table 1).

Table 1: Design Of Experiments

reference	*wood population*	*compression ratio in the oven (CR)*
PM1S20	PM1	20%
PM1S50	PM1	50%
PM1S80	PM1	75%
PM2S20	PM2	20%
PM2S50	PM2	50%
PM2S80	PM2	75%
PRS20	PR	20%
PRS50	PR	50%
PRS80	PR	75%

Characterization of fibres and panels properties

Characterization of the morphology of wood fibres

The distribution of wood fibres lengths was achieved using Bauer MacNett equipment (Figure 3). This equipment provides information on the distribution of fibre size in the various samples. Weight of fibres retained by the sieve of Bauer MacNett and converted to a percentage based on the original weight of the sample is termed a 'fraction'. A fraction is, therefore, limited to the size of the sieve. The sieves 8/14/28/35 with openings accordingly 2.4 mm; 1.4 mm; 0,84mm; 0,5mm were used in this study. 10 grams of dry matter were introduced for each wood fibres population.

Figure 3: Overview of Bauer McNett workbook with 4 tanks

The distribution of wood fibres diameters was achieved using SkyScan X-ray microtomograph (up to 6µm 3D spatial resolution). This non-destructive imaging technique allows to characterize 3D internal microstructure of materials. It relies on a 3D reconstruction based on a series of X-ray projections and image treatments performed on a virtual sample. The X-ray beam passes through the sample and the signal transmitted is recorded by CCD sensors (Figure 4). After 3D reconstruction of X-ray projections, the diameter distribution of a set of wood fibres is measured by performing successive openings of growing size 5Serra 1982, Lux 2006, Tran 2012) on the virtual volume. The 3D images resolution is 12.3 microns/voxel and the analysed volume is of 8.6 x 8.6 x 12.3 mm^3.

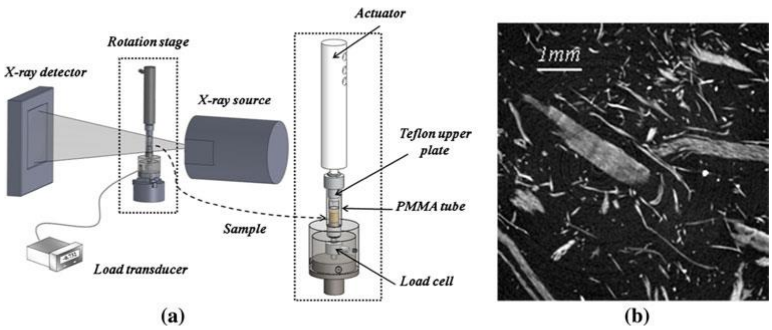


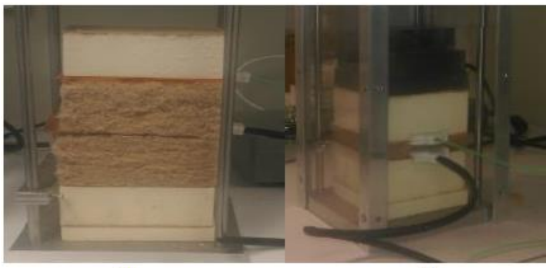
Figure 4: a) In-sity setup in X-ray microtomography and b) 2D slice [TRA, 12a]

Characterization of the thermal properties of the panels

Thermal properties of the panels are measured by the hot plate technique with a Desprotherm device of Epsilon Alcen. It gives us indirectly the apparent thermal conductivity λ^*_{app} ($W{\cdot}m^{-1}{\cdot}K^{-1}$) of the material by assessing its equivalent thermal effusivity b ($W{\cdot}K^{-1}{\cdot}m^{-2}{\cdot}s^{1/2}$) and its bulk volumetric heat capacity $\rho^* \cdot C_p$ ($J{\cdot}m^{-3}{\cdot}K^{-1}$), where C_p is the massic heat capacity (relation 2). The apparent thermal conductivity is then deduced by:

$$\lambda^*_{app} = \frac{b^2}{\rho^* \cdot C_p} \qquad [2]$$

In both cases, thermal equilibrium of the sample is disturbed by providing a uniform and unidirectional heat flux on one of its isolated face. Induced temperature changes are measuring in front (heated) face of the sample for thermal effusivity (Figure 5a) and in rear face for volumetric heat capacity (Figure 5b). All samples have dimensions of 100 x 100 x e mm^3, with e is the thickness.



a) b)

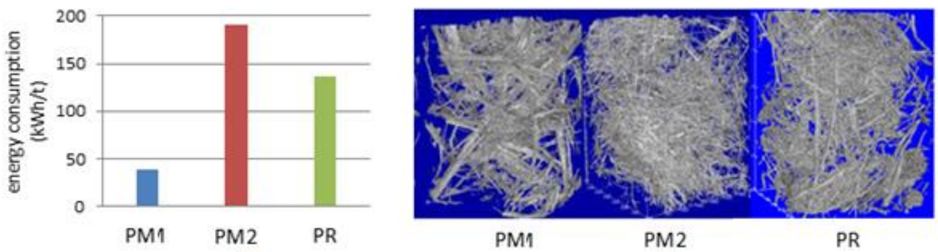
Figure 5: device measurement of a) thermal effusivity b) volumetric heat capacity

Measurements are repeated 3 times for references. It is important to note that all measurements are done on stabilized samples at 20°C/65%RH. According to the equilibrium moisture content, in these conditions, the moisture content of solid wood is 12% (Stramm 1964).

RESULTS AND DISCUSSION

Energy consumption during defibering and morphology of wood fibres

The recorded defibration energy is related with the morphology of wood fibres obtained according to the methodology presented in section 3.1 of materials and methods. (Figure 6a) shows the respective energy consumption for each population of wood fibres and (Figure 6b) their respective volume rendering acquired by X-ray microtomography (after leaving the defiber). The 3D images resolution is 12.3 microns/voxel and the analysed volume is of 8.6 x 8.6 x 12.3 mm^3.



a) b)

Figure 6: a) respective energy consumption of wood fibres b) 3D volume rendering imaging of their population

PM2 requires 5 times more energy consumption to be produced than PM1 (190kWh/t / 38kWh/t). PR is 29% less energy intensive (136kWh/t) than PM2. Corresponding fibres

size population are illustrated by the distribution of their lengths in (Figure 7a) and of their diameters in (Figure 7b).

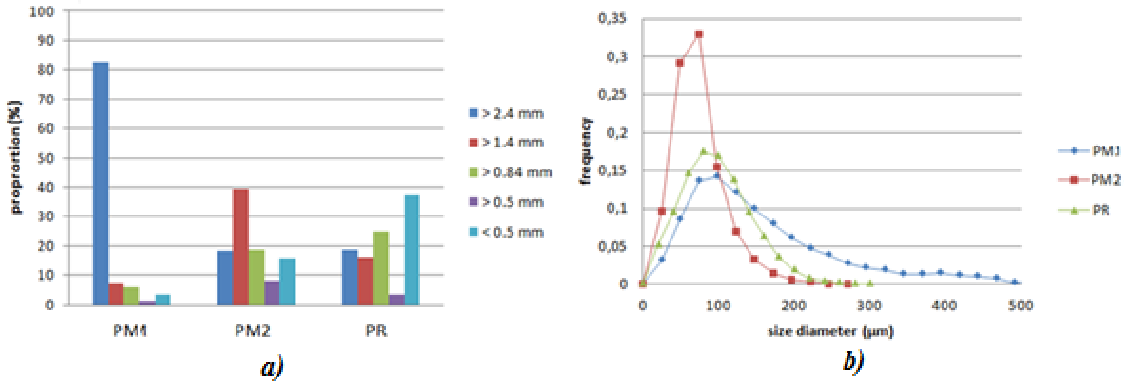


Figure 7: Population size of wood fibres classified by a) Mac Nett length distribution b) 3D images diameter distribution

As explained in section 3.1 of materials and methods, the fraction of the refusal 8 contains the biggest elements. The retained fibres have dimensions that do not allow them to pass through an opening of 2.4 mm. The PM1 population has a strongest rejection, close to 80% of its distribution while PM2 and PR have less than 20% (Figure 7a). Otherwise, contrary to the PM1 population, PM2 and PR populations contain few non-defibrated elements which are in agreement with their current use.
The defibering of the PR population generates 2.5 times more fine elements (opening <0.5mm) than it does for the PM2 population (Figure 7a) although it requires 29% less energy consumption (Figure 6a). This can be explained by the anatomical difference between softwood (maritime pine) and hardwood (poplar) species. Due to their structure, hardwood fibres are intrinsically finer than softwood fibres (Jodin 1994). Poplar is also relatively less dense than maritime pine.
(Table 2) presents two representative variables that describe the diameters distribution of the wood fibres population, i.e. arithmetic G_n and contraharmonic mean G_w. The arithmetic is affected by a large number of small entities while the contraharmonic mean emphasizes the presence of long ones. Usually used to characterize the width of the molecular weight distribution of polymers, the ratio G_w/G_n assessed the dispersion of a distribution.

Table 2: Representative variables describing the diameters distribution of the wood fibres population

population	Gw [µm]	Gn [µm]	Gw / Gn
PM1	234.7	162.1	1.45
PM2	90.5	74.4	1.22
PR	119.3	98	1.22

The PM1 population has the coarser mean diameters. Although the PR population contains finer elements than PM2 population (opening <0.5mm), its arithmetic mean G_n is 25% higher than the G_n of PM2 (98 / 74.4µm). This may come from the fact that poplar chips are more sensible to the cutting force than maritime pine chips. Thus,

poplar fibres would tend to be more easily fibrillated than fragmented. Reducing the plate gap causes a progressive degree of destructuration of wood chips and a homogenization of its distribution (G_w/G_n).

Variability of apparent bulk density of the panels

All measurements were done on specimens with dimensions 100 x 100 x e mm^3 (4 specimens per reference). Their thickness is comprised between 35 and 82mm function of the blend and the compression ratio applied during the consolidation in the oven.
Relationships between compression ratios in the oven (CR), average values of bulk densities ρ^* and thickness recoveries Δ are illustrated in (Figure 8). The thickness recoveries are calculated by the relation (3):

$$\Delta = (OT - IT) / IT \qquad [3]$$

With *IT*, the imposed thickness corresponding to space between conveyor belts in the oven and *OT*, the obtained thickness corresponding to real thickness of batts on leaving the oven.

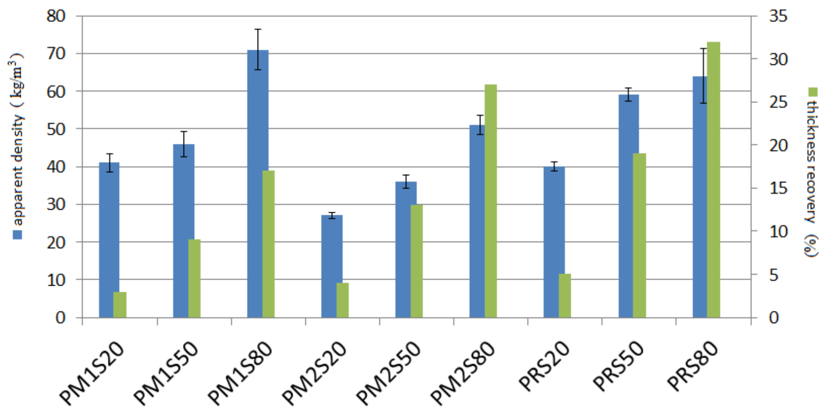


Figure 8: apparent density and thickness recovery of the panels

Materials produced with such a process have a low bulk density (27 to 71 kg/m3). Compared to the cell wall density of wood equal to 1.53 (Jodin 1994), the fibrous panels have a solid fraction lower than 5% and are therefore highly porous. Panels made with the coarser wood fibres PM1 are denser than those made up of PM2 (traditionally used for MDF in the southwest of France). Note that we observe more dense webs leaving the napper opener. The progressive increase of thickness recoveries with the rising of bulk densities can be justified by a lack of cohesive bonds formed between two synthetic fibres (mass quantity of thermoplastic fibres lower than 10%) to maintain the fibrous network at the desired thickness. Wood/thermoplastic bonds being weaker than bonds between synthetic fibres, these links could be break during/after the cooling phase leaving a higher capacity to the fibrous network to recover in thickness. The more important thickness recoveries observed in panels made up of finer wood fibres (PM2 and PR) can be the consequence of a greater interconnectivity between wood and thermoplastic fibres (thanks to higher surface area per unit volume). Compared with panels made up of PM2, the higher bulk densities and thickness recoveries observed for those made up of PR can be explained by the relative higher presence of fine elements (<0.5 mm), itself responsible for denser webs leaving the napper opener.

Apparent thermal properties: bulk density and thermal conductivity

Thermal conductivities are calculated, as described in the section 3.2 of materials and methods, from measurements of effusivity and the value of heat thermal capacity considered to be equal to 1800 J/(kg.K). The moisture content at equilibrium state (20°C/65%RH) of these materials is comprised between 10 and 11% by mass. (Figure 9) compares the evolution of apparent thermal conductivities for each blend in function of their bulk densities.

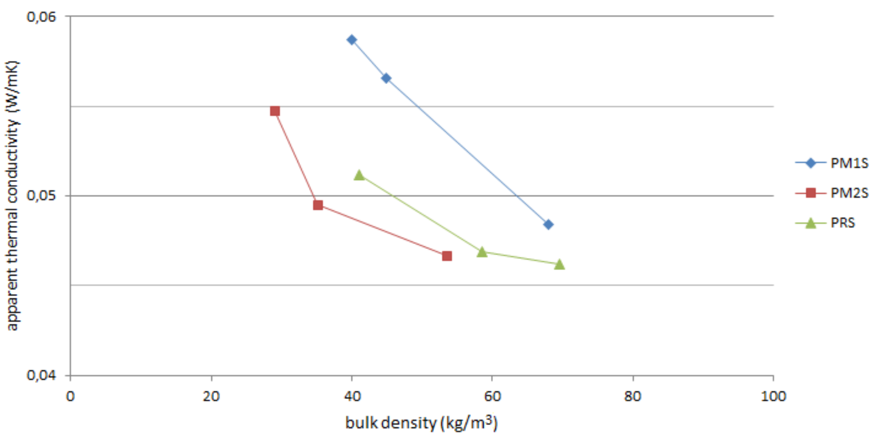


Figure 9: Apparent thermal conductivities function of bulk density for each blend of wood/synthetic fibres

With these machines settings and the characteristics of raw materials used, the apparent thermal conductivity (corresponding to bulk densities of the panels manufactured) appear to be above of a minimum apparent conductivity (at an optimum bulk density) for all the wood based fibrous materials as illustrated in (Figure 1). The increase of the apparent thermal conductivities with low bulk densities is justified by a more and more important contribution of the radiation component in the apparent thermal conductivity.
Identification of an optimum bulk density (at which the apparent thermal conductivity is mimimum) requires a largest range of bulk densities. Langlais and Klarsfled (2004) suggested a semi-empirical model (4) to simulate the evolution of the different modes of heat transfer inside fibrous insulating materials regarding its bulk density:

$$\lambda^* = f(A + B\rho^* + \frac{C}{\rho^*}) \qquad [4]$$

With *A* conduction in the air, *Bρ** conduction in the solid matrix and *C/ρ** radiation inside the fibrous network.
At 25°C, the thermal conductivity of motionless dry air is equal to 26mW/mK. The unknown parameters B and C can be estimated from the experimental data obtained for the panels by applying a non-linear parameter estimation method. The nonlinear optimization problem applied to obtain these parameters consists of finding the minimum of sum-of-square defined by the relation (5):

$$S = \sum_{i=1}^{m} (\boldsymbol{\lambda}^{*}_{app_{calc_i}} - \boldsymbol{\lambda}^{*}_{app_{\exp_i}}) \quad [5]$$

With $\boldsymbol{\lambda}^{*}_{app_{\exp_i}}$ the experimental values of apparent thermal conductivities and $\boldsymbol{\lambda}^{*}_{app_{calc_i}}$ the calculated values of apparent thermal conductivities.
An iterative technique, based on the Levenberg-Marquardt algorithm (LMA), is used to solve this linear parameters estimation problem (Marquardt 1963). From the calculated values of B and C, it is possible to estimate from the derivative of the relation (4) the optimum bulk density at which the apparent thermal conductivity is minimal.
(Table 3) presents the values obtained for parameters B and C, the coefficient of determination R^2 and the root mean square error (RMSE), the optimum in bulk density and the minima of apparent thermal conductivity for each blend wood/synthetic fibres. (Figure 10) illustrates the evolution of apparent thermal conductivities in function of the bulk density of the blends from the relation (4).

Table 3: values obtained for parameters B and C, R^2, RMSE, ρ^*_{opt} and λ^*_{min} from the relation 4 for each blend of wood/synthetic fibres

Blend	**B**	**C**	**R^2**	**RMSE**	**ρ^*_{opt}**	**λ^*_{min}**
	$mW.K^{-1}.kg^{-1}.m^{-2}$	*$mW.kg.K^{-1}.m^{-4}$*			$kg.m^{-3}$	$mW.m^{-1}.K^{-1}$
PM1S	0.1	1074.3	0.874	1.44	103.6	46.7
PM2S	0.136	698.8	0.941	0.82	71.7	45.4
PRS	0.116	836.1	0.998	0.12	84.9	45.7

Compared to representative variables describing the diameters distribution of the wood fibres population in (Table 2), the parameter B increases with their reduction while the parameter C decreases. With these experimental results and the methodology used to determine parameters B and C, we have respectively for the blends PM1S, PM2S and PRS, a R^2 equal to 0.874, 0.941, 0.998 and a RMSE equal to 1.44, 0.82 and 0.12. From these experimental results, the minimum of apparent thermal conductivity is estimated at 72kg/m^3 for panels made up of the finer wood fibres PM2. The minimum gradually increases up to 104kg/m^3 for panels made up of the coarser fibres PM1. Thanks to its closest granulometry distribution to the PM5 population, the minimum for panels made up of PR population is observed at 85kg/m^3. Related to previous observations in (Figure 7), it seems that the diameters of wood fibres have more impact than their length on the value of the optimal bulk density.

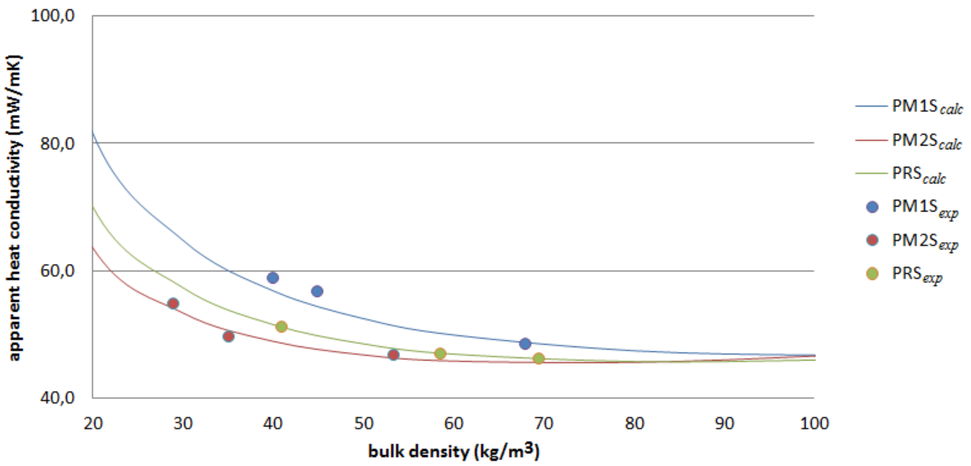


Figure 10: Evolution of the apparent thermal conductivity in function of bulk density for each blend of wood / synthetic fibres from the semi-empirical relation (4)

According to the shape of the experimental curves in (Figure 9) and the curves calculated using the relation (4) in (Figure 10), the degree of division of solid matrix, represented by the fineness of the wood fibres, allows to decrease the radiation component as soon as it is not negligible (at equal temperature, same moisture content and bulk density). Otherwise, increasing the degree of destructuration of the wood prevents the radiation contribution. Physically in this case, the fibrous medium has a larger surface area per unit volume to interact with radiation through scattering and absorption phenomena (only these phenomena can stop its propagation) (Langlais and Klarsfled 2004). It is observed that this influence is particularly important when bulk densities are very low. Consequently, although finer fibres require more energy consumption to be produced, their use seems to be justified at low density where radiation is no longer negligible and become preponderant. In this context, as poplar fibres are naturally finer than pine maritime fibres currently used for insulation purpose (PM1), poplar fibres could be valorized in wood fibre-based insulating materials.

CONCLUSIONS

In this work, the influence of the manufacturing settings and morphology of raw materials on the thermal behaviour of wood fibre-based insulating materials were investigated. The process used is adapted to the conception of these materials in which the porosities can exceed 98%. It is also adapted to design products made up of fine wood fibres (traditionally used for MDF or coming from hardwood).
The results highlight the overriding impact of the bulk density (adjusted by the compression ratio in the oven) on apparent thermal conductivity. The degree of destructuration of wood chips (adjusted by the plate gap of the refiner) is another morphological parameter allowing to modulate heat transfer mecanisms at very low density (at equal temperature, same moisture content and bulk density). Thanks to their larger surface area per unit volume (related to fibres fineness), wood fibre-based materials made up of a poplar fibres population (PR) exhibit a lower apparent thermal conductivity than insulating materials made up of current morphology of maritime pine fibres (PM1) as soon as radiation is no longer negligible (below 100 kg/m^3). Panels made up of a maritime pine fibres population similar of ones used in MDF (PM2) and those made of PR have a quite similar evolution in their apparent thermal conductivity

as long as bulk densities are above 45 kg/m^3. Moreover, requiring less energy consumption to be produced than maritime pine fibres used for MDF, this population of poplar fibres (PR) could be valorised in wood-based fibre insulation materials in this range of bulk densities.
Future works will focus on the compressibility of these materials (thickness recovery after being compressed). Wood fibre-based insulation materials being bulky and slightly compressible, transport costs have a strong impact of the final prices (20 %) (Nomadeis 2012). Mechanical tests will evaluate the compressibility according to compression rates and compression duration (Petureau *et al*. 2016). This work will be followed by the introduction of new species and other binders. These data will be combined, with that obtained from the environmental and economic objectives. Then by using a multi-objective optimization technique, the best compromises that simultaneously satisfy these conflicting goals will be found (Hobbaallah *et al*. 2016).

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Study of the stress-grading of poplar for a structural use

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Keywords: Poplar, bending, structural use, stress-grading.

ABSTRACT

Northern France has important poplar resources. This species has been used through the production of pallets and packaging. Within the context of an environmental, economical and global approach, supported by Région Nord Pas de Calais, we have worked on the increase in economical value of indigenous species. This study fits into the development of the timber industry for the use of poplar as structural timber. Drawing on previous experiments carried out on the use of polar as structural timber, we have shown the interest of the structural qualities of poplar for a structural use. However, it is currently necessary to have recourse to laboratory testing owing to a lack of accurate regulations for poplar. The norm for the grading of woods for their structural use (EN 408 2012) allows to categorize them into coniferous trees (C) and deciduous (D). In this norm, poplar is considered as a broadleaf tree but is this classification relevant? Moreover, the nodosity of poplar is not a determining factor. The grading of poplar must therefore be tackled differently so as to use it as structural timber. The purpose of this paper is to put forward an approach for the grading of poplar. To start with, the norm and its different criteria will be expounded. Six groups of local poplar pieces coming from six different cultivars (about 25 m^3 in use dimensions) have therefore been tested through destructive testing and then categorized by using this norm. The result is that the five groups comprise a great number of rejected pieces in spite of using wood with a high failure stress. Non-destructive supplementary tests, conducted in conditions adapted to local sawmills, have allowed to refine the grading and upgrade a maximum of pieces. Finally, all these tests have made it possible to validate a method of non-destructive grading of poplar.

INTRODUCTION

The use of poplar wood for structural use in north of France has begun a few years ago. It is a handcrafted activity and the wood volumes are quiet small. This study is really connected with the local forest economy. The timber used, selected from the Centre Régional de la Propriété Forestiere, was composed by six clones cultivated in Nord of France. The average perimeter at 1,50m was 162 cm; the trunks were between 7,5 m and 10 m. The six clones used were: Robusta, Trichobel, Flevo, Koster, Ghoy and Dorskamp. Each trunk was cut in 2,5m logs. The sawn timbers, before drying, were 72 mm x72 mm. It is really difficult for the sawmills to know exactly which type of poplar they have bought. They are important differences in mechanicals performance between

different poplar clones (Référentiel qualités du bois des cultivars de peuplier 2009). This study allows us to confirm the very large range of mechanical characteristic (EN 384 2010). The test done, according to EN 408 norm, gives for each clone the Modulus of rupture and the modulus of elasticity (MOR and MOE). The great sample size gives a fine view of the local poplar supply.

Table 1: Clones Classification

Clones	#		MOR	MOE
clones as a whole group	1483 pces	mean value	45,5	8 859
		standard deviation	12,6	2 141
		coefficient of variation	0,277	0,242
		charateristic value	23,9	5 174
Trichobel	250 pces	mean value	45,1	9 089
		standard deviation	8,7	943
		coefficient of variation	0,192	0,104
		charateristic value	30,9	7 834
Flevo	173 pces	mean value	38,7	7 699
		standard deviation	8,7	928
		coefficient of variation	0,223	0,121
		charateristic value	25,1	6 513
Ghoy	186 pces	mean value	41,9	7 232
		standard deviation	9,2	885
		coefficient of variation	0,219	0,122
		charateristic value	27,2	6 118
Koster	211 pces	mean value	41,6	7 223
		standard deviation	9,5	1 104
		coefficient of variation	0,227	0,153
		charateristic value	23,4	4 521
Dorskamp	382 pces	average value	47,4	9 844
		standard deviation	13,9	2 079
		coefficient of variation	0,294	0,211
		charateristic value	24,9	6 547
Robusta	281 pces	mean value	53,5	10 556
		standard deviation	14,4	2 286
		coefficient of variation	0,269	0,217
		charateristic value	30,2	6 851

The different tested clones of poplar have very different distribution of MOE.

As you can see on Figure 1, Robusta and Dorskamp have the highest MOE and the highest mean MOE but a very large distribution. Ghoy Koster, and Flevo have a much lower mean value of MOE but a smaller distribution. Trichobel had a small distribution and an interesting mean value for structural use. Systematically testing the beams seems

to be the best solution to avoid the risk of structural lacks. The scope of investigation is to determine the accuracy of a non-destructive high-speed 3 points bending method in different poplars clones.

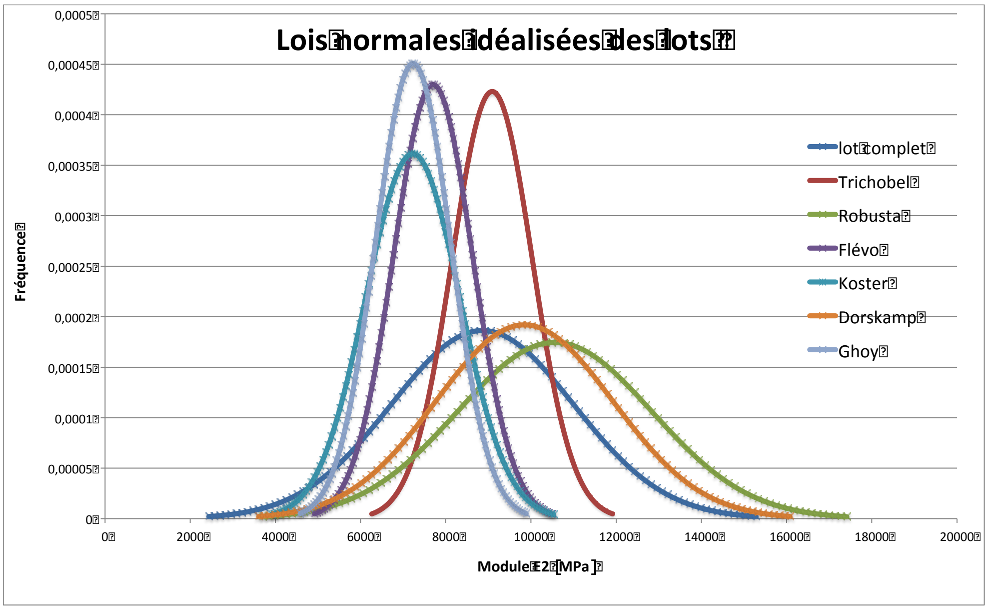

Figure 1: Streamlined distribution of MOE for the different clones of poplar

EXPERIMENTAL

The timber used, selected from the ***Centre Régional de la Propriéte Forestiere***, was composed by six clones cultivated in Nord of France. The boards (1483 samples) were tested wet in the 3 points high speed-bending machine, developed by Alternative structure bois, called Modulo. The Modulo test consist to bend the board with a hydraulic cylinder and to consign load and displacement at two different stress levels.

$$HSE = \frac{l_1^3}{48l}\frac{(F_2-F_1)}{(w_2-w_1)} \qquad [1]$$

These tests determine for each board an high speed MOE, we called it HSE. In this case by wet wood: HSEw

The boards were then kiln-dried in a vacuum drier. An approximately 15% wood moisture was reached. They were stacked for one month to stabilise and make moisture uniform.

The boards were then four faces planed to a 60 mm x 60mm section and test again dry with the Modulo. We get then by dried wood HSEd.

The wood density, the knot distribution, and the growth rings dimensions were registered.

On about 10% of the samples, ultrasound tests, with a portable Sylvatest were done.

Finally the samples were tested, in accordance to the EN 408, to determine the MOR and MOE from each sample.

Figure 2: Modulo high-speed 3 points bending machine

RESULTS AND DISCUSSION

Density and knots

In previous works, we suspect that density and knots had only a very little influence on structural wood properties, after testing this large group of samples we can affirm that only very big knots, it means larger than 75% of the board dimension had influence on the MOE. In facts, when they are so big knots on a board, the deformation that occurs by getting dry are so important that it couldn't be used.

Strength and rigidity

The MOE is relevant for grading poplar (CNPF – FCBA 2009). The test has shown that even the samples with low MOE have a good MOR. 22 boards have an MOR between 3.1 and 19.8 MPa. The MOE of these 22 samples is between 14 and 94 GPa. 14 of these 22 samples are Robusta clone and are mainly boards with the center of the log. If we set a limit for the MOE at 60 GPa then 12 samples of the 22 are detected and 9 from the other samples have a MOR between 17 and 20 MPa. The only sample which is not detected is a very bad board with heart. it would be rejected at the sawmill.

Ultrasound speed

To complete the investigation the ultrasound speed was tested by a portable Sylvatest. No correlation between ultrasound Speed and MOE was found.

High speed three-point bending

All the boards were tested wet and dry on the 3-point bench called Modulo (Figure 2). It was developed by Alternative Structure Bois to secure his poplar supply.

Loading speed has an important effect on the HSE. To avoid difference in experience we fixed the loading speed by 2 l/min oil it means at 8.9 mm/s. It means 50 to 100 times

faster than the EN 408 prescription. The tests were first done with wood by a relative humidity over 30%.

On Figure 3 the regression line correlating HSEw with MOE is plotted. The relation is clearly shown. The coefficient of determination is, in the case of non dried wood, 0,786.

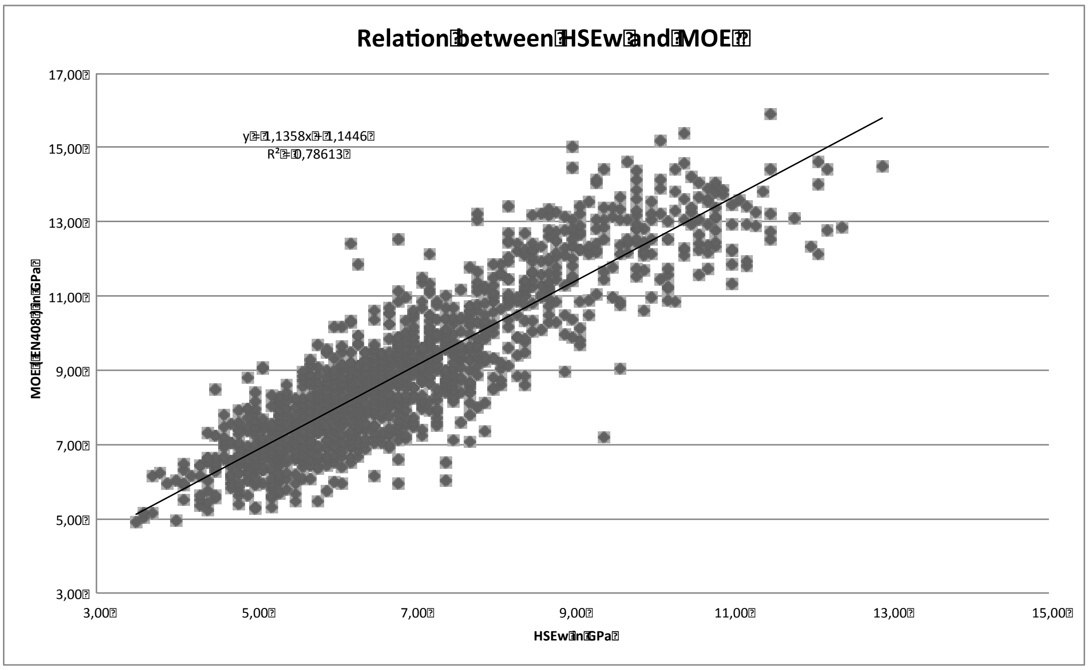

Figure 3: relation between HSEw and MOE

The tests were then done with wood by a relative humidity by 15%.

On Figure 4 the regression line correlating HSEd with MOE is plotted. The coefficient of determination is, in the case of dried wood, 0.890. This method gives very reliable results.

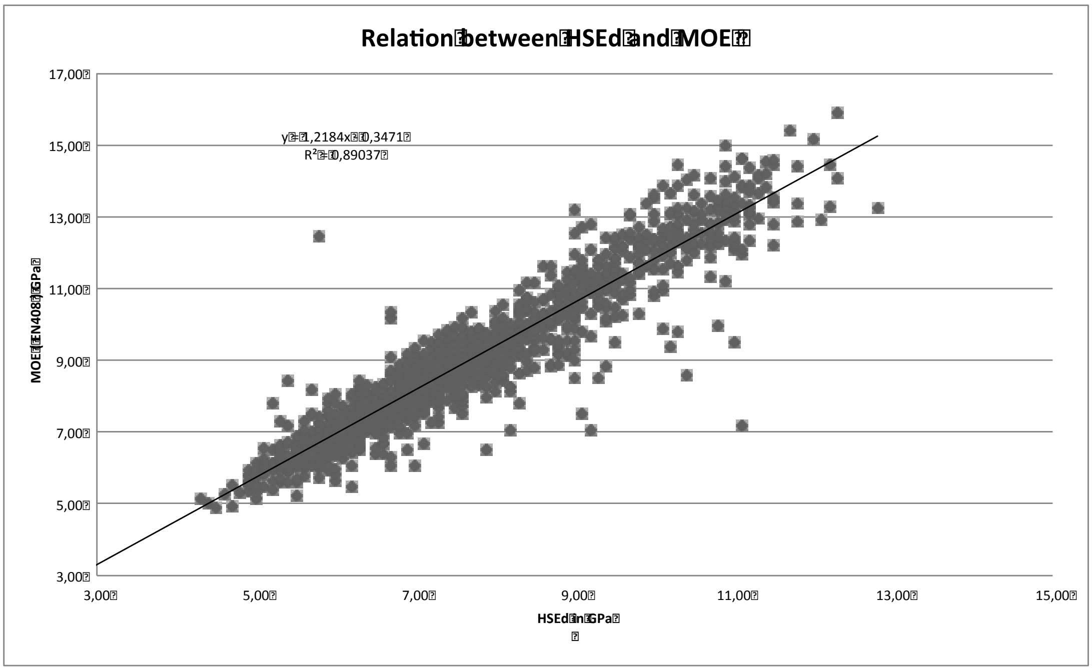

Figure 4: Relation Between HSEd and MOE

CONCLUSIONS

From the analysis of the entire data set the following conclusion can be drawn:

- The knot density doesn't seem to be relevant for grading poplar,
- The tests based on ultrasound speed were inconclusive.
- The wood density doesn't really affect the MOE.
- As soon as MOE fits to EN 384 specifications, MOR is higher than request.
- The high speed 3 points bending test gives very reliable results.
- This method is cheap and easily mountable in the local sawmills and it will not be an obstacle to the production output.

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Kiln drying properties of poplar hybrid clones from three growing sites

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Keywords: Clones, drying behavior, hybrid poplars, moisture content, wood drying.

ABSTRACT

Kiln-drying quality of seven hybrid poplar clones from three growing sites was evaluated on 35-mm thick boards following three types of drying schedules, high temperature (HT, 95-115°C), elevated temperature (ET, 82-90°C), and conventional temperature (CT, 50-82°C). Drying quality assessment was based on drying rate, final moisture content variation, shrinkage, warping, surface and end-check frequency, casehardening, and color change. Overall, drying performance was affected in decreasing order by kiln-drying treatments, log position, and clones. The high initial moisture content of poplar boards combined with their low density and apparent variable permeability made them prone to collapse, especially during HT drying. Drying time varied with a ratio of 2, 1.5 and 1 for CT, ET, and HT, respectively. ET and CT drying schedules were found more suitable to minimize shrinkage in thickness, checking, and color change. Two clones were selected as more suitable for drying.

INTRODUCTION

Long time considered with low commercial value, poplar species (*Populus* spp.) have become an economically important part of Canadian forest products industry. In Quebec, for instance, the annual wood consumption increased from 240 Mm^3 in 1960 to 5357 Mm^3 in 2004. The economic value of poplar (mainly aspen) has been predominantly created by the pulp and paper and the wood based panel industries (Ménétrier 2008).

Considering that timber supplies from natural forests in the future would become scarce, the Quebec Ministry of Natural Resources and Wildlife has initiated in the late ’60s an active poplar breeding program. High growth rate of genetically improved hybrid poplar clones in Eastern Canada could reach sawlog size in 15-20 years, with an annual yield of 8-12 m^3/yr/ha, the rotation period in hybrid poplar plantations being two to three times shorter than that of natural stands of poplar (Périnet 1999). However, wood properties from improved and intensively managed trees associated with short-rotation harvest are different and generally contain higher proportion of juvenile wood than from natural stands. Large volumes of tension wood have been observed in juvenile wood of poplar species (Bendtsen 1978). Tension wood shrinks more than normal wood, often causes distortion in lumber during drying, is prone to collapse, and it is also more difficult to machine (Ritter *et al.* 1993).

To use wood more efficiently in the development of value-added products, physical, mechanical, drying, and machining properties must be taken into account. Genetic selection of poplar hybrid clones for specific solid wood end-use applications have received some attention (Hernández *et al*. 1998, Koubaa *et al.* 1998a,b, Kretschmann *et al.* 1999, Peters *et al.* 2002, De Boever *et al*. 2007). Significant utilization of *Populus* spp. in the secondary wood-processing sector has been limited due to substantial kiln drying defects. Adapted drying schedules, new sawing patterns, or a combination of both approaches for *Populus* spp. have been studied by Mackay (1974), Mackay *et al.* (1977), Beauregard *et al*. (1992), and Kärki (2002) to minimize lumber drying degrade. Very little work is available for kiln drying wood of hybrid poplar clones. Kang *et al*. (2007) studied the variation in lumber quality of five clones following three kiln drying schedules. The results demonstrated that the drying schedule has a greater effect on grade recovery and the degree of deformation than the hybrid poplar genotype. It was also shown that an aggressive conventional temperature drying schedule with a maximum dry-bulb temperature of 80°C gives the best results in comparison to conventional temperature mild schedules.

The objective of this study was to assess drying characteristics of seven poplar hybrid clones coming from three growing sites using three kiln-drying schedules adapted for the production of value-added wood products for interior end-use applications.

EXPERIMENTAL

Wood procurement

Material for this study came from the experimental plantation sites of Platon (lat. 46°40’N, long. 71°51’W), St-Ours (lat. 45°53’N, long. 73°11’W), and Windsor (lat. 45°42’N, long. 71°48’W), which were established by the Ministry of Natural Resources and Wildlife of the Quebec province, Canada. The growing sites, originally abandoned agricultural lands, represent typical soil types available for planting hybrid poplar clones in Southern Quebec. Detailed description of the experimental sites is given elsewhere (Pliura *et al*. 2007).

Seven clones, each represented by five trees for each site, were selected for this study (Table 1). These clones are mainly recommended for Southern Quebec, based on growth rate, bolt form, adaptability, and disease resistance (Vallée 1995). A total of 105 trees were hence harvested in summer time, after 15 growing seasons for St-Ours and Windsor sites and after 17 seasons for Platon, except for those of clone 915508 that were felled after 13 growing seasons. Each tree was cross-cut in three segments: a butt log of 1.50 m (used in another part of the study for basic wood properties evaluation) followed by two logs of 2.45 m in length, designated hereafter as bottom log and mid log, respectively. Boards of 36-38 mm thick were sawn with a WoodMizer portable bandsaw and stored under a plastic sheet in a freezer at approximately -4°C until required for the drying tests.

Drying tests

The drying tests were conducted on pre-surfaced boards of 34 mm thick in average, 70 to 215 mm wide, and 2450 mm long. The boards were dried to a target moisture content

Table 1: Clones of three poplar hybrids selected for the study

Clone	**Hybrid[1]**
131	D x N
3230	T x D
3565	D x N
3570	D x N
3586	D x N
4813	D x N
915508	DN x M

[1] *D x N: Populus deltoides Bartr. ex Marsh x P. nigra L.*
T x D: P. trichocarpa Torr. & Gray x P. deltoides Bartr. ex Marsh
DN x M: (P. deltoides Bartr. ex Marsh x P. nigra L.) x P. maximowiczii A. Henry

(MC) of 7% in a 2.5 m^3 experimental kiln using three treatments: a conventional (CT) schedule, an elevated temperature (ET) schedule, and a high-temperature (HT) schedule (Table 2). Each schedule included an equalizing step of 15 h and a conditioning step of 4 h. Top restraint loading (3.8 kN/m^2) was used in each case (Figure 1). Drying packages were formed using 15 rows of boards separated by nine 19-mm stickers. Air velocity was 3.5 m/s in average. Flow direction was reversed every 2 h. In all, six matched loads were processed, three for the bottom logs and three for the mid logs. The three drying tests for the mid log position were entirely conducted on a time basis so as to impose the same climate conditions to the boards coming from both tree positions. A full load would contain 105 boards: 3 sites x 7 clones x 5 trees x 1 board. Each tree should be hence represented by one board within each drying schedule. However, some trees had not the required diameter dimension or quality to provide adequate boards.

Six from the 105 pieces were used as sample boards. Each sample board was cross-cut into two parts of 1.22 m long, end-sealed with silicone and aluminum paper. One part was used to fix moisture probes (back of the charge) and the other part was used for periodic weighing (front of the charge) (Figure 1). The initial MC of sample boards was estimated from three 10-mm diameter cores extracted with a tenon borer. The presence of a double-door arrangement behind the front doors of the kiln permitted the weighing of the sample boards during drying without disturbing the kiln climate. The average basic density (oven-dry weight to green volume ratio) of the lumber was 329 kg/m^3 with a coefficient of variation of 10%.

Following each drying run, all boards were evaluated for drying quality (final MC, shrinkage, warping, surface and end checks, and casehardening in the transverse section). Color measurements (lightness = L*, ranging from black (0) to white (100)) were also conducted before drying and after drying and planing, on the tangential surface of each board, using a portable BYK-Gardner color-guide 45/0

spectrophotometer. Warp assessment was made after planing all pieces to a thickness of 31.5 mm.

Table 2: Kiln drying schedules used in this study

Step	Mean MC [%]	Dry-bulb [ºC]	Time [h]	Wet-bulb [ºC]	RH [%]	EMC [%]
			CT schedule			
Heating up		60.0	3	58.0	90.4	18.0
1	> 60	60.0		55.5	79.4	13.4
2	60-40	65.5		57.5	67.2	9.9
3	40-25	71.0		60.0	59.0	8.0
4	25-15	77.0		60.5	46.0	5.9
5	15-7	82.0		57.0	30.5	4.0
Equalizing		82.0	15	66.0	48.9	5.9
Conditioning		82.0	4	76.0	77.5	11.0
			ET schedule			
Heating up		60.0	3	58.0	90.4	18.0
1	> 60	60.0		55.5	79.4	13.4
2	60-40	65.5		57.5	67.2	9.9
3	40-25	71.0		60.0	59.0	8.0
4	25-15	82.0		66.5	50.0	6.1
5	15-7	90.0		65.0	33.3	3.9
Equalizing		90.0	15	74.5	52.4	5.9
Conditioning		90.0	4	84.5	80.3	11.0
			HT schedule			
Heating up		99.0	5	98.0		
Pre-steaming		95.0	6	95.0		
1	> 45	105.0		94.0	66.8	7.0
2	45-7	115.0		90.0	40.5	3.5
Cooling		90.0	2	74.5	57.3	6.0
Equalizing		90.0	15	74.5	57.3	5.9
Conditioning		90.0	4	84.5	80.3	11.0

RH, relative humidity; EMC, equilibrium moisture content

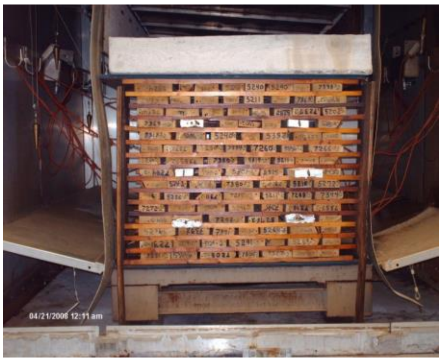


Figure 1: Drying load with top load restraint and end-sealed sample boards

Statistical analysis

Statistical analyses of drying tests were carried out as a split-split-plot experimental design. ANOVAs were performed using the SAS (2004) MIXED procedure. MIXED provides parameter estimates for generalized linear models including both fixed and random factors in the same model. Clones, growing sites and log position were considered fixed effects, whereas drying treatments and other sources of variation were considered random effects. Assumptions of normal distribution of residuals and variance were tested using SAS UNIVARIATE procedure. The repeated instruction from SAS MIXED procedure was used to test homogeneity of variances. When statistically significant effects ($p < 0.01$) were found, least-squares means multiple comparison tests were performed using the least significant difference option from the LSMEANS function within the SAS MIXED procedure.

RESULTS AND DISCUSSION

Evolution of drying curve

The drying time and the mean and standard deviation values of the initial moisture content (IMC) and final moisture content (FMC) obtained for the six drying runs are presented in Table 3. The drying time of the CT schedule was about 195 h, which is twice as long as the one of the HT schedule. The ET schedule drying time was half way between CT and HT schedules. The IMC, which was inferred from the initial and final board weights and FMC, as determined with capacitive moisture meter, is shown to be very variable. Despite that, the FMC standard deviation was smaller than 1.0% MC, except for one run. The mean FMC was within 1% of the target value of 7%, with a slight over-drying in five of the six runs. As it is generally the case, the average IMC of the three drying runs for the bottom log was higher than that of the mid log. However, all IMC values appear smaller than those normally found with poplar species, which would indicate that some pre-drying took place during the sawing process and storage.

Table 3: Drying time and mean values (SD) of IMC and FMC

Position	Drying schedule	Drying time [h]	IMC [%]	FMC [%]
Bottom log	CT	**195**	122 (29)	6.5 (0.5)
	ET	**152**	115 (27)	6.6 (1.0)
	HT	**96**	120 (25)	6.5 (0.4)
Mid log	CT	**195**	102 (25)	6.7 (0.6)
	ET	**152**	97 (25)	7.9 (1.6)
	HT	**100**	122 (29)	6.6 (1.0)

Figures 2 and 3 present the average drying curve of each drying schedule used for the bottom log and mid log positions, respectively. It can be seen that the warming up period was followed by a significant increase of wood moisture content, likely due to water vapor condensation on board surface at the start of the heating phase. Both the CT and ET schedules show similar drying rates above 25% MC, the CT schedule slowing down afterwards. This was expected since these two schedules were identical above

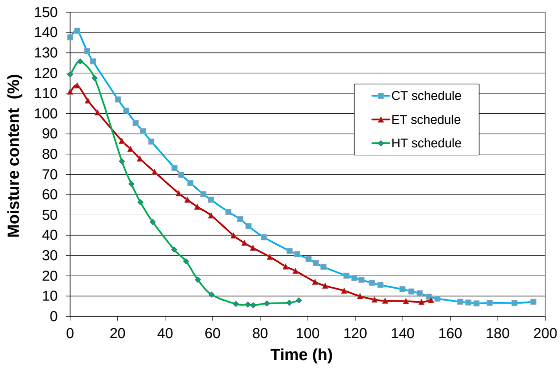


Figure 2: Mean drying curve for the three drying schedules of the boards coming from the bottom log

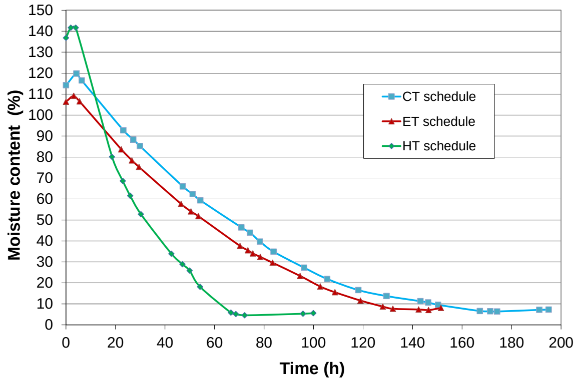


Figure 3: Mean drying curve for the three drying schedules of the boards coming from the mid log

25% MC (Table 2). In contrast, the HT drying curve is very steep with an average drying rate of 3% MC per h during the first 30 h of drying. Figures 2 and 3 indicate a fairly similar drying behavior for both log positions.

Drying quality

The results of shrinkage, checking and warping assessment for the boards coming from the two log positions are presented in Table 4. One first observation is that the shrinkage in thickness increases with the drying temperature. It is even greater than the shrinkage in width in the case of the HT schedule. This is a well-known phenomenon in the literature (Milota 2000, Beaulieu *et al*. 2003), although the HT schedule in Table 4 shows abnormally high values of thickness shrinkage. This was likely due to internal checking and collapse, which were observed in a high proportion of the boards while conducting machining tests (Hernández *et al.* 2011, Kuljich *et al*. 2015). Huffman and Cech (1976) observed the same phenomenon during HT drying of 25-mm thick aspen lumber. As expected, the HT schedule also caused the highest proportion of end checks and surface checks.

Table 4: Shrinkage, checking and warping assessment values (Means and standard deviation)

Position	Drying schedule	Thickness shrinkage [%]	Width shrinkage [%]	End checks [%]	Surface checks [%]	Bow [mm]	Crook [mm]	Twist [mm]
Bottom log	**CT**	**4.4 (1.4)**	**5.4 (1.4)**	**20.0**	**12.4**	**2.8 (1.9)**	**4.1 (3.3)**	**1.6 (2.0)**
	ET	**5.2 (1.8)**	**4.9 (1.4)**	**13.3**	**18.1**	**3.1 (2.0)**	**4.1 (2.9)**	**1.3 (1.4)**
	HT	**6.2 (1.9)**	**5.0 (1.2)**	**79.0**	**23.8**	**3.1 (2.0)**	**4.0 (2.4)**	**1.9 (1.9)**
Mid log	**CT**	**4.5 (1.8)**	**5.2 (1.4)**	**35.0**	**13.2**	**2.6 (2.8)**	**4.7 (4.2)**	**2.4 (2.6)**
	ET	**4.7 (2.9)**	**4.9 (4.1)**	**71.0**	**15.9**	**2.1 (1.9)**	**5.4 (4.3)**	**2.6 (2.5)**
	HT	**6.7 (2.0)**	**5.2 (2.5)**	**68.3**	**16.5**	**3.8 (2.9)**	**5.4 (4.8)**	**2.0 (1.6)**

Warping values indicate that crook was the main drying deformation, which is common for poplar species (Beauregard *et al.* 1992, Wengert 1986). Overall, except for bow deformation which was smaller in this study, crook and twist followed the same tendency of those reported by Kärki (2002) and Kang *et al.* (2007). Top restraint loading was likely responsible for the relatively low value of bow in this study. Conversely, top restraint loading has little effect on crook due to the way this defect develops (horizontal plane deviation).

As far as lightness is concerned, there was some darkening taking place with HT drying, especially for the bottom logs (Table 5). The two other schedules even showed an increase of lightness, which is unusual but could be advantageous for end use value-added products of hybrid poplar wood.

Table 5: Color (lightness) change due to drying (Means and standard deviation)

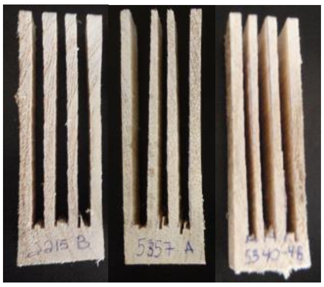
Position	Drying schedule	Lightness	
		Before drying	After drying and planing
Bottom log	**CT**	**79.9 (8.4)**	**82.3 (3.6)**
	ET	**76.9 (6.6)**	**80.7 (5.9)**
	HT	**80.2 (6.5)**	**72.5 (3.3)**
Mid log	**CT**	**79.6 (7.8)**	**81.9 (3.9)**
	ET	**73.3 (8.8)**	**80.7 (3.2)**
	HT	**72.8 (7.7)**	**72.1 (3.3)**

Casehardening, as evaluated by prong tip deviation after conditioning and before planing, revealed very low residual internal drying stresses for the three drying schedules (Figure 4).

Effect of drying treatment, site, clone and position on drying quality

A summary of the results obtained from the analysis of variance on drying properties is outlined in Table 6. Only independent variables and their interactions significantly

affecting the dependent variables are shown. The effect of site is observed only on IMC and FMC. Clone effect was detected for IMC, FMC, thickness and width shrinkages. The drying schedule affected FMC, thickness and width shrinkages, bow, twist, and



a ***b*** ***c***

Figure 4: Prong test result after conditioning and before planing:
a) MT schedule; b) ET schedule; c) HT schedule

lightness change. As reported by Kang *et al.* (2007), drying schedules had a greater effect on warping than that due to the poplar clone. Board position in the stem had some influence on the drying quality, although in interaction with the drying schedule. Comparing bottom log and mid log positions of boards, Table 6 reveals no significant differences in width and thickness shrinkages. There was a log position effect on IMC, FMC, bow, twist, and lightness change. Based on the F values (not shown), the overall drying performance was affected in decreasing order by kiln-drying treatments, log position, and clones.

Table 6: Summary of the results of ANOVA (α = 0.01) and interactions

Dependent variables	**Global analysis**
IMC	Site; Clone; Position; Drying; Site*Clone; Site*Drying
FMC	Site; Clone; Position; Drying; Position*Drying
Thickness shrinkage	Clone; Drying
Width shrinkage	Clone; Drying
Bow	Position; Drying; Position*Drying
Crook	–
Twist	Position; Position*Drying
Lightness change	Position; Drying

Effect of drying treatment on thickness and width shrinkages

Comparisons of thickness and width shrinkage means by drying treatment (sites, log positions, and clones pooled) are shown in Table 7. If there is no clear tendency concerning the effect of kiln schedule on width shrinkage, thickness shrinkage of the HT schedule was significantly greater than that of the CT and ET schedules. As mentioned above (Table 4), this can be partly explained by the development of collapse during drying at HT. However, this phenomenon is also typical of HT drying. A higher shrinkage value in thickness and a lower shrinkage value in width was observed on plantation-grown white spruce by Beaulieu *et al*. (2003) when compared to CT drying. Milota (2000) found for hem-fir stud lumber that HT kiln drying increased shrinkage in

thickness but did not significantly affect shrinkage in width. This phenomenon would be related to the amount of permanent creep deformation taking place under the high temperature and moisture content conditions prevailing in the early stages of drying.

Table 7: Comparisons of thickness and width shrinkage means by drying treatment (sites, positions and clones pooled)

Drying treatment	Width shrinkage [%]	Thickness shrinkage [%]
CT	5.3 C	4.5 A
ET	4.9 A	5.0 A
HT	5.1 B	6.4 B

Means within a column followed by the same letter are not significantly different at the 1% probability level.

Effect of clone on thickness and width shrinkages

Comparisons among thickness and width shrinkage means of clones (sites, drying schedules and log positions pooled) are shown in Table 8. Clones 4813 and 3565 show the highest shrinkage values while clones 3570 and 131 show the lowest shrinkage values. The fact that clones 4813 and 3565 presented the highest basic density from the seven clones (Table 9) would explain in great part their high shrinkage values. Based on the shrinkage values, we would be tempted to favor clones 3570 and 131 for best drying quality. Clone 915508 is also interesting in that point of view.

Table 8: Comparisons of thickness and width shrinkage means by clone (all drying schedules pooled)

	Clone code						
Clone	3570	131	915508	3586	3230	3565	4813
	Width shrinkage						
Mean	4.6 A	4.6 A	5.1 A	5.2 A	5.2 A	5.2 A	5.7 B
	Thickness shrinkage						
Mean	4.7 A	4.9 A	5.1 A	5.5 B	5.6 B	5.6 B	6.0 B

Means within a row followed by the same uppercase letter are not significantly different at the 1% probability level

Table 9: Means of basic density of the seven hybrid poplar clones (all sites and drying treatments pooled)

Clone	Basic density [kg/m^3]
4813	360
3565	348
915508	324
3570	321
131	321
3586	316
3230	315
Average	329

Effect of drying treatment on warp (bow and twist)

Comparisons of warp means by drying treatment for each log position are presented in Table 10. Only bow and twist are shown since crook did not show any significant difference between drying treatments and log position (Table 6). As indicated by the uppercase letters, there is no drying treatment effect on bow for the bottom log but the HT schedule for the mid log shows a significant higher mean value of bow as compared to CT and ET schedules. Concerning twist deformation, only the bottom log shows a significant higher mean value for the HT schedule. A significant effect of log position within the same drying treatment (lowercase letters) is shown on bow for the ET schedule. No clear explanation can be given for the low value of bow of the mid log for the ET schedule. The bottom log reveals significant lower twist mean values as compared to the mid log for both CT and ET drying treatments, likely explained by the smaller mean board width for the mid log position, the effect of top load restraint being less efficient when board width decreases.

Table 10: Comparisons of bow and twist means by drying treatment for each log position

Position	Drying treatment	Bow [mm]	Twist [mm]
Bottom Log	CT	2.8 Aa	1.6 Aa
	ET	3.1 Ab	1.3 Aa
	HT	3.1 Aa	1.9 Ba
Mid Log	CT	2.6 Aa	2.4 Ab
	ET	2.1 Aa	2.6 Ab
	HT	3.8 Ba	2.0 Aa

Means followed by the same letter are not significantly different at the 1 percent probability level. Within a column, upper case letters are for drying treatment comparison within the same log position and lower case letters are for log position comparison within the same drying treatment.

CONCLUSIONS

Drying properties of seven hybrid poplar clones from three growing sites and five trees per site were evaluated. Drying time varied with a ratio of 2, 1.5 and 1 for CT, ET, and

HT, respectively. Drying performance was generally affected in decreasing order by kiln-drying treatments, log position, and clones. Crook was the main warping defect for the CT, ET, and HT schedules. There was a log position effect on IMC, FMC, bow, twist, and lightness change. Thickness shrinkage of the HT schedule was found significantly greater than that of the CT and ET schedules. The high initial moisture content of poplar boards combined with their low density and apparent variable permeability made them prone to end checking and collapse, especially during HT drying. The ET and CT drying schedules were more suitable to minimize shrinkage in thickness, checking and color change. Clones 3570 and 131 performed best for thickness and width shrinkages. In short, the kiln drying of hybrid poplar for value-added products for interior end-use applications can be a successful process if an appropriate drying schedule combined with top restraint loading is used.

ACKNOWLEDGEMENTS

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OPTISOUNDWOOD project: enhancing poplar plywood with sound absorption properties

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ABSTRACT

The paper presents the results of a project funded by the Piedmont Region – Northern Italy – aimed at developing, testing and manufacturing innovative wood-based products for acoustic improvement and mainly realized with poplar plywood. This species was chosen both for its remarkable lightness and because it is the only local wood, with long arboricultural tradition, for which the offer of timber can meet the industrial needs. After an introduction on the state of the art and trends of poplar cultivation in Italy, the paper describes the artifacts (sound absorbing perforated panels, frames and bass traps) developed within the project. The research envisaged a preliminary investigation through physical models that guided the realization of perforated small-scale specimens. Tests were carried out with the impedance tube method and the more interesting drilling patterns were realized on products in end-use dimensions. These were installed and tested in a dining hall and their sound absorption properties were also determined using the reverberation room method. Since developed products are also proposed as furniture elements their appearance represents a fundamental issue. For this reason different kinds of surface finishing were experimented: painting, milling of decorative figures, image printing and tissue coverings. Technical aspects related to assembly and installation of end products were also considered. The final products showed interesting sound absorption properties in the low frequency range and poplar plywood turned out adequate for satisfying the requirements foreseen by the proposed uses.

INTRODUCTION

Acoustic quality is a fundamental parameter of large environments intended for speech such as dining rooms, open space offices or restaurants (Everest and Pohlmann 2009). These spaces are often subjected, when crowed, to high noise levels, mainly determined by people's voice. Poor acoustics have negative rebounds on the usability of these environments and on their occupants who can perceive high levels of stress (Yost 2014,

Kuttruff 2009). Therefore, products for improving the acoustics of closed spaces are often in good demand, also due to the high amount of buildings affected by low acoustic quality (Negro *et al.* 2010).
The OPTISOUNDWOOD project was carried out by a Temporary Association of Scope constituted by a plywood manufacturer (the project leader), two academic partners (Dept. Agroselviter – University of Torino and DiPRADI – Politecnico di Torino), an acoustic consultant and the Province of Torino. The main goal was to develop, test and realize innovative wood-based panels and composites (Figure 11 and 2); these were mainly made of poplar plywood, produced using timber of local provenance and intended for acoustic purposes (Negro *et al.* 2016).

Figure 11: Examples of developed sound absorbing panels (left) and frames (right)

Figure 12: Examples of developed cubic (left) and cylindrical (right) bass traps

In particular the project envisaged the production of some prototypes intended for optimizing the acoustics of their end-use environment through the Helmholtz resonance and the membrane effects (Everest and Pohlmann 2009); these physics principles enable to confer sound acoustic properties to wood-based products (Bucur 2006).
Helmholtz resonance is based on a mass-spring system made of two communicating volumes named *neck* and *cavity*. When the acoustic waves hit the air in the neck (the mass), they push it inside the cavity; the air already laying there is thus compressed and reacts (like a spring) expanding itself and rebounding the incoming air. This originates an oscillatory movement that dissipates high quantities of sound energy, particularly in correspondence of a specific frequency named "of resonance". In the developed products, the holes drilled on their surface represent the necks, while the empty spaces placed inside or at their back are the cavities. Holes and cavities were dimensioned

according to physical models (Kuttruff 2009) in order to place the resonance within the low frequency range, i.e. where human voice is mainly emitted.
Further, two new types of bass traps were also realized: the first is cylindrical and made of bendable poplar plywood; the other has a cubic shape with a movable partition. Both interact with sound through their membrane resonance effect: the acoustic waves hit the front panel inducing a vibration that (like a membrane) absorbs the incident sound.
All of the above products were realized using poplar wood, that was chosen for several technological reasons (see also Box): its remarkable lightness enables to produce light and easy to install elements; its low density can also be exploited for realizing the vibrating elements of membrane resonators; its anatomical features and workability make it suitable for producing bendable plywood that constitutes the main component of one of the developed products; its light color is suitable for several finishing types, among which surface printing; finally, poplar is the only local species able to meet the national industrial needs in terms of adequate and continuous supply of wooden raw material for plywood manufacturing (Castro and Zanuttini 2008).
After testing the Helmholtz resonators on small-scale specimens by means of the impedance tube method, the sound absorption properties of a prototype for each final product were assessed in end-use applications and in reverberation room; in particular their acoustic behavior within the low frequency range was investigated.
The project also considered some environmental and eco-sustainability targets. The use of natural adhesives, without formaldehyde and alternative to the traditional thermo-hardening resins, was investigated for the production of panels and artifacts; further, the use of new poplar clones, selected by CRA – Research Unit for Wooden Products Outside Forest, has been assessed. A relevant part of the study regarded the installation methods and the finishing or aesthetic solutions (for instance printing on wood and surface milling using a CNC machine).
This contribution aims to give an overview of the project, presenting the experimental design and some properties of the developed products that, as a further result of the research, are currently ready for commercialization.

BOX - Trends in poplar cultivation in Italy

Problems of environmental sustainability, particularly regarding conservation of tropical rainforests, have brought a growing diffusion of certified wood products on the market (Castro and Zanuttini 2008). Even poplar had to deal with the necessity to obtain such recognition.
The first step towards the certification of poplar plantations was the tuning, within the frame of a preliminary project (ECOPIOPPO), of appropriate guidelines for cultivation with special attention to the environmentally sensitive areas; agreed upon by the interested parties, these indications foresee limitations in the use of chemical products and a reduction of farming operations. Their integration at national level into the PEFC and FSC standards for a sustainable management of poplar stands favoured their adoption as technical reference, facilitating monitoring and inspections from the certification bodies.
Features shared by such standards are the necessity to reduce the environmental impact of the plantation management, to adopt an accurate planning, an adequate care to staff training and workplace safety. The FSC standard is however more demanding as for the obligation to reserve part of the surface for the native vegetation growth, a stricter threshold in terms of clone differentiation, the

prohibition to use dithiocarbamates and a size of plantations accepted to be homogenous for age and clone composition which cannot be larger than 10 hectares. The PEFC standard, which is better suited to the critical issues of the Italian poplar cultivation, shows greater attention to traditional practices, which is probably the reason for its greater success among poplar growers (AA.VV. 2008).
Both standards have however generated positive feedback. Firstly, the possibility of choosing and obtaining group certification has brought to new form of association aimed at reaching economies of scale. On the other hand, they have become a keystone for facilitating the introduction of new poplar clones, which although not yet widely accepted by the plywood industry, show advantages from the productivity and the environmental point of view (requiring fewer cultural practices) as well as in terms of technical features that make them interesting for new, unconventional, uses.
At the moment in Italy there is only a very little amount of FSC-certified hectares, all privately owned and generally destined to meet the demand for plywood production destined to foreigner markets, while the PEFC-certified hectares are much more diffuse. As far as the processing industries that use poplar wood are concerned, given that there is no mutual recognition between the two schemes, many have resorted to the double implementation of their Chain of Custody (CoC). Among them certification is frequent and concerns dozens of companies having implemented both schemes.
The market of certified poplar, however, is quite young and a well-structured planned demand still does not exist. The processing industries, moreover, despite the higher costs incurred by poplar growers, are not willing to accept a premium price for certified wood. Growers decide then to obtain certification mainly to maintain their market quota and to be visible in wider contexts, improving in the meantime their relationship with local stakeholders.
Recently, new poplar clones have been selected (and legally registered for commercialization) which need fewer treatments thanks to their good resistance to a wide range of biotic stresses. Some of them, following results from experimental trials, have been recognized as "MSA clones" (from the Italian acronym for "clones having with more environmental sustainability"). In the framework of the new financial resources aimed to sustain the rural development some Regions have therefore decided to provide funding only for plantations including a high percentage of these clones.
Finally, some innovative models of polycyclic plantations have been tried where poplar is mixed with valuable hardwoods (for example walnut and cherry) and, in some cases, with secondary shrub species, added to have growth synergies, better conformation of the trunk, multifunctional objectives and the reduction of the risks of single-species cultivation. In these new types of plantation poplar provides an income at an early stage of the overall rotation. The first results seem encouraging, although it is too early for a general judgement (Buresti Lattes *et al*. 2008, Castro *et al*. 2013, Buresti Lattes *et al*. 2015).
Often the poplar material obtained from the above “non-conventional” plantations is quite different to that from traditional ones: timber is slightly heavier and the derived material is generally less homogeneous, since various clones are used. It is therefore important to find differential uses in which poplar wood can better satisfy *ad hoc* requirements like lightness (typical for the ‘I-214’) or higher mechanical performances (with many other clones).

EXPERIMENTAL

The prototypes realized within the project are listed below; types 1 and 2 exploit the Helmholtz resonance, while types 3 and 4 the membrane resonance effect:

1. *Panels*: made of drilled poplar plywood installed on a plywood frame with a sound absorbing mat inside (Figure 1, left);
2. *Frames*: sandwich panels made of plywood skins (one of which thicker and designed to remain in view) bonded to an inner core constituted by a honeycomb structure of veneered cells (Figure 1, right);
3. *Cubic bass traps*: cubic structures made of plywood with a face of limited thickness (the membrane element); this partition can be moved in order to vary the frequency of resonance and can be covered with sound absorbing materials (Figure 2, left).
4. *Cylindrical bass traps*: made of a cylindrical body of bendable poplar plywood covered with a sound absorbing mat and placed between two circular plywood plates (Figure 2, right).

A preliminary investigation of the sound absorption properties of drilled panels was performed using the impedance tube method according to EN 10534-2. The most suitable drilling schemes were realized on prototypes in end-use dimensions: panels of 2120x1250x9 mm, frames of 600(and multiples)x600(and multiples)x38 mm, cubic bass traps of 616x616x336 mm, cylindrical bass traps of 600x500 mm.

The sound absorbing properties of all prototypes were validated in a dining room of a Small Medium Enterprise in order to simulate a real application. The selected environment is highly reverberant and characterized by poor acoustic quality. This situation is typical of large enclosures with plane and rigid walls, ceilings and floors (Kang 2002). In detail, its volume of 243.81 m^3 and its surface of 231.55 m^2 meet the dimensional requirements envisaged by EN ISO 354. During testing the room was arranged with plastic tables and chairs. Measurements intended to assess the reverberation time and the maximal noise level when the room is occupied by 10/25 users (depending on working shift) were also made.

The room was arranged with the following prototypes installed on its walls and distributed uniformly in place:

- 8 sound absorbing panels, for a total surface of 21.2 m^2;
- 26 acoustic frames, for a total surface of 14.4 m^2.

Investigation methodology was set according to EN ISO 3382, that prescribes the measurement criteria and parameters on the basis of the impulse response; the testing and the assessment of the results were performed according to EN ISO 354. Two acoustic measurements (for a total of 10 repetitions) of reverberation were realized using the technique of pink interrupted noise; this enabled to obtain the noise levels during the lunch and dinner breaks.

The acoustic properties of end-size samples were also determined in a reverberation room according to EN ISO 354 (Figure 13). This enabled to better compare the performances of the developed products with those of other materials already available on the market.

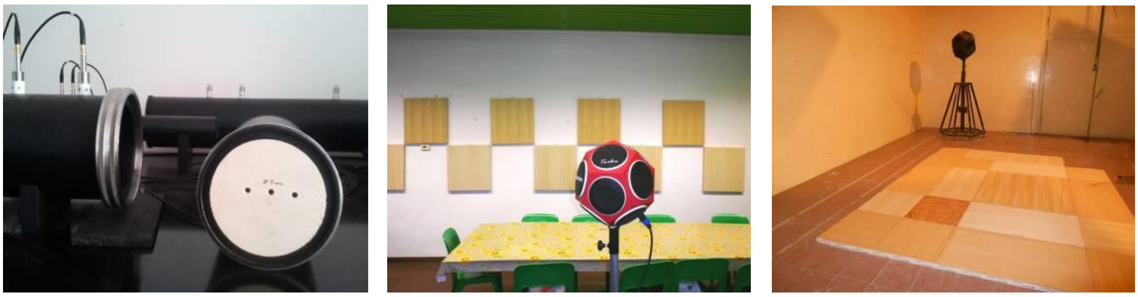

Figure 13: Main phases of the acoustic testing: on small specimens through impedance tube (left), on end-size samples in a dining room (center) and in reverberation room (right)

Finally, during a lunch break a questionnaire was submitted to 14 workers in order to assess their perception of the effect of the acoustic products installed within the room.

RESULTS AND DISCUSSION

The acoustic properties determined by means of the impedance tube were confirmed by testing on samples in end-use dimensions in the dining and in the reverberation room. The absorption values of the developed panels, frames and bass traps achieved absorption peaks of about $\alpha = 0.90$ (which means that the 90% of the incident sound is absorbed) at frequencies of 100, 300, 400 and 800 Hz (Figure 14 top and bottom). These fall within the low frequency range (that includes frequencies up to 1600 Hz), where the main sound emitted by human voice is perceived.

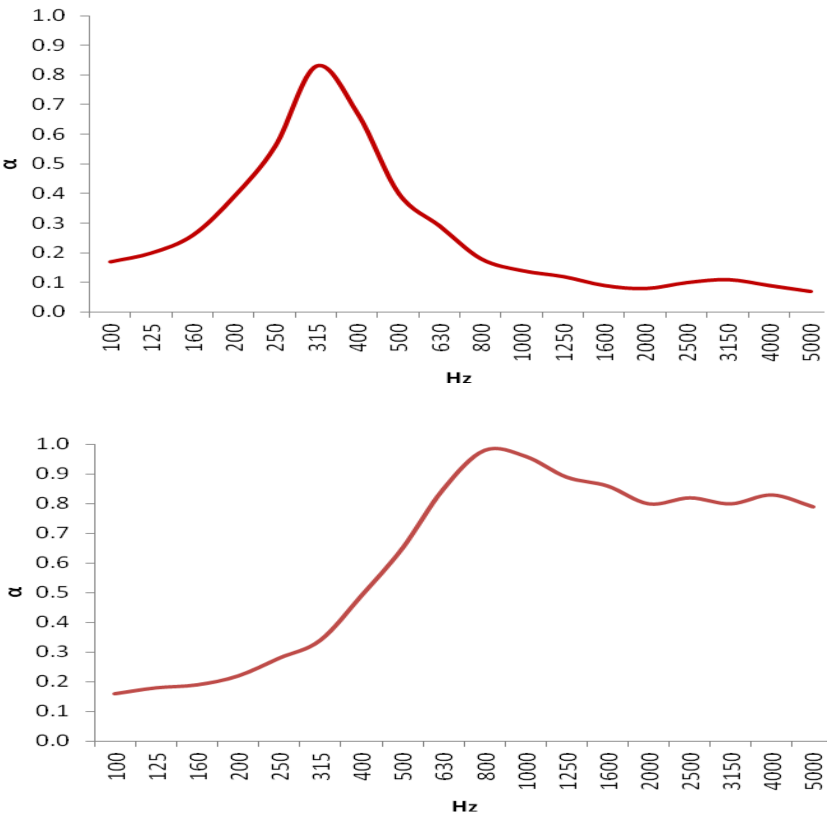

Figure 14: Examples of the sound absorption properties achieved by the acoustic panels (top) and by the bass traps (bottom)

The absorption curves of some prototypes show rapid slopes (meaning that the absorption behavior is selective around the frequency of resonance). These can be enlarged by adding sound absorbing mats (behind, inside or ahead depending on the product), even if this solution determines a lowering of the peak values (Everest and Pohlmann 2009).
The results of the survey concerned to the acoustics of the dining room indicated that the presence of the realized products was clearly perceived by the workers. On the whole the users stated that the overall background noise was lowered, that they heard the conversation better and that the acoustic quality of the room significantly improved. Further it is also important to note that a more complete acoustic recovery of the environment would require to add a higher amount of sound absorbing products, that would result in an even better comfort.
A relevant part of the project included the study of the best solutions for installing the acoustic panels and assembling the bass traps (Figure 15). These facets were carefully investigated since the developed products are intended for end-users.
As for the acoustic panels, aluminum profiles that guarantee a rapid and solid fastening to the walls were individuated through a market research; their compatibility with the acoustic panel was assessed on prototypes in standard dimensions. As for the bass traps, the best assembling methods were chosen among various realized on a series of prototypes.

Figure 15: Detail of an installation system made of aluminium profiles

Different types of surface finishing were also experimented and evaluated, among which the covering with tissues, the milling with a CNC machine and the printing with specific tools (Figure 16). This latter is particularly interesting since the picture can be provided directly by the final user, who can thus customize his purchase. Surface printing can also be designed to conceal the holes on the surface: for some applications this represents an innovative aesthetic solution.

Figure 16: Examples of decorative milling (left) and surface printing (right) of drilled panels

CONCLUSIONS

The OPTISOUNDWOOD project enabled to develop, test and realize at industrial level a series of new panels and composites made of poplar veneers coming from local plantations. Products were designed to provide sound absorption within the low frequency range; their finishing was also considered.

The project constituted an opportunity of collaboration among different subjects operating in the poplar chain. Their competencies contributed to find technical solutions suited to reach products with higher value added. These enable to differentiate the production of the manufacturer towards new market niches and non-traditional applications.

The results obtained confirmed the interesting performance of the prototypes and allow to propose veneered products specifically intended for the acoustic improvement of confined environments. In particular, they can be used in closed spaces subjected to be highly crowded, such as dining rooms, theatres, commercial centers, open offices, restaurants etc. They are also suitable for use in environments in which a fine tuning of the acoustics is required, such as recording rooms, television studios or workshop areas in fairs.

Poplar plywood turned out to be adequate for realizing the designed products. From the acoustic point of view, while in Helmholtz resonators the key parameter is the geometry of holes and cavities, in membrane resonators the lightness of poplar wood enabled to activate the sound absorbing vibrations. In the cylindrical bass trap poplar veneers resulted suitable for producing the easily bendable panel that constitutes the main element of this artifact. Finally, the availability of poplar timber of local provenance was relevant to meet the demand of raw material from the plywood industries and to place on the market some new value-added wood-based products with a better and more sustainable environmental profile.

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Durability of exterior wood works in poplar from France in real conditions of use

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Keywords: Poplar wood, exterior works, degradation.

ABSTRACT

The project "*Durability of exterior wood works in real conditions of use*" aims are to improve the knowledge about the degradation of different wood species from France, including poplar, in exterior applications and considering the main factors: material resistance, decay, insects, moulds, disfiguring fungi and cracking. There is degradation inherent to each location, conditions of use and details design.

Experimental test devices related to use class 3 were installed in 2009 in the facilities of FCBA-Bordeaux, France, to study the degradation of exterior wood, related to “durability by design” made of different wood species and designed, including poplar from France. Poplar specimens sampled from the test devices used in the work carried out by FCBA made of different designs have been examined in order to identify the parameters influencing and improving and learning from the research. Results will provide inputs for the development of a model of poplar degradation in exterior applications, by using data on biological degradation of wood, use conditions, climate and design.

The applications of these researchers are to poplar industry, architects, builders and end users.

INTRODUCTION

Wood is susceptible to biological decay. The natural durability to biological agents depends on: wood species, geographical origin, age and growth conditions of the tree and the presence of heartwood or sapwood and their relative proportions.

The service life of exterior wooden commodities, which means how long a product is expected to perform under specific environmental conditions, depends on many factors,

which include the material's inherent characteristics and environmental factors. Exposing wooden commodities to exterior conditions such as rain, wind and sun highly increases the risks of the material being damaged by biological organisms such as wood-boring insects and wood-destroying fungi. Therefore, proper design and protection of wooden products for exterior use is crucial to ensure the best service life for them as expected by the market and final users.

The main biological agents that may damage wood when used in exterior conditions of Use Class 3 (European standard EN 335) are:

- moulds and stains which are wood colonising fungi that do not cause decay but aesthetically damage the wood, thus lessening the commercial value of the product
- decay fungi, divided into brown rot, white rot and soft rot fungi, which cause severe mass and strength losses to wood
- Wood boring insects and termites, which feed on different wood compounds (starch, cellulose) and thus cause significant damage

Biological agents usually attack the exterior part of the wood (sapwood), which constitute the non-durable part of wood. However, heartwood has normally natural durability, which may vary from "highly durable" (Durability Class 1, European standard EN 350-2) to "non-durable" (Durability Class 5), depending on the wood species. In order to ensure the best service life, non-durable wood must be treated according to a carefully chosen wood preservation procedure (surface application or impregnation with biocidal products, wood modification, physical protection, etc.). The choice of a particular wood protection technology should be dictated by the wood natural durability (durability class), its susceptibility to preservative treatments (impregnability) and its exposure to environmental parameters (use class). However, assigning a wooden commodity to a specific Use Class is often difficult and controversial. Additionally, current knowledge about what the reference life in service of exterior wood structures should be is still limited. As a consequence, biological damage (mainly fungal decay) is frequently reported, chiefly caused by inappropriate use of wood, poor design and bad maintenance generating water traps and increasing the moisture content of the wood. This is particularly true about such common wooden commodities used exterior as decking, cladding, wooden houses and exterior carpentry, which are at constant risk of being prematurely damaged.

The idea for the "*Durability of Wooden Components*" research project arose from the combined desire of the French public authorities and of wood industry professionals to optimize the systematic use of biocidal preservatives meant for wood products used exterior in response to the general bad knowledge regarding proper design and use and design, and to value the natural durability of selected French wood species and in this case focusing in poplar. The general aim of this project is to improve the life expectancy of commodities made with untreated poplar and used exterior under different conditions of exposure and weathering.

EXPERIMENTAL SET UP

The current test methods used to evaluate the durability of wood species do not very well correspond with the ways of evaluating service life of finished wooden exterior

products; therefore more work is needed to improve these methods. Field tests are more time-consuming compared to laboratory tests, but they render results which more closely reflect real-life conditions (Nilsson and Edlund 1995, Brischke and Rapp 2010).

The aim of the experimental phase of the project, initiated in 2009, is to work out an experimental protocol which will make it possible to estimate, in terms of service life, the performance in a real-life situations of a range of currently used wooden commodities made of different wood species and in this case focusing in poplar from France, This will involve quantifying the impact of material, climate, exposure, and design on the expected service life of selected outdoor wooden poplar components.

The wood species

Poplar (*Populus sp.*) is one of wood species used for the study which is of economic importance for the construction industry in France. It was specifically chosen because it´s a non-durable and thus subject to attacks by insects and fungal decay (Durability class 5, i.e. non-durable according to the European Standard EN 350-2).

Including non-durable species in the experiment will allow evaluating the impact of design on fungal decay’s kinetics after a short period of time (<10 years), which would certainly not be the case with durable species. It should be noted, however, that in reality poplar is rarely used without any preservative treatment for exterior applications.

The experimental sites

Climatic parameters such as heat, rain, wind and UV radiation strongly affect the esthetic durability and susceptibility to fungal decay of wood used for exterior applications. While the test set-up may be identical, climate conditions vary from one trial to another.

In order to compare the service life of wooden commodities under different climatic conditions, four experimental sites were selected in France as follows (see Figure 1): Montpellier (Mediterranean), Charrey sur Saône (continental), Bordeaux (oceanic) and Kourou-French Guyana (tropical). Prior to initiating this experiment, climatic data were collected over the previous ten years at the selected sites and then analyzed in the last six years, focusing in the site of Bordeaux.

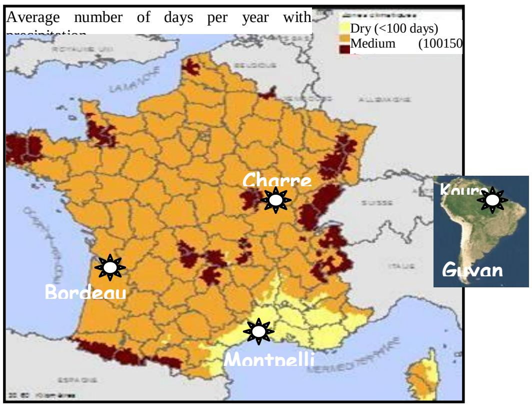

Figure 1: Locations and climatic data from the experimental sites

The wooden commodities

Deficiencies in current practices used in designing exterior wooden commodities often result in the woods excessive or abnormal moistening of wood. Wood products can contain zones where rainwater may accumulate, stagnate in a quasi-permanent way, which are generally places where fungal attacks occur. Mistakes made at the conception stage often lead to a switch of the in service situation of the wood: wooden elements initially meant for Use Class 3 are finally exposed to a level of biological risk that is higher than expected in this Use Class, such as soft rot fungi which develop more frequently on wood in Use Class 4. As a result, in situations where wooden components are not in ground contact but may permanently accumulate water due to their design or surface deposits, it may be necessary to consider that these situations are equivalent to contact with the ground or fresh water and thus require a higher level of natural or preservative-based protection.

To estimate the decay potential of different wood species under various exposure situations, various wooden commodities typically meant for exterior use were manufactured. Sets of commodities were made with poplar, one of the less durable species (set of commodities No. 1, Figure 2). Set No. 1 includes:

- A horizontal structure made of six elements (decks) that are fixed on concrete blocks;
- A house-like metallic structure with different vertical (clads, logs, posts) and inclined elements (posts) attached to it by screws. The orientation of the two sides of the structure was specifically chosen in order to have one side severely exposed to wind-driven rain and one side with less severe exposure. Both sides are comprised of exactly the same wooden elements.

A total of two No. 1 sets were exposed on each of the four selected experimental fields. Identical sets of experimental devices have been so far installed in Montpellier, Charrey sur Saône, Bordeaux and Guyana.

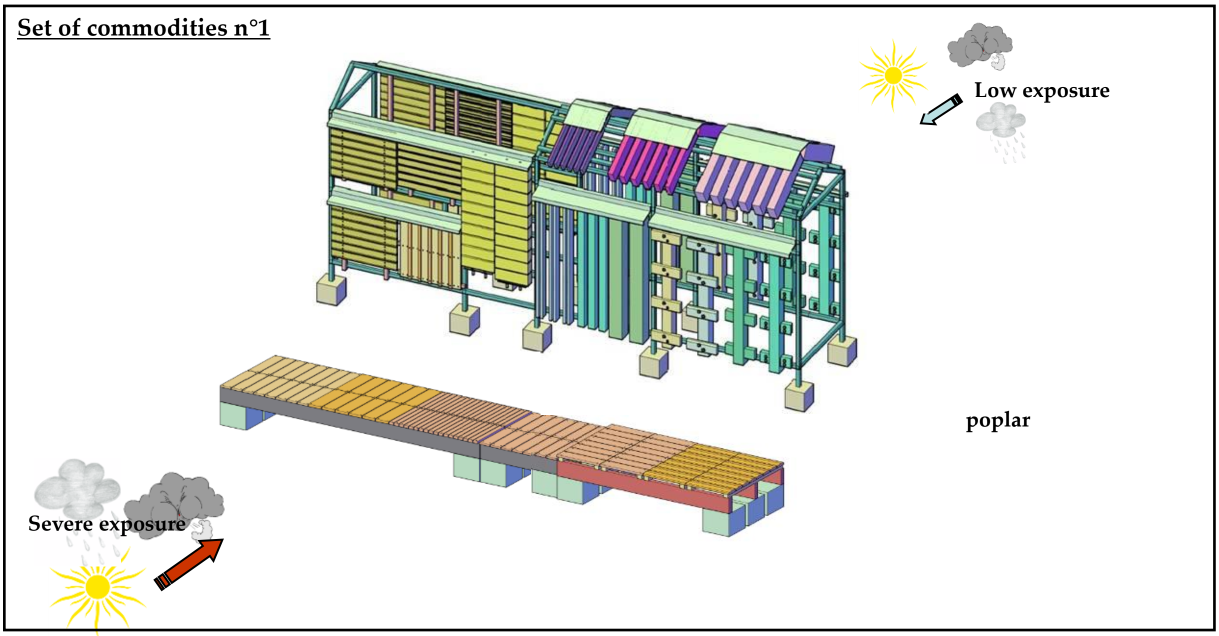

Figure 2: General presentation of the test devices installed on each experimental site

The selected designs

For each family of commodities, different designs were selected in order to progressively decrease the risk of water being entrapped in the wood.

Decks: Horizontal structures are regarded as the most severely affected by weathering because of the possibility of rain-water accumulation and stagnation on the wood's surface. Six different designs were chosen, the main differences between them being the thickness (22 or 30 mm) and the width (5 or 12 cm) of the boards, their shape (plain or slope-shaped), the way of screwing them on the joists (top or bottom screwing), and the number of wood-to-wood contact zones generating water traps (direct contact between boards and joists or insertion of nylon or rubber joints, boards overhanging the joists or not). Six different deck units (squares of 1 m x 1 m) were made of poplar, only two (with the worst and the best designs, as presented in Figure 3) with the four other species.

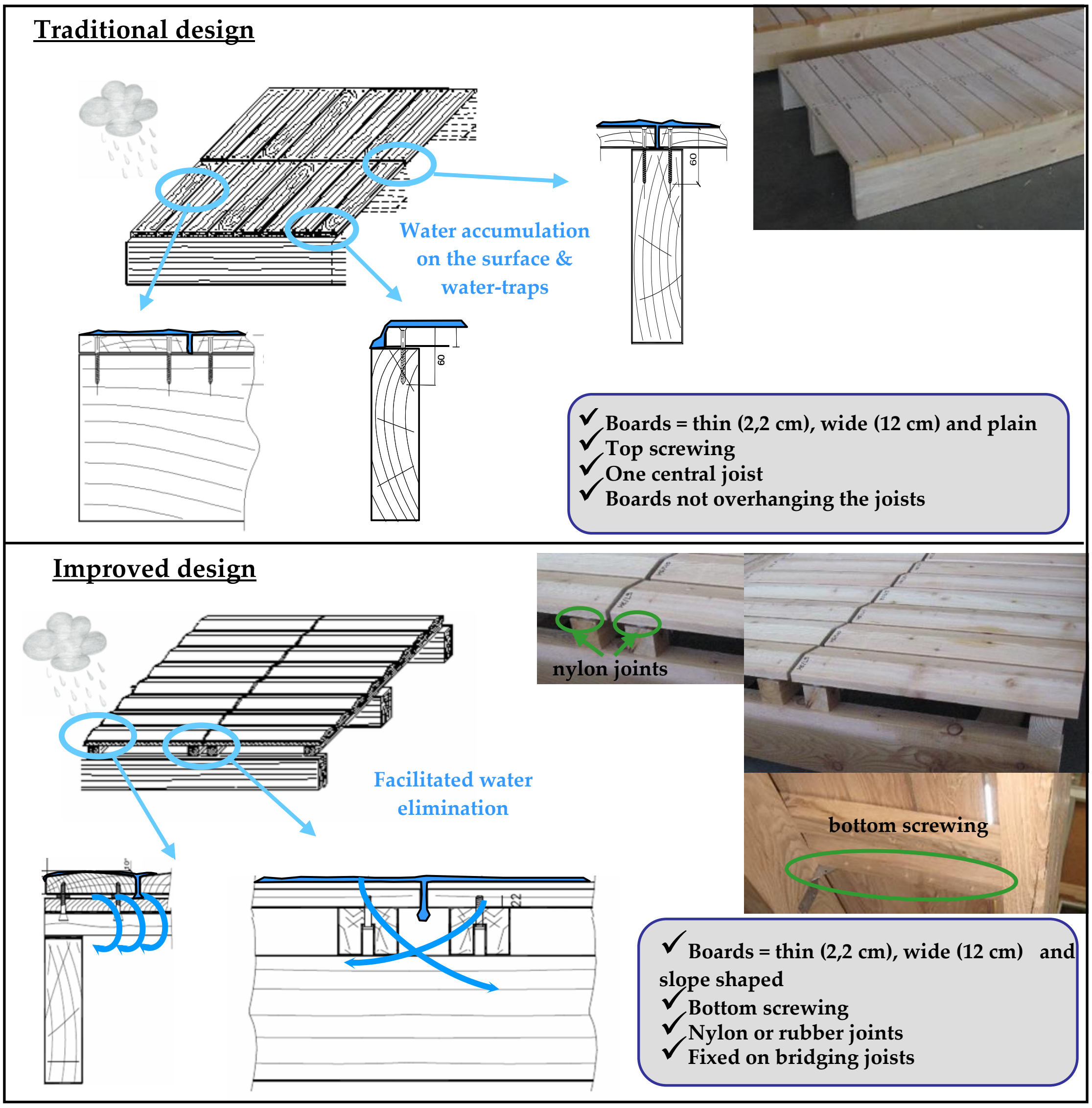

Figure 3: Examples of traditional and improved designs that have been chosen to represent the worst-case and the best-case scenario of exposure for terrace decking.

Cladding: facade elements were built after choosing four different designs, the main differences between them being the thickness (20 or 30 mm) of the test boards, the way of assembling and screwing them on the battens (tongue and groove boards with visible nails or lap joint boards with hidden nails), and the orientation of the wood's fibers (three horizontal and one vertical cladding). Each selected design was applied to manufactured cladding units of 1m x 1m.

Eight facade elements were made of poplar. The same set of elements (four elements made of poplar) was installed in situations that either allow or prevent their direct exposure to driven rain. The end-grain of the vertically exposed boards was protected from rainwater by stainless steel sheets.

Log walls: two different designs were chosen, the main differences being the shape of the logs and thus their ability to facilitate water drainage. Identical sets of log walls were installed in situations that either allow or prevent their direct exposure to driven rain. Two different walls 2 meters high and 50 cm wide were made with poplar.

Posts: the durability of wooden posts is being tested along their incline (vertical or semi-horizontal with a 10% slope) and their thickness (from 3 to 25 cm). The initial assumption is that thicker posts may be more sensitive to deformation that can generate shrinks and cracks and thus water-traps. The end-grain of the posts was protected from rainwater by stainless steel sheets.

Posts connected to beams: different kinds of joinery are being tested which are representative of traditional carpentry: the mortise and tenon joint, which has been used for centuries around the world to connect wooden elements, mainly when the adjoining pieces connect at an angle of 90°, and the cross lap joint, which occurs in the middle of two elements being at right angles to each other. Two innovative types of joint are also being tested, both including the use of stainless steel connectors which reduce the wood-to-wood contact zones and allow for efficient water drainage from the two connected elements. The posts were screwed to the metallic frames. Their end-grain was protected from rainwater by stainless steel sheets.

RESULTS AND DISCUSSION

The test specimens of poplar are exposed in different configurations producing a decay risk corresponding either to Use Class 3 or 4. The cumulated impact of the type of wood, exposure conditions and effectiveness of different protective measures by design on the service life of wooden components can be quantified through the quotation of biological and physical degradation. The progress of molds, blue stain, fungal decay as well as UV aging and the appearance of shrinks, cracks, swelling and all kinds of mechanical defects is monitored once a year, starting in 2010.

Due differences among exposure sites and different designs are expected to begin to manifest themselves only after a couple of years, the experiment will be conducted over a period of ten years.

In this case, the study is focusing in Poplar and Bordeaux site.

The poplar test specimens are evaluated yearly by rating the extent and distribution of decay according to EN 252 (1989) as: 0 (sound), 1 (slight attack), 2 (moderate attack), 3 (severe attack), or 4 (failure). Regarding to the mechanical behaviour and physical degradation of the exposed wood, swelling and shrinking as well as cracks, wooden movements were evaluated.

In the case of Bordeaux site, after six year of exposure, all the specimens located in the set of commodities No. 1 were rated a minimum of 1 for decay and depending of design even is possible to find in some test specimens in the severe exposure rating 4 (failure), the most common is rating 2 (moderate attack) and even in some cases rating 3 (severe attack).

Regard to the mechanical behaviour, physical degradation, progress UV aging and the appearance of shrinks, cracks, swelling and all kinds of mechanical defects, in the set of commodities No. 1 big differences were reported with test specimens exposed to severe exposure (South-West) where cracking, UV aging swelling and shrinking strongly affecting the wooden poplar elements in comparison with low exposure facade (North-East).

In the case of deckings, significant differences in terms of durability were found between the different designs. In the best design detail decking the majority of poplar test specimens were evaluated by rating 1 (slight attack) and 2 (moderate attack); and in the case of worst design detail decking the majority of poplar test specimens were evaluated by rating 2 (moderate attack) and 3 (severe attack) and even there are some test specimens with rating 4 (failure).

Regarding in deckings to the mechanical behaviour, physical degradation, progress UV aging and the appearance of shrinks, cracks, swelling and all kinds of mechanical defects no big differences were reported of the exposed poplar test specimens.

However, after only six year of exposure, the results need to be considered as preliminary.

CONCLUSIONS

The durability of wood is either natural or a result of appropriate treatment. Whether natural or preservative-based, it needs to be adapted to the end use of particular wooden products, commodities or structures, as their service life depends so strongly on their design and exposure to biological and physical agents.

In the case of poplar test specimens exposed in test site Bordeaux, after six year of exposure there are significant differences in terms of durability, mechanical behaviour and physical degradation

In the set of commodities No. 1 significant differences in terms of durability, mechanical behaviour and physical degradation, were reported in test specimens exposed to severe exposure in comparison with low exposure (with better results) and also depending on different designs.

In the case of deckings, significant differences in terms of durability were found between the different designs.

The research project presented here contributes to the knowledge of how to extend the service life of commodities made with untreated poplar and increase the quality and value of wood and different wooden products.

However, after only six year of exposure, the results need to be considered as preliminary.

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Poplar Wood Related Research in Hungary

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Keywords: Poplar wood, energetic use, glulam structures, oil-heat-treatment, thermo-mechanical treatment.

ABSTRACT

The aim of the poplar-related research work in Hungary is mainly about enhancing the technical performance of the poplar (*Populus x euramericana*) wood material. Poplar plantations with high growing rates deliver valuable raw material for different sectors in the wood industry (plywood, WPC's, construction wood, and even solid wood for different applications). However, there are some disadvantageous properties like low mechanical strength, low surface hardness, and nevertheless the unexciting texture and appearance. The last mentioned properties restrict the use of poplar in many fields of applications, e.g. the furniture and the flooring industry. By upgrading the unfavourable properties of poplar wood new and very promising applications could be defined. The energetic use of poplar wood is a common way for poplar utilization, but with optimization of the species selection having regard to the type of the production site it can be more efficient. Several wood modification methods like thermal treatments and thermo-mechanical treatments are a good opportunity to increase aesthetical and mechanical performance of poplar wood. However, poplar wood is traditionally not used as a material for load bearing elements, according to the mechanical performance of several poplar varieties it is also possible.

INTRODUCTION

Utilization of poplar wood has a long tradition in Hungary, thus it is used in countless utilization fields. There are several reasons for this diversified utilization of poplar wood. On the one hand, several poplar species are indigenous in Hungary, which can have significant differences in the physical and mechanical properties, e.g. *Populus alba* and *Populus nigra*. On the other hand, there is an intensive work being done in Hungary to breed new varieties (clones) with very different physical and mechanical properties, what ensures the possibility to utilize poplar wood at a large scale of utilization fields. Beside the "traditional" utilization fields of poplar wood like packaging material, crates, pallets, plywood, paper- or cellulose production, nowadays it is used also for furniture production and in the wooden architecture as well. It was used rarely for wooden architecture in the past as well, because of its good mechanical properties related to its density. But it was never a traditional building material, however several poplar species or varieties have mechanical properties close to in the building sector traditionally used Norway spruce. Research fields related to improve its properties are the different wood modification techniques and the production of different glued poplar products like LVL

or glulam elements. The use of such techniques and production of such products can widen the utilization fields of poplar wood. But of course not to forget about the well-known potential in the use of poplar varieties in the energy production as renewable raw materials. One of the most important source among the renewable energy sources, especially in Hungary, is the biomass. Researches has clearly shown that different biomasses, agricultural-, sylvicultural residues and wastes have and will have a key role in the renewal of the energy production worldwide. Despite, that Hungary has a great agricultural potential, the most important source of the biomass are the energy plantations. For energy plantations fast growing species can be taken into consideration, mainly poplar, willow or robinia. In accordance with these information, the number of both the national and international researches related to poplar wood is showing an increasing tendency. This is reflected as well in the research activity of the Institute of Wood Science at the University of West Hungary, as our research is much diversified in this topic. The range of our poplar wood related research covers the traditional wood testing, different wood modification techniques, energetic use, or utilization as a building material in the form of a glulam element.

ENERGETIC CHARACTERIZATION AND USE

The role of biologically renewable resources is continuously increasing in the energy sector. Wood plantations belong to this group, and Kyoto convention also recognized them as a tool for decreasing the emissions of greenhouse gases. Especially the fast growing species, like poplar, willow or robinia can be considered for energetic plantations. The reason for this is the high production rate of dry matter and the high sprouting capability. These plantations with short harvesting cycles can produce a large amount of biomass as a renewable energy source. To maximize the occupancy of the plantation fields, species and variety have to be chosen fitting the best for the given conditions. By choosing the variety several factors need to be considered. One of our latest research was related to the calorific value of poplar energy plantations on production sites having different quality. The energy yield of a plantation based on the calorific value is an important factor for their characterization.
According to the different characters, three production sites have been chosen in Hungary (Celldömölk, Sárvár, Borjád) (Figure 1). The investigated varieties were 2 years old ’I-214’,’Kopecky’ and a new variety bred by ERTI (Forest Research Institute). Samples were taken from 3 different heights of trees – bottom, middle and upper side. Excepting the upper side, the calorific value was determined for the xylem and the bark as well.

Figure 1: Experimental plantations of 'I-214' poplar with different production site conditions (Borjád, Celldömölk, Sárvár)

It was stated that there was no significant differnce by weight between the calorific values of the investigated varieties. However, there was a huge difference by volume (Figure 2). The best calorific value by volume was found for 'Kopecky', followed by 'ERTI' and 'I-214'. No significant differences could be found between the calorific values (by volume) of the different production sites. But if we consider the different yields of the sites and count the calorific value per hectars according to that, huge differences can be found. It can result in two times higher energy yields per hectars, if the species and variety is chosen properly, considering the conditions of the site (Figure 3).

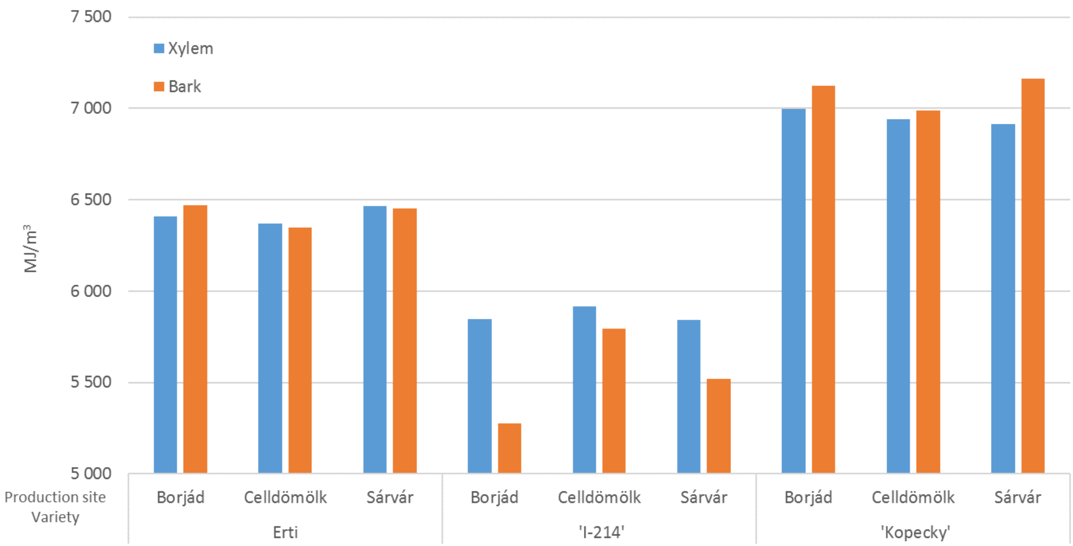

Figure 2: Calorific value of the different poplar varieties at different production sites

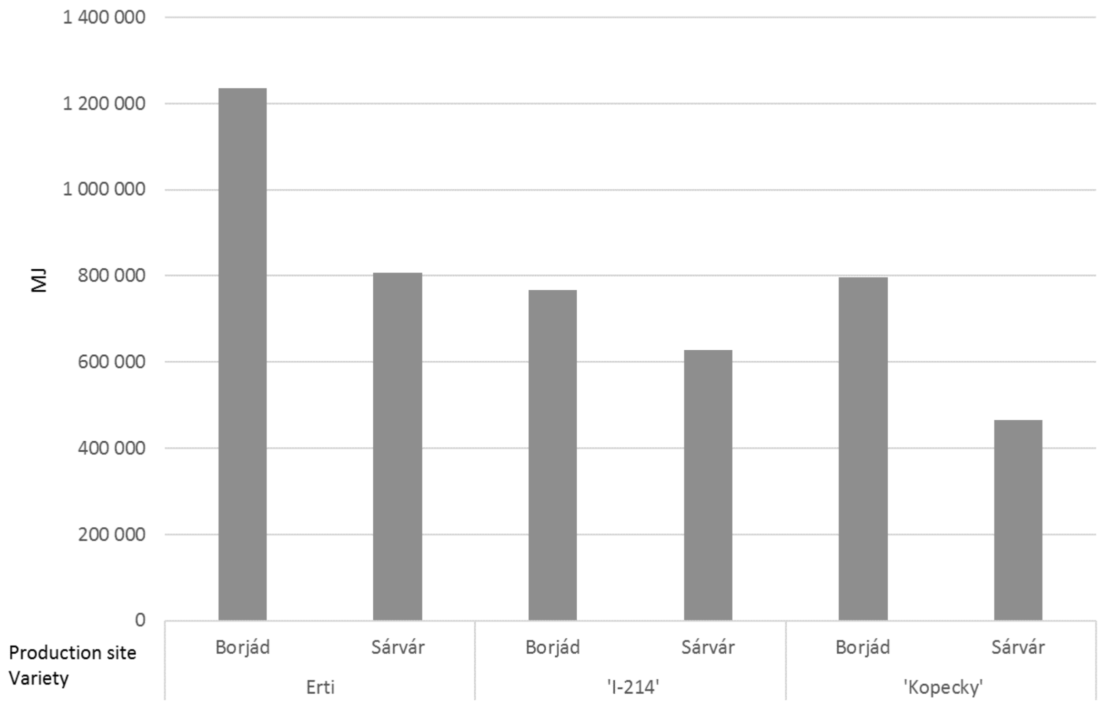

Figure 3: Calorific value of the different poplar varieties per hectare

THERMOMECHANICAL TREATMENT OF PANNONIA POPLAR (*POPULUS X EURAMERICANA* CV. 'PANNONIA')

In order to surmount the obstacles, we focussed our research work to enhance the relevant physical, mechanical and esthetical properties of poplar wood. The specific aim was to establish the scientific background for a thermo-mechanical modification method. The process should enhance the surface hardness, the strength and the appearance of this low density wood with thin fibre walls.

Poplar laths were densified in hot press across the grain at 3 different temperatures. 160°C, 180°C and 200°C. Three different starting thicknesses (25.0mm, 28.5mm and 33.3mm) were used. The final thickness of the laths was set to 20mm for all laths. Thus the grade of the densification was 20%, 30% and 40%. After the densification under heat, the wood material was kept for 10, 20 and 30 minutes in the hot press at the corresponding temperature. After the treatment the change in different material properties were studied. The investigated properties were: the colour change, moisture related shrinking and swelling, surface hardness, MOR and the grade of densification across the thickness.

Studying the total colour change, values over 3 can be found by all treatments. Thus the colour change is visible even at the lowest duration, temperature and densification grade to the naked eye (Figure 4.). As for all the three investigated colour coordinates (L*, a*, b*) showed similar changes, the ΔE* is influenced particularly by the temperature (highest changes at 200°C, 30% and 30 min.). The longer duration of the pressing treatment did not result in significantly higher total colour changes at 160°C and 180°C. The densification grade did not influence the colour change.

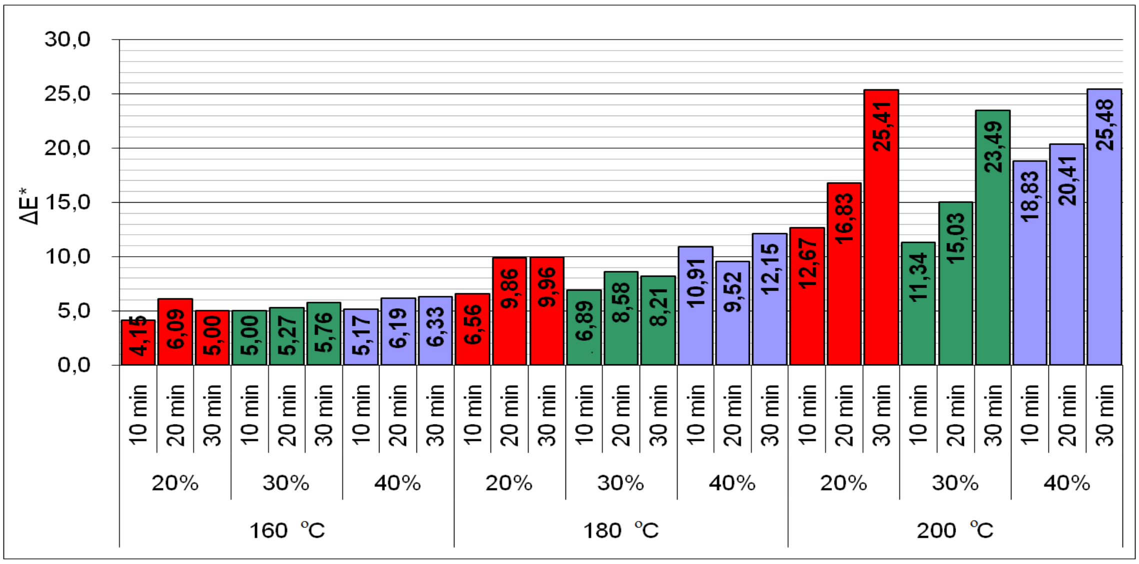

Figure 4: The effect of treatment parameters on ΔE*

One of the main targets of this research work was to enhance the surface hardness of poplar wood. The corresponding values for untreated timber were in the range of 8-11 MPa. The relative low values could be increased by the applied thermal densification method up to the range of 15-22 MPa. Figure 5 shows a clear positive effect of the treatment in terms of hardness change. From the results we can conclude that the densification grade is the most prevailing among the treatment parameters.

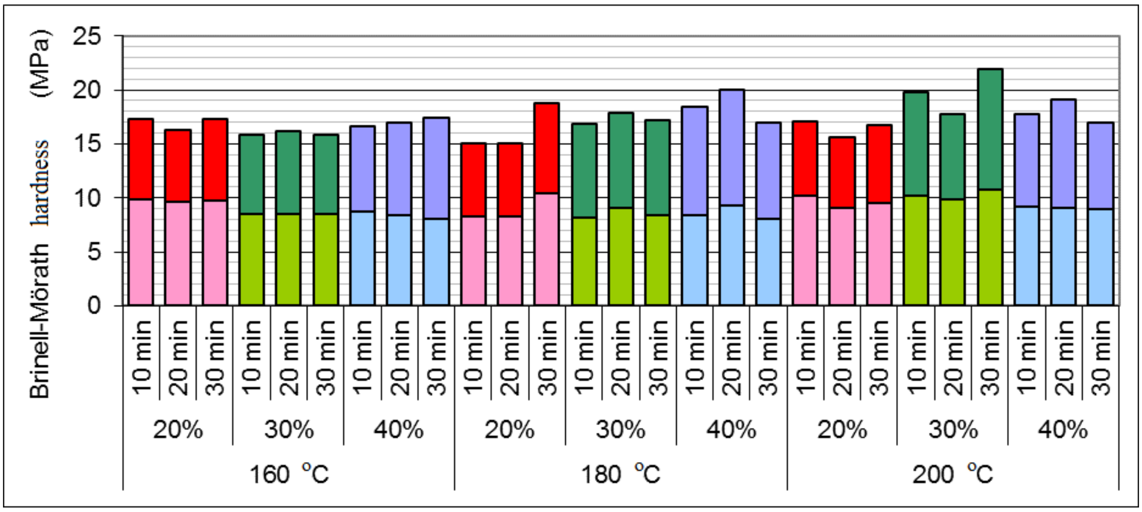

Figure 5: The effect of treatment parameters on the Brinell-Mörath hardness (light column before and dark column after the treatment respectively)

The average MOE of control material amounted to 79,85 MPa. These values could be increased to the range of 87-116 MPa. The treatments enhanced the MOE of the material. No clear influence could be proved for single treatment parameters (temperature, duration and densification grade). It has to be mentioned that the coefficient of variation (20-25% cv) for treated MOR values increased compared to the cv of the controls.

The shrinking ability was determined in three directions: parallel to the grain, across the grain and parallel to the pressing force (thickness), across the grain and perpendicular to the pressing force (width). The shrinking coefficients (treated and control) in thickness and width are shown on Figure 6. No differences could be found for shrinking parallel to the grain and in width, while in thickness considerable increase in shrinkage could be proved. At all investigated temperatures the higher densification grade resulted in higher shrinkage. Because of the relative short treatment time, the thermal treatment modified the surface only, even at the highest value (200°C). Thus no thermal degradation occurred in the inner layers, therefore, no stabilisation effect could be aimed.

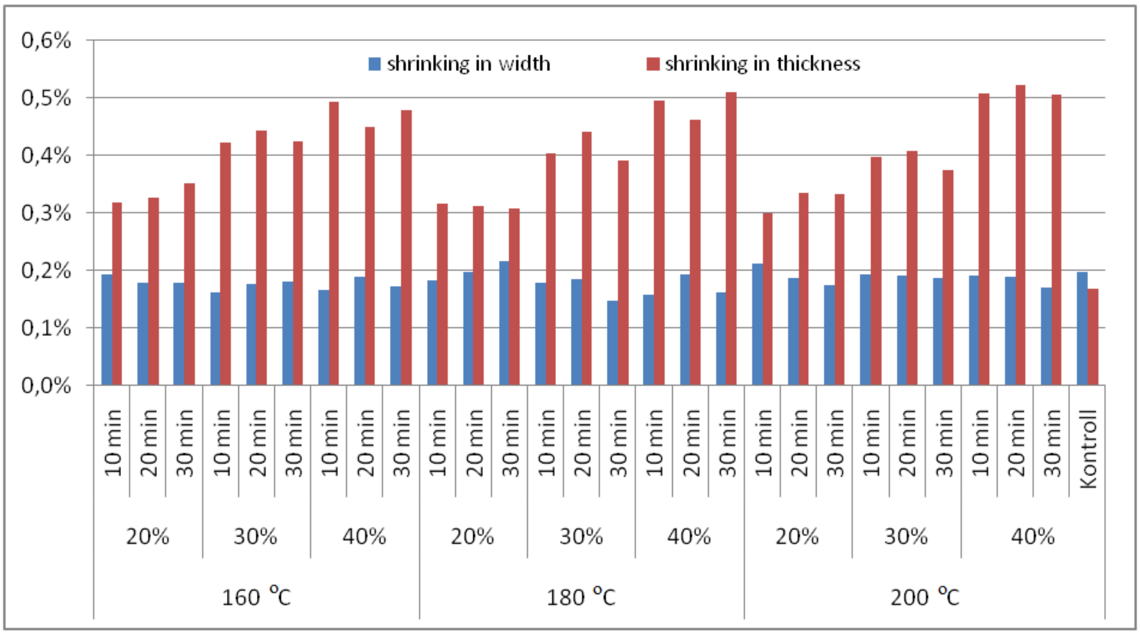

Figure 6: The effect of treatment parameters on the shrinking coefficient in width and in thickness

It was stated that there is a positive correlation between the densification grade and the ovendry density. The final density value is determined by the initial density of the laths.
It should be mentioned that the densification grade is not evenly distributed across the whole thickness. Studying the deformations of the straight lines which were drawn on the side surface of the laths prior to the treatment we can get information concerning the distribution of the densification across the (half)thickness (Figure 7). Applying the lowest bulk densification grade of 20% the local densification of the upper 1/3 layer amounts to 40%, while the inner parts show rather slow 0-10% local densifications. Applying the moderate densification grade of 30% the local densification of the upper 1/3 layer amounts to 45-50%, the second 1/3 layer shows 30% densification, while the inner part densifies ca. 10-15%. Applying the highest densification grade of 40% the local densification of the upper 1/3 layer amounts to 50-55%, the second 1/3 layer shows ca. 30%-40% densification, while the inner part densifies about 20-25%.

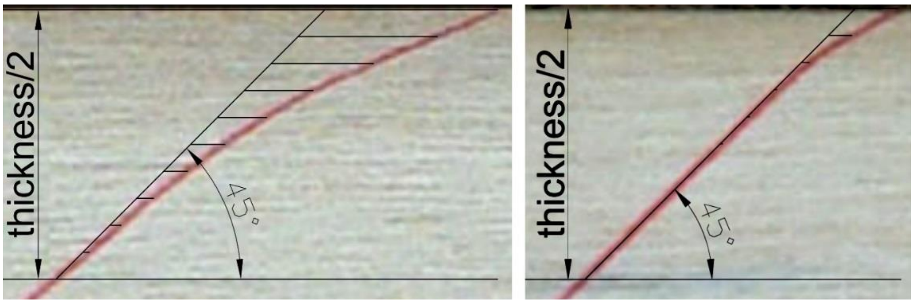

Figure 7: The densification of different layers due to densification values of 40% (left) and 20% (right)

OLEOTHERMIC TREATMENT (OHT) OF POPLAR WOOD

The interest for different heat treatment methods increased continuously during the last decades. The reason for that is the decreasing amount of accessible tropical timber with high value and durability, and of course the increasing demands on environmental friendly, or even chemical free wood preservation from both customer and governmental sides.

The thermal treatment of wood was a research topic long ago, and the processes were permanently optimized in different countries. The first trials were made already in the ’20-s, but targeted investigations only began decades later. Since that time 5 different processes have been widely used in Europe. They are: ThermoWood – Finland, Plato wood – The Netherlands, Retification and Perdure – France, and OHT (Menz Holz) Germany. The basic technology parameters are more or less the same in case of all treatment technologies (treatment temperature and time), but there are major differences in the used treatment medium. The type of the medium has essential impact on the final result, thus this is the main difference between the different technologies. Heat treatment in vegetable oils (OHT) is probably the fastest technology, because the treatment time is usually not more than 8 hours, in spite of the 10-20 hour treatment times of other technologies using gases or steam as a treatment medium. (Esteves and Pereira 2009). As a result of heat treatment the utilization fields of less used wood species can be widened. In Hungary these species are mainly plantation grown timbers like robinia (*Robinia pseudoacacia*) and poplar (*Populus × euramericana*). Mainly the utilization of poplar wood is limited only to several fields (energy, pallets, plywood and panel industry), however it is available in large quantities. With the help of heat treatment products with more added value can be produced from this material available in large quantities.

Equilibrium moisture content (EMC) of heat-treated poplar wood decreased significantly, which is strongly correlated with the improvement in dimensional stability. The dimensional stability of heat-treated poplar wood improved significantly (Figure 8) A reduction in swelling was already noticeable under the mildest treatment (160°C/2h), decreasing 21% in the radial direction and 29% in the tangential direction. The best dimensionally stabilisation was obtained at 200°C with 6 hours of treatment, as expected. This treatment resulted in a 39% decrease in the radial direction and a 46% decrease in the tangential direction. The anti-swelling efficiency in the tangential direction was higher for all treatments. The difference between ASE values in the radial and tangential directions was observed between 7 and 11%, irrespective of the treatment time and temperature. This result shows that although the swelling anisotropy decreases, it will not disappear. The result that the difference between ASE values in the radial and

tangential directions is constant by the several schedules shows, that the effect of treatment time is independent from the treatment temperature.

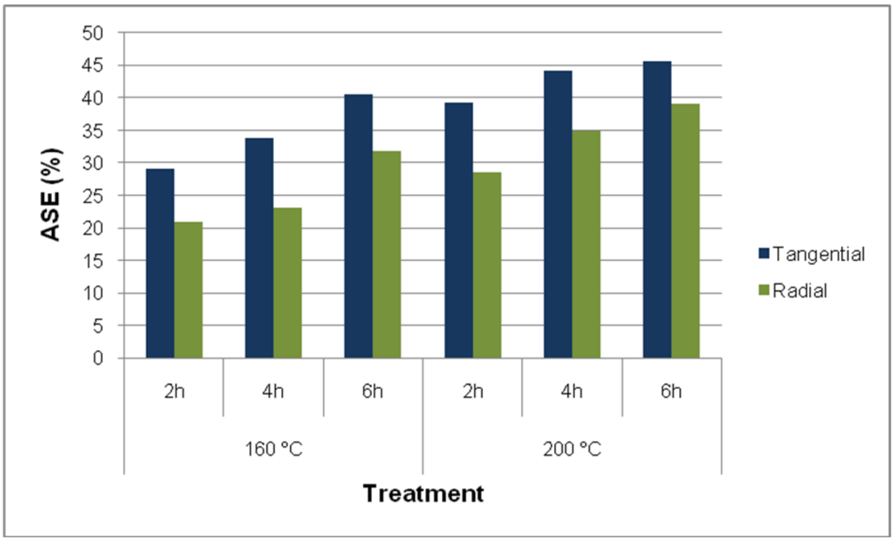

Figure 8: ASE values after OHT in linseed oil (T= 20°C, φ= 65%)

During the service life of a product the surrounding climate is regularly changing, thus the EMC, and therefore the dimensions, are changing too. These changes are usually more or less cyclic and short term. The moisture content of heat-treated specimens was lower at all of the investigated time intervals, compared to the untreated wood. The change in moisture content of oil heat-treated wood was similar to that of the untreated wood, as after 48 hours the moisture content increased only slightly, and all specimens were close to the EMC (Figure 9). It can be stated that OHT treatment reduces the moisture uptake rate because heat-treated samples adsorb less moisture during the same amount of time than untreated samples. But, considering that saturation occurs during the same time by natural and heat-treated wood, it is revealed that a decrease in the moisture uptake rate in OHT wood is due to the decrease in water storage capacity. However, a decrease in moisture uptake rate is only apparent. By dividing the reduced equilibrium moisture contents (due to OHT treatment) by the momentary moisture contents, no significant differences can be found between untreated and OHT samples. This result shows also that due to chemical changes during heat treatment, moisture uptake into the cell wall and the bounding of water molecules is not blocked, because all samples reached EMC nearly at the same time. The apparent decrease in moisture uptake rate is therefore due to the reduction in the amount of sites, which are able to bound water molecules. Namely, the water bounding capacity decreases, not the water bounding capability. Apart from that, under changing climatic conditions the use of heat-treated wood is preferable. Also, due to this apparent decrease in moisture uptake rate, swelling/shrinking will be smaller in heat-treated wood compared to natural wood for the same time interval.

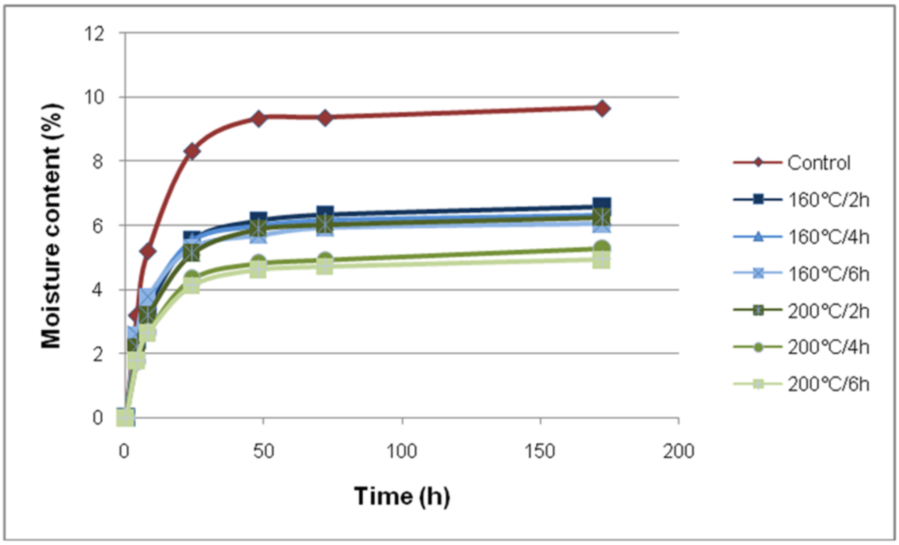

Figure 9: Changes in moisture content of OHT and untreated poplar wood at normal climate (T= 20°C, φ= 65%) as a function of time (Treatment medium: linseed oil)

In general, moisture transport through the untreated samples was significantly higher compared to the heat treated samples in both radial and tangential direction (Figure 10). As a result of heat treatments, diffusion decreased ~65% in tangential and ~80% in radial direction. As expected, diffusion of untreated material was lower in tangential direction compared to the radial direction. In case of heat treated samples these differences were diminished between the anatomical directions. Namely, in case of OHT samples the diffusion was the same in the different anatomical directions, significant differences could not be established. One reason for getting the wood more water vapour resistant as a result of heat treatment can be the decreasing hygroscopicity and equilibrium moisture content. These phenomena decrease the moisture content difference between the two surfaces of the wood, which are exposed to different climatic conditions (in this case 0% and 65% RH). Thus, the moisture gradient is becoming smaller. On the one hand this slows the moisture diffusion through the wood. On the other hand as a result of de-composition of the sorption sites during heat treatment, the distance between the hydroxyl groups in the cell wall will increase which will slow the diffusion as well. However, the diminishing the differences between the moisture transport rate of radial and tangential direction is an advantage during utilization.

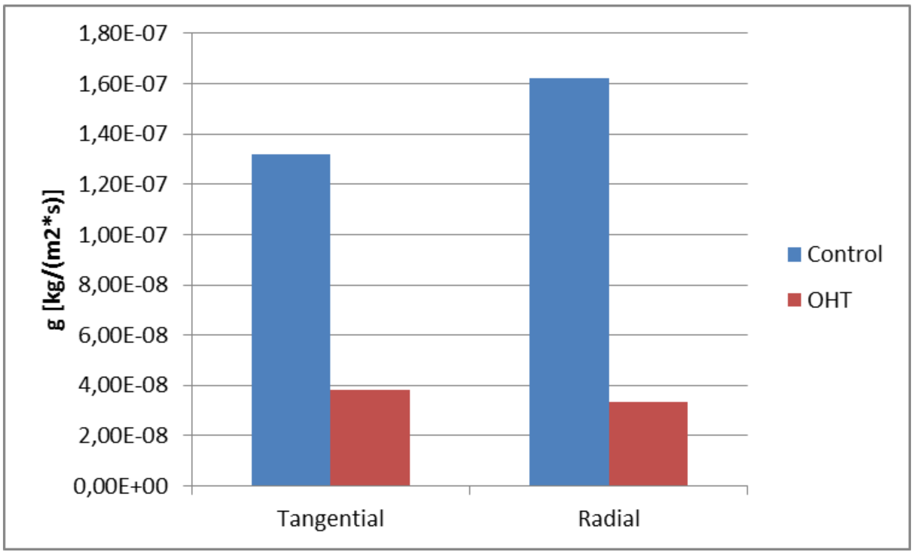

Figure 10: Density of water vapour flow rate for untreated and oil-heat-treated (OHT) wood material in tangential and radial directions

PRODUCTION OF POPLAR-BASED GLUED-LAMINATED ELEMENTS

The focus was set in this research on the poplar clone called I214 (*Populus×euramericana* cv. I 214), which is not only important and widely used in Hungary but in Europe as well. This variety is named also as suitable variety in the European standard EN 14080 which describes the requirements of glued-laminated timbers.

Material properties

Material was provided by the Pilis Forestry Company from the Middle-Hungarian region. Average density at normal climate of the material was 368,3 kg/m^3 with the standard deviation of 20,6 kg/m^3. Equilibrium moisture content at normal climate was 10,6%. Shrinking anisotropy was 1,6, which is suitable for the production of glulam products from the point of view of possible delamination.

Production of prototypes

Straight glued laminated elements were produced from the material. The lamellae dimensions were 20×70 mm. Lamellae were graded by a non-destructive equipment, which was developed at the University of West Hungary. The material was sorted to mechanical classes according to the standard EN 338. After ranking, finger jointing of the lamellae was made to the length of 2000 mm. The glue type used for the production of the glulam elements was a fibre reinforced one component polyurethane glue (Jowat 686.60). The prototypes were made of 5 layers of lamellae. For the external layers lamellae from the mechanical classes C27 and C30 were used, while for the middle layers C22 and C24. Final dimension of the prototypes was 20×70×2000 mm.
Mechanical testing of the prototypes was made with a three-point bending test according to the standard EN 408 (Figure 11). Results showed that the modulus of elasticity of the prototypes was 11316,22 MPa in average, while bending strength was 45,9 MPa. However, these results are promising, further tests are required in terms of dynamic properties or susceptibility for delamination.

Figure 11: Bending test of a poplar glulam prototype

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OHT of poplar round wood – the wood's resistance to white rot

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Keywords: *C. versicolor*, OHT, *Populus maximowiczii*, *Populus trichocarpa.*

ABSTRACT

Heat treatment is often used to improve the decay resistance of wood. The object of the research was a 3-year-old poplar wood stump of *Populus maximowiczii* and *Populus trichocarpa*. Segments of trunk in bark were subjected to Oil Heat Treatment (OHT) process at 180°C. The trunk segments in the form of roller samples were treated in hot palm oil bath. Test block wood samples were obtained from the heat treated trunk segments and subjected to ageing procedure by leaching and then tested for their resistance to fungi. The aim of the research was to determine their resistance to *Coriolus versicolor*. The estimation of wood resistance to fungi was made on the basis of mass loss after 8 weeks of incubation of the samples. The investigation into wood durability was also performed for unmodified poplar wood. Enhanced durability was observed for the modified wood. The obtained results revealed a correlation between the wood species variety and the duration of OHT process.

INTRODUCTION

Poplar wood is characterised by very low natural durability. Therefore, additional protective treatments are necessary in order to increase its resistance to wood destroying factors, including wood decay fungi. On the other hand, however, poplar wood is considered a prospective raw material due to its high mass growth rate and low price. Thermal modification is one of the commonly used methods for poplar wood durability enhancement. This method leads to the improvement of wood properties by decreasing its hygroscopicity, augmenting its dimensional stability and resistance to biotic factors (Stamm 1937, 1964, Burmester 1973, Giebeler 1983). Heat-related changes of properties are the effect of physico-chemical processes occurring in wood. The improvement of the above-mentioned properties is primarily a result of hemicelluloses degradation by the action of heat provided during modification (160-240°C). At a temperature exceeding 250°C cellulose is slowly decomposed to H_2O, CO and CO_2. Moreover, in such conditions the degree of cellulose polymerisation is significantly reduced, although its reduction from 2600 to 600 does not lead to wood mass loss (Broido 1976). Cellulose that is heated in the conditions of negative pressure and the

temperature of 200°C demonstrates increased degree of crystallinity, and non-cellulose carbohydrates at temperatures below 200°C form dextrin and branched polysaccharides (Basch 1973, 1974). This phenomenon is accompanied by the release of H_2O, CO and CO_2. Lignin, which is the most thermally resistant wood component, softens already at a temperature of 100-180°C (Hatekeyama 1969). Furthermore, at a temperature below 200°C one observes slight decomposition of lignin (Ramiach 1970). In contrast to other thermal treatments (Mazela *et al*. 2003), OHT method uses hot oil instead of protective gas, which allows the use of relatively simple apparatus and better sanitization of wood throughout its cross section. This process is usually conducted at a temperature of 180-220°C. The protective effect is a result of thermal transformation of lignocellulosic substances, and oil, as a heating medium, not only conducts thermal energy to raw material, but also protects it from the action of oxygen. The emitted gases make it impossible for the oil to penetrate wood during the process, thereby the wood subjected to modification does not absorb the heating medium (Sailer 2000). An advantage of this method is the fact that the oil present on the sample's surface after the treatment causes its fast drying. A disadvantage of this treatment is introduction of resins and other substances from wood to oil, thereby the oil changes its consistency and parameters.

EXPERIMENTAL

Wood of *Populus maximowiczii* and *Populus trichocarpa* species, originating from 3-year-old plantations, was subjected to thermal modification by OHT method. The wood, in the form of rollers in bark with a relative moisture content of approx. 20%, was subjected to a thermal treatment process by the method of hot palm oil bath. The purpose of leaving the bark on was to provide an additional protection of the samples against absorbing the oil during the modification process. Thermal modification was conducted on 230mm long rollers with a diameter of 50mm. The modification was conducted in two stages. The first stage, whose aim was to dry the wood, lasted 24h at a temperature of 100°C. The second stage lasted 24h or 48h at a temperature of 180°C. The heating medium was palm oil. Modified wood was conditioned and then block samples of the dimensions of 5x15x40 mm (the last dimension along the grain) were cut out from it with the intention of subjecting them to mycological tests. For 8 weeks the samples were exposed to *Coriolus versicolor* fungus at a relative humidity of RH=70±5% and a temperature of 22±1°C.

RESULTS AND DISCUSSION

Following thermal modification (24h), *P. maximowiczii* wood reduced its mass approximately 45% in relation to raw wood, and after successive 24h of modification the mass of the sample increased and was approximately 20% lower than the mass of unmodified sample. The considerable wood mass loss at the first stage of modification was most probably related to the loss of water contained in wood; whereas the mass increase, observed between the 24th and 48th hour of modification, could be the effect of absorption of the heating medium by the sample (Table 1). In the case of *P. trichocarpa* no significant differences in wood mass resulting from thermal modification were observed.

Table 1: Change of the mass of poplar rollers subjected to thermal modification

Wood species	Modification time at 180 °C	Sample code	Change of the samples' mass [%]	
			24h	**48h**
P. maximowiczii	24	1	65	-
P. maximowiczii	48	2	66	81
P. trichocarpa	24	3	100	-
P. trichocarpa	48	4	100	109

In the case of both *P. maximowiczii* and *P. trichocarpa* wood OHT modification had a positive effect on the wood's resistance to the test fungus. The mass loss of *P. maximowiczii* samples after 24-hour modification and exposure to *C. versicolor* was 12%, while the mass loss of non-modified wood reached 39%. As a result of OHT modification, the equilibrium moisture content (WMC) of wood decreased. After the mycological test, the moisture content of *P. maximowiczii* wood subjected to modification was 39%, while that of control wood equalled 200%. Similar results were observed for wood subjected to leaching. The mass loss of *P. maximowiczii* wood modified for 24h and non-modified wood was 12.4% and 38%, respectively. The WMC of samples after leaching was slightly lower and equalled 30% for modified wood and 187% for control samples. The mass loss of wood modified for 48h and then exposed to the fungus amounted to 14.7% and was 2.6% greater than the mass loss of wood modified for 24h. It was also observed that the moisture content of wood modified for 48h increased approx. 10% compared to wood modified for 24h. One did not observe any significant differences in mass loss of wood modified for 24h and 48h and then subjected to leaching. OHT process conducted for 24h reduced the decomposition of *P. trichocarpa* wood, and after the mycological test the mass loss of modified wood and wood not subjected to heat treatment was 12.2% and 38.4%, respectively. However, the values of WMC observed for modified wood (21%) and control samples (144%) were considerably lower than in the case of *P. maximowiczii* wood. The mass loss of samples modified for 48h was similar to the results obtained for *P. maximowiczii* wood and equalled 13.7% for modified wood and 37.7% for control samples. In this case the WMC of *P. trichocarpa* samples was also considerably lower than in the case of *P. maximowiczii* ones. The results for *P. trichocarpa* after leaching are also worthy of notice. In the case of wood modified for 24h mass loss was 8.4% (and the mass loss of control samples 39.9%), which allows classification of the wood durability to class 2. On extending the modification time to 48h, mass loss increased twice and reached 16%. Said results are presented in Table 2. In the case of both wood species, due to the possibility of undesirable absorption of the heating medium by wood during the lengthy thermal treatment (penetration along the grain), the leached samples demonstrated a higher resistance to the fungus than samples which did not undergo artificial ageing. This phenomenon could probably be explained by the additional portion of oil absorbed by the surface of the cross-section of the modified wooden elements. This oil could be an additional portion of nutrients for the test fungus, thus contributing to the increase in mass loss. On the other hand, in the case of wood subjected to artificial ageing this oil was easily leached from wood.

Table 2: Wood mass losses and wood moisture content as a result of the test fungi action

Sample Code	Non leaching					Leaching				
	Density [kg/m^3]	Mass Loss [%]	RSD	WMC after test [%]	Durability Class	Density [kg/m^3]	Mass Loss [%]	RSD	WMC after test [%] [%]	Durability Class
1	467	12.11	3.54	38.62	3	472	12.44	1.11	30.61	3
control	341	39.21	4.74	202.55		340	37.95	2.92	187.06	
2	506	14.74	1.89	49.63	3	509	12.93	1.55	41.91	3
control	329	39.75	2.58	174.09		303	37.83	2.53	205.50	
3	797	12.42	3.51	21.21	3	822	8.37	2.02	18.80	2
control	413	38.36	4.41	143.86		411	39.98	5.29	152.26	
4	568	13.68	2.24	28.64	3	604	16.00	2.41	28.52	3
control	422	37.76	2.34	142.68		349	37.47	6.63	184.63	

CONCLUSIONS

Thermal modification by OHT method enhanced the resistance of *P. maximowiczii* and P. *trichocarpa* wood to *C. versicolor*. Irrespective of the thermal treatment parameters and differences in mass loss values resulting from modification, the durability of wood of both species was reclassified from class 5 (not durable) to class 3 (moderately durable) acc. to EN350. Moreover, in the case of *T. trichocarpa* modified for 24h and subjected to leaching, a mass loss of approx. 8% allowed classification of this wood as durability class 2.

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Potential of thermally modified poplar wood for construction products

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Keywords: Poplar, willow, construction products, thermal modification, grading, gluing.

ABSTRACT

Thermal modification is a proofed technological transformation to improve the biological durability and/or the dimensional stability of wood. It has been demonstrated in literature that several modification treatments can be accurately controlled to increase the natural durability of poplar wood (originally attributed to durability class V or D5) to a durability class of preference. As such, the modification can be adapted to the end use of the intended product.

However, most treatments alter the mechanical properties of the wood. The recorded lower strength values are not critical as such, however the induced variability of the mechanical parameters (elasticity and strength) is high and mostly unpredictable. The high levels of uncertainty limit the use of thermally treated poplar beams for timber constructions.

It can be concluded that when poplar timber is used for structural applications mechanical grading should be performed. This grading will remain clone dependent, however groups of similar clones can be identified and allowed to be sorted with the same settings. Since mechanical properties for these low density hardwoods are critically influenced by features like grain direction and the related fibre angle (MFA), which are not measured today, it can be recommended to establish different settings for grading classes for the latter group of wood species (e.g. poplar, willow, eucalyptus) within EN 338.

Thermally modified poplar wood can be used for 'structural' applications with positive characteristics like enhanced durability and/or dimensional stability but also the combination light weight, sufficient stiffness and adequate thermal insulation is aimed at. Limitations at this moment are lack of a certified grading system and most probable clonal dependency of grading.

INTRODUCTION

Thermal modification is a proofed technological transformation to improve the biological durability and/or the dimensional stability of wood. It has been demonstrated in literature that several modification treatments can be accurately controlled to increase the natural durability of poplar wood (originally attributed to durability class V or D5)

to a durability class of preference. As such, the modification can be adapted to the end use of the intended product.
However, most treatments alter the mechanical properties of the wood. The recorded lower strength values are not critical as such, however the induced variability of the mechanical parameters (elasticity and strength) is high and mostly unpredictable. The high levels of uncertainty limit the use of thermally treated poplar beams for timber constructions. Figure 1 shows the selected beams for modification. It concerned 8 different clones, all of the crossing *Populus deltoides x nigra*.

Figure 1: Timber of select poplar clones for thermal treatment.

THERMAL MODIFICATION

This research reports on two thermal treatment schemes for 6 different poplar clones. The treatment process itself is based on modification by contact heat applied under elevated pressure. The modification schemes were previously characterized for the optimization towards durability classes III and II respectively. To explore the potential of the treated material for construction purposes it is essential to evaluate the potential of grading (strength control in reference to CE marking), and gluing (potential of larger constituted beams).

Grading is an essential and by law required step (CE-marking) in the production of structural sawn timber. As such, the potential of visual and mechanical grading of poplar timber was assessed. Visual grading of poplar timber is highly clone dependent. Only the clones „Robusta‟ and „Gibecq‟ could be graded according to the only approved standard NF B52-001 (EN 1912).
Yield and as such profitability still remain low, however. Other assessed clones did not show sufficient intrinsic wood properties to be appointed to the strength classes C18 and C24 as prescribed in the standard (EN 1912). It was demonstrated that „Primo‟, „Ghoy‟, „Gaver‟ and „Tardif‟ could be assessed using the same visual criteria but lower assigned strength classes, respectively C14 and C20. The lower correlations between visual defects and strength and stiffness, additionally limit the potential of

higher strength classes and the yields within. The latter also implies that for poplar timber other parameters did influence the mechanical properties more significantly. The lower prediction power of only density and knot area ratio towards bending and tensile strength is confirmed in literature.

It could be demonstrated that mechanical grading of the treated material is possible according to EN 14081 series. The beams were graded using density and dynamic modulus of elasticity. Grading was shown to be clone dependent. However, groups of clones could be detected which can be graded with the same settings. Moreover, the particular treatment process is so precise that a prediction of the strength class of the treated material is possible based on the grade of the initial poplar beams. In fact, as a function of the treatment severity (temperature and time) the initial grade dropped one to two classes after treatment. Further research is needed before industrial implementation as the number of repetitions (100 beams per clone) is insufficient when looking at the European standard and, furthermore, for this research only one dimension was used (cross section of 95 by 50 mm). The fracture mode is also a good indication of a process which allows structural wood use afterwards. Some clones display over 50% of splinter type failure (Figure 2), where others display almost 100% of brittle failure.

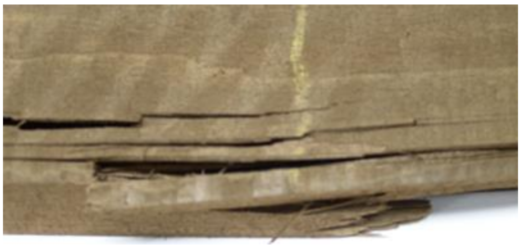

Figure 2: Grading of thermally modified timber. Example of splinter type failure.

LAMINATED BEAMS

The potential of laminated beams (Figure 3) for load-bearing (EN 14080) and non-load-bearing (EN 13307) applications was evaluated using six different glue types. Two component poly-urethane and emulsion glues show the highest potential for a qualitative bonding (Figure 3), while PVAC based glues all fail.
The investigation of the failure showed that a sufficient structural bond is not reachable using the most severely treated poplar wood (towards durability class II) as 100% of wood failure was demonstrated. The increased brittleness of the surface counters the good mechanical interlocking of the glue line. However, a durability class III is sufficient for the applications at hand. As such, the focus shifts towards a reliable grading technique to ensure that over-treated timber does not enter the production process of the laminated beams.

Figure 3: Laminated TMT poplar

A complementary study was performed to evaluate the potential of thermal treated poplar timber in combination with oak and insulation materials (PIR and XPS). For massive oak lamination a 2 component PVAC type shows the highest bonding strength according to EN 13307 while the glues suited for bonding thermally modified poplar timber did not pass the evaluation. However, when bonding thermally modified poplar to oak, again PVAC glues are well suited and surpass the set requirements. Most likely, the higher moisture absorption of the oak wood and its open structure overcomes the lower wettability of the water based PVAC glues on the modified surface.
This study concluded that thermally treated poplar wood can be suitable for laminated timber constructions and window joinery. The only drawback remains the dependency of the necessary underlying grading system on the clone or clonal group.

CONCLUSIONS

It can be concluded that when poplar timber is used for structural applications mechanical grading should be performed. This grading will remain clone dependent, however groups of similar clones can be identified and allowed to be sorted with the same settings. Since mechanical properties for these low density hardwoods are critically influenced by features like grain direction and the related fibre angle (MFA), which are not measured today, it can be recommended to establish different settings for grading classes for the latter group of wood species (e.g. poplar, willow, eucalyptus) within EN 338.

Thermally modified poplar wood can be used for ‘structural’ applications with positive characteristics like enhanced durability and/or dimensional stability but also the combination light weight, sufficient stiffness and adequate thermal insulation is aimed at. Current limitations are the lack of a certified grading system and most probably clonal dependence of grading.

ACKNOWLEDGEMENTS

We greatly acknowledge the company Lignius for facilitating the heat treatment process. The results presented are related to several INBO projects (Flemish Region), the project DO-IT HOUTBOUW (Flemish region) and a PROFCOL project (Walloon Region).

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Bending properties of tangentially and radially sawn European aspen and silver birch wood after industrial scale thermo-mechanical modification

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Keywords: Aspen, bending, birch, grain direction, modification, MOE, MOR.

ABSTRACT

A process of thermo-mechanical timber modification (TMTM^{TM}), developed and commercialised by a company Nextimber Ltd in Finland, enables drying, compression and thermal modification of sawn timber in a single treatment unit. The aim of this study was to analyse the effect of sawing pattern on modulus of elasticity (MOE) and modulus of rupture (MOR) of TMTM^{TM} modified European aspen (*Populus tremula* L.) and silver birch (*Betula pendula* Roth) wood. Total of 79 tangentially and 33 radially sawn aspen boards, and 73 tangentially and 31 radially sawn birch boards were produced for study material. All boards had green cut dimensions of 40 × 100 × 2,700 mm^3. Modifications were carried out in two optional ways: the compression was started either on green state or after pre-drying to approximately 20% MC. After the compression phase, half of the boards were thermally modified at 190°C. The entire modification process lasted for 52 hours. Small clear wood specimens were sawn from the boards, conditioned in normal climate, and analysed, as a rule, according to ISO 3349 and ISO 3133 to determine MOE and MOR, respectively. MOE of aspen increased in all treatments and MOE of birch in thermal treatments. MOR of aspen increased in non-thermal treatments. The results indicated smaller MOR value for aspen at 20% MC initial state than at green state. Furthermore, thermal modification increased MOE of birch and decreased MOR of both birch and aspen. This decrease indicates thermal degradation of wood material and increased degree of crystallization of cellulose structures at high temperature. MOE was greater in radially than in tangentially sawn birch boards. MOR was greater in radially sawn birch boards than in tangentially sawn boards at 20% MC initial state and without thermal modification. A possible reason for the greater response of radially sawn boards is the equal densification of both early wood and latewood layer during compression. Differences in MOE and MOR between radially and tangentially sawn aspen boards were insignificant. According to the results, compressing sawn timber by TMTM^{TM} method compensates the decreased bending strength properties of thermally modified wood.

INTRODUCTION

The density of wood has a strong correlation with mechanical properties. The average basic density of mature European aspen (*Populus tremula* L.) is 420 kg/m³ (Heräjärvi 2009) and Silver birch (*Betula pendula* Roth) 512 kg/m³ (Heräjärvi 2004) – these species representing relatively light and dense Finnish hardwoods, respectively. The inherent mechanical properties of wood have often been tried to get improved with various modification methods, including compression (Kollman and Côté 1984).

Compression is a process where the density of wood increases as the void volume of lumens decreases (Navi and Sandberg 2012). The viscoelastic behavior of wood plays an essential role in compression. When heated, wood softens, with the lignin, hemicellulose and cellulose displaying different softening behavior depending upon the temperature and moisture content (Hillis and Rozsa 1978, Uhmeir *et al.* 1998). Above its glass transition temperature wood can be compressed without rupturing the cell walls (Rautkari *et al.* 2011).

After compression, cellular structure of wood changes either temporarily or permanently (Sandberg *et al.* 2013). Structural changes in cell wall have a substantial effect on the strength and dimensional stability of wood. Compression has a positive impact on hardness, bending strength and compression strength but its effect on shear and tensile strength is negative (Möttönen *et al.* 2015).

Densified wood has a tendency to recover back to its original shape as a result of variation in temperature and moisture. This springback effect prevents the use of densified wood in applications with high dimensional accuracy requirements. However, one of the emerging methods in wood modification is the combined use of temperature, moisture, and compression, *i.e.* Thermo-Hydro-Mechanical (THM) treatment (Navi and Sandberg 2012). This combination makes possible to increase the density of wood and simultaneously reduce the set-recovery problem. Also the colour of wood darkens. Still, the set-recovery problem has not been totally solved and only few industrial THM systems exist.

According to Shi *et al.* (2007), thermal treatment increases modulus of elasticity (MOE) both for aspen (*Populus* spp.) and birch (*Betula* spp) and modulus of rupture (MOR) for birch but decreases MOR on aspen. Also Heräjärvi *et al.* (2009) noticed increase in MOE and decrease in MOR in thermally modified European aspen compared with conventionally dried specimens. Contrary to this, Gong *et al.* (2010) observed that heat-treatment decreased the MOE of aspen, densification increased MOE, and combined densification and thermal treatment resulted in slightly decreased MOE compared with the reference samples. Johansson and Morén (2006) observed reduction in bending strength of thermally treated birch clearwood compared with untreated birch.

A process of thermo-mechanical timber modification (TMTM™), developed and commercialised by a company Nextimber Ltd in Finland, enables drying, compression and thermal modification of sawn timber in a single treatment unit. The objective of this study was to investigate the effect of TMTM™ modification on modulus of elasticity (MOE) and modulus of rupture (MOR) in European aspen and silver birch wood.

EXPERIMENTAL

Altogether 79 tangentially and 33 radially sawn (in total 112) European aspen (*Populus tremula* L.) boards, and 73 tangentially and 31 radially sawn (in total 104) silver birch (*Betula pendula* Roth) boards were sawn from freshly harvested logs to nominal cross-cut dimensions of 40 mm × 100 mm for modification. Logs were procured from final fellings from fresh heath forests: birch logs (100 years) from Maaninka, Finland and aspen logs (50–70 years) from Kuopio, Finland. Diameter of logs was over 25 cm.

The boards were modified using four different combinations of compression, initial moisture content and thermal modification (Table 1). The modifications were executed in a pilot modification kiln. Specimens for gravimetric moisture content (MC) and basic density measurements were cut from the ends of the boards before modification treatments. The length of the boards was then adjusted to 2,700 mm, which corresponds to the effective length of the modification kiln (Figures 1 and 2).

Table 1: Wood species, initial moisture content, target degree of compression, and thermal modifications used in the process.

Species	N, tangential	N, radial	N, total	Initial moisture in compression	Target degree of compression	Thermal modification
Aspen	19	9	28	Green	30%	–
Aspen	20	8	28	Green	30%	3 h at 190°C
Aspen	20	8	28	20 % MC	30%	–
Aspen	20	8	28	20 % MC	30%	3 h at 190°C
Aspen[a]	20	8	28	–	–	–
Birch	20	8	28	Green	10%	–
Birch	20	8	28	Green	10%	3 h at 190°C
Birch	16	8	24	20 % MC	10%	–
Birch	17	7	24	20 % MC	10%	3 h at 190°C
Birch[a]	5	7	12	–	–	–

[a]*Reference group*

Figure 1 and 2: A set of boards (40 × 100 × 2,700 mm³) before and after the modification. Photos: Nextimber Ltd.

The modification system allows drying, compressing and thermal modification in a single process, and different combinations of process and modification parameters can be used. The boards are stacked between aluminium plates structured of hollow pipes and the compression is executed using hydraulic press in the kiln. The kiln air circulates through the hollow aluminium plates which are also perforated in order to enable moisture evaporation from the wood surface. Air and wood temperature, MC of wood, compression force and degree of compression (relative thickness decrease) were

monitored at two different locations in batch during the compression. In this study, compression was started either when wood was fresh or when it was pre-dried down to 20% MC.

In the two modification processes for aspen including thermal modification, the wood material had to be rewetted by immersing in water, because wood had dried down to the fibre saturation point during the storage prior to the modification.

During the process, the wood temperature was first elevated gradually up to 100 ºC in 3 hours, and stabilized until the MC of wood dropped to a level of 30%. Below the 30% MC, the wood temperature was elevated up to 130 ºC for the rest of the drying phase. The target degree of compression (relative thickness decrease) for birch and aspen were set to 10% and 30%, respectively. The different degrees of compression were based on differences in the initial basic density of the species. Further on, half of the wood material of both species was thermally modified at 190 °C after the drying and compression phases. The entire modification process lasted for 52 hours including thermal modification.

In addition, 28 aspen and 12 silver birch boards were sawn for references. The reference boards were air dried outdoors until their average MC was approximately 15%. Then they were moved indoors and further dried in the conditions of the production facilities until they reached a final MC of 8–10%.

Modulus of elasticity (MOE) and modulus of rupture (MOR) of the modified and reference specimens were determined. Tests for MOE for birch and MOR of aspen and birch were conducted using static four-point and three-point bending test method according to standards ISO 3349 (1975) and ISO 3133 (1975), respectively, with 20×20×340 mm^3 clearwood specimens from the boards. Tests for MOE of aspen was conducted using three-point bending test, otherwise the test method followed ISO 3349.

According to the standards, MOE and MOR are determined in tangential direction, but in order to determine differences between grain directions, also specimens with radial direction were tested. Specimens were tested in the direction of thickness of the original board for both tangential and radial patterns which is also parallel to the direction of compression.

Independent samples t-test was conducted to compare MOE and MOR between various combinations of compression, initial moisture content and thermal modification, and between radial and tangential grain direction.

RESULTS AND DISCUSSION

Effects of treatments and grain direction on MOE of European aspen wood

MOE of aspen increased in all treatments compared with reference samples (Figure 3). There was a clear difference in MOE between reference samples (Mean=10.9 GPa, SD=2.0 GPa) and thermally treated (G+TM, MC20+TM) samples (Mean=12.4 GPa, SD=1.9 GPa) (Table 2). No significant differences in MOE between thermal (G+TM, MC20+TM) and non-thermal (G, MC20) treatments, and between different initial

moisture contents (G, G+TM vs. MC20, MC20+TM) were observed. These results suggest that compression increases MOE but initial moisture and thermal treatment has no significant effect on it.

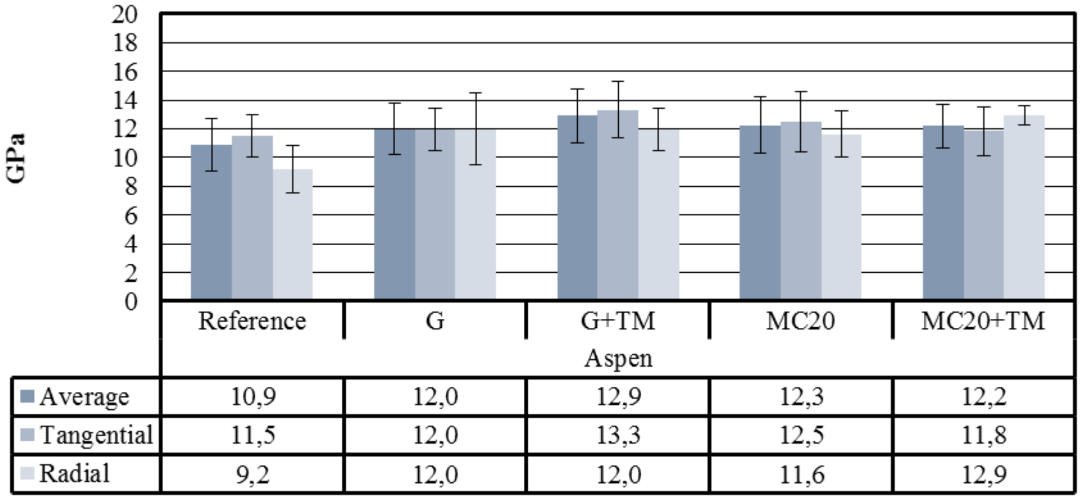


Figure 3: MOE (GPa) of aspen in tangential and radial direction in the modification groups. G = compression started with green wood, MC20 = compression started at 20% MC, TM = thermal modification.

Table 2: MOE (GPa) of aspen between modification groups, and significance of difference according to t-test.

MOE, aspen		**N**	**Mean**	**Std. Dev**	**t**	**df**	***p***
All	G, G+TM	56	12.4	2.0	0.683	110	0.496
All	MC20, MC20+TM	56	12.2	1.8			
All	G, MC20	56	12.1	1.9	-0.859	110	0.392
All	G+TM, MC20+TM	56	12.4	1.9			
All	Reference	27	10.9	1.8	-3.444	81	0.001***
All	G+TM, MC20+TM	56	12.4	1.9			

Significant difference between tangential (M=11.5 GPa, SD=1.5 GPa) and radial (M=9.2 GPa, SD=1.6 GPa) grain directions was observed only in reference group (Table 3). MOE of radial and tangential specimens did not differ between the treatment groups. Therefore, compression equalizes the differences in MOE related to grain direction in all treatments and increase in MOE caused by compression is substantial especially in radial direction.

Table 3: MOE (GPa) of aspen in tangential and radial direction in modification groups, and significance of difference according to t-test.

MOE, aspen		N	Mean	Std. Dev	t	df	*P*
Tangential	G, G+TM	39	12.6	1.9	0.893	54	0.376
Radial	G, G+TM	17	12.0	2.0			
Tangential	MC20, MC20+TM	40	12.1	2.0	-0.263	54	0.793
Radial	MC20, MC20+TM	16	12.3	1.3			
Tangential	G, MC20	39	12.2	1.8	0.783	54	0.437
Radial	G, MC20	17	11.8	2.1			
Tangential	G+TM, MC20+TM	40	12.4	2.2	-0.141	54	0.889
Radial	G+TM, MC20+TM	16	12.5	1.2			
Tangential	Reference	20	11.5	1.5	3.448	25	0.002**
Radial	Reference	7	9.2	1.6			

Effects of treatments and grain direction on MOE of silver birch wood

Effect of compression on MOE of silver birch boards was smaller than corresponding results with aspen (Figure 4). However, significant difference in MOE between non-thermal (G, MC20; Mean=14.5 GPa, SD=1.5 GPa) and thermal treatments (G+TM, MC20+TM; Mean=15.1 GPa, SD=1.5 GPa) was detected (Table 4). Combined thermal treatment and compression (G+TM, MC20+TM) increased MOE compared with reference samples (Mean=14.0 GPa, SD=1.7 GPa).

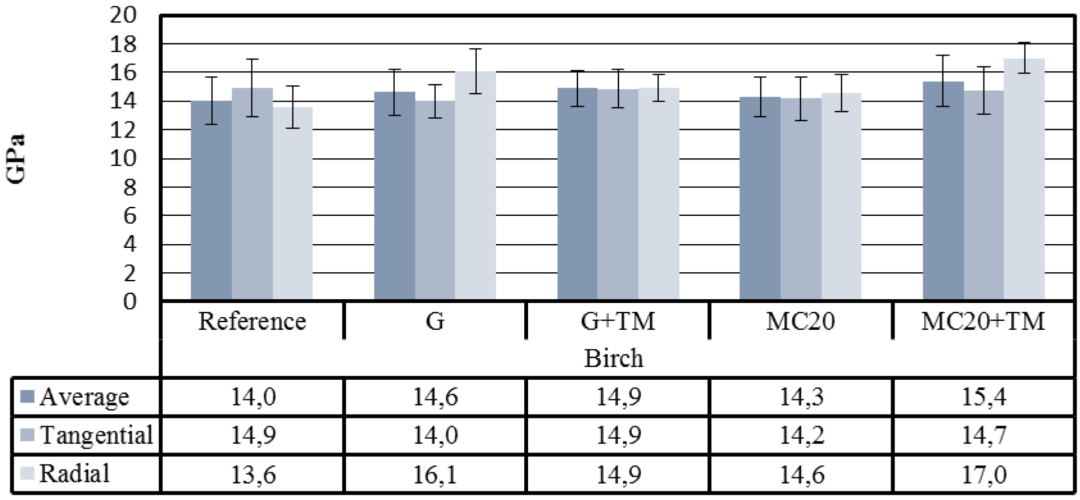


Figure 4: MOE (GPa) of birch in tangential and radial direction in the modification groups.

Table 4: MOE (GPa) of birch between modification groups, and significance of difference according to t-test.

MOE, birch	Group	N	Mean	Std. Dev	t	df	*p*
All	G, G+TM	56	14.7	1.4	-0.353	102	0.725
All	MC20, MC20+TM	48	14.9	1.7			
All	G, MC20	52	14.5	1.5	-2.211	102	0.029*
All	G+TM, MC20+TM	52	15.1	1.5			
All	Reference	12	14.0	1.7	-2.208	62	0.031*
All	G+TM, MC20+TM	52	15.1	1.5			

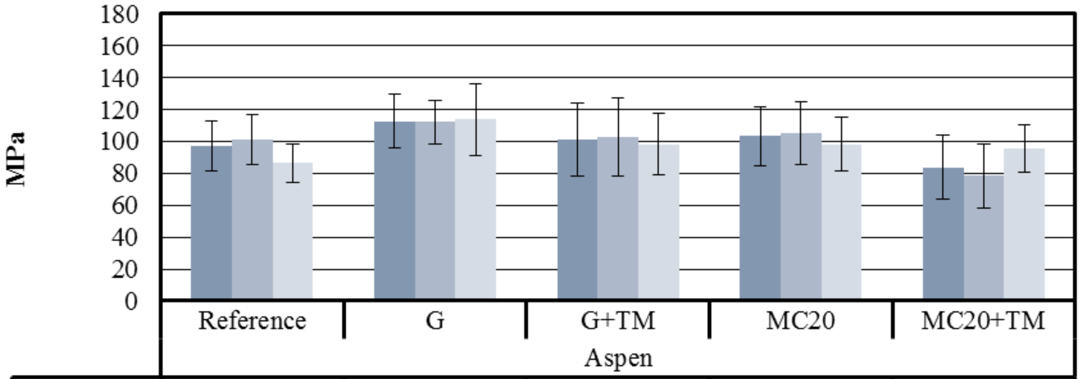
Significant differences in MOE were detected in all treatment groups between tangential and radial direction (Table 5). No differences in reference group occurred, which may be due to the small sample size. These results are completely opposite to the corresponding results with aspen. As for aspen, compression increased MOE of birch especially in radial direction.

Table 5: MOE (GPa) of birch in tangential and radial direction in modification groups, and significance of difference according to t-test.

MOE, birch	Group	N	Mean	Std. Dev	t	df	*p*
Tangential	G, G+TM	40	14.4	1.3	-2.660	54	0.010**
Radial	G, G+TM	16	15.5	1.4			
Tangential	MC20, MC20+TM	33	14.5	1.6	-2.499	46	0.016*
Radial	MC20, MC20+TM	15	15.7	1.7			
Tangential	G, MC20	36	14.1	1.3	-2.983	50	0.004**
Radial	G, MC20	16	15.3	1.6			
Tangential	G+TM, MC20+TM	37	14.8	1.5	-2.409	50	0.020*
Radial	G+TM, MC20+TM	15	15.9	1.5			
Tangential	Reference	4	14.9	2.0	1.344	10	0.209
Radial	Reference	8	13.6	1.4			

Effects of treatments and grain direction on MOR of European aspen wood

Different treatments had a strong effect to MOR of aspen (Figure 5). Significant difference occurred in MOR between green (G, G+TM; Mean=106.1 MPa, SD=22.4 MPa) and 20% (MC20, MC20+TM; Mean=92.4 MPa, SD=23.9 MPa) initial moisture contents (Table 6). Also difference was observed between non-thermal (G, MC20; Mean=108.0 MPa, SD=18.2 MPa) and thermal (G+TM, MC20+TM; Mean=90.4 MPa, SD=26.0 MPa) treatments. Thus, compression at green state increases and thermal treatment decreases MOR on aspen wood. Compression completely compensated the decreased MOR in the G+TM group.



	Reference	G	G+TM	MC20	MC20+TM
Average	97,3	112,7	101,3	103,3	83,9
Tangential	101,1	112,3	102,8	105,4	78,5
Radial	86,7	113,7	98,2	98,2	95,9

Figure 5: MOR (MPa) of aspen in tangential and radial direction in the modification groups.

Table 6: MOR (MPa) of aspen between modification groups.

MOR, aspen	Group	N	Mean	Std. Dev	t	df	*p*
All	G, G+TM	56	106.1	22.4	3.139	110	0.002**
All	MC20, MC20+TM	56	92.4	23.9			
All	G, MC20	56	108.0	18.2	4.137	110	0.000***
All	G+TM, MC20+TM	56	90.4	26.0			
All	Reference	27	97.3	15.8	1.268	81	0.209
All	G+TM, MC20+TM	56	90.4	26.0			

In MOR, no differences were detected between tangential and radial direction in combined treatment groups of aspen (Table 7).

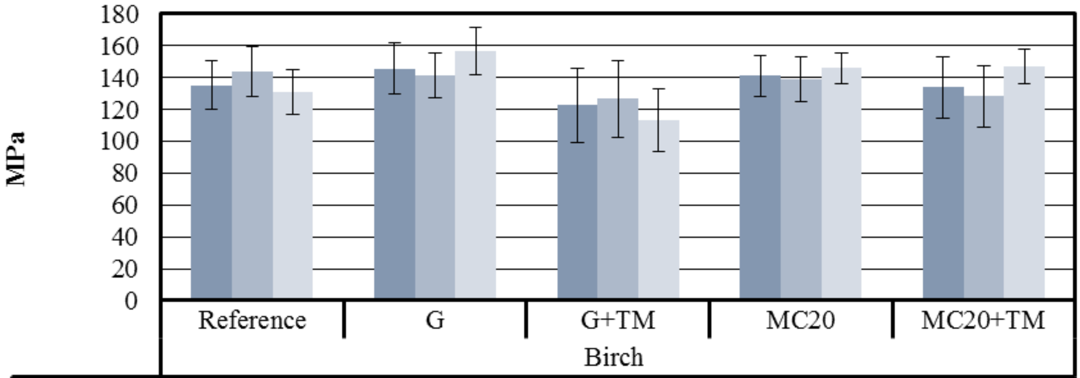
Table 7: MOR (MPa) of aspen in tangential and radial direction in modification groups, and significance of difference according to t-test.

MOR, aspen	Group	N	Mean	Std. Dev	t	df	*p*
Tangential	G, G+TM	39	105.8	22.7	-0.142	54	0.888
Radial	G, G+TM	17	106.7	22.4			
Tangential	MC20, MC20+TM	40	91.2	26.4	-0.596	54	0.554
Radial	MC20, MC20+TM	16	95.4	16.4			
Tangential	G, MC20	39	108.7	17.0	0.441	54	0.661
Radial	G, MC20	17	106.4	21.1			
Tangential	G+TM, MC20+TM	40	88.3	28.4	-0.969	54	0.889
Radial	G+TM, MC20+TM	16	95.8	18.4			
Tangential	Reference	20	101.1	15.5	2.229	25	0.350
Radial	Reference	7	86.7	12.1			

Effects of treatments and grain direction on MOR of silver birch wood

In MOR of birch boards, a difference was observed between non-thermally treated (G, MC20; Mean=143.6 MPa, SD=14.7 MPa) and thermally treated (G+TM, MC20+TM; Mean=127.9 MPa, SD=22.0 MPa) groups (Figure 6, Table 8). Thermal treatment clearly reduces MOR. However, compression compensates this effect on MOR, because in

comparison between reference boards and thermally treated boards no significant difference was detected.



	Reference	G	G+TM	MC20	MC20+TM
Average	135,3	145,7	122,8	141,1	133,8
Tangential	144,0	141,3	126,6	138,7	128,4
Radial	131,0	156,9	113,4	146,0	146,9

Figure 6: MOR (MPa) of birch in tangential and radial direction in the modification groups.

Table 8: MOR (MPa) of birch between modification groups, and significance of difference according to t-test.

MOR, birch	Group	N	Mean	Std. Dev	t	df	*p*
All	G, G+TM	56	134.3	22.9	-0.795	102	0.429
All	MC20, MC20+TM	48	137.5	16.5			
All	G, MC20	52	143.6	14.7	4.290	102	0.000***
All	G+TM, MC20+TM	52	127.9	22.0			
All	Reference	12	135.3	15.4	1.106	62	0.273
All	G+TM, MC20+TM	52	127.9	22.0			

A difference was observed between grain directions in the treatments with initial moisture of 20% (MC20, MC20+TM; tangential: Mean=133.4 MPa, SD=17.5 MPa, radial: 146.4 MPa, SD=9.9 MPa) and in non-thermal treatments (G, MC20; tangential: Mean=140.1 MPa, SD=14.0 MPa, radial: 151.5 MPa, SD=13.4 MPa) (Table 9).

Table 9: MOR (MPa) of birch in tangential and radial direction in modification groups, and significance of difference according to t-test.

MOR, birch	Group	N	Mean	Std. Dev	t	df	*p*
Tangential	G, G+TM	40	133.9	20.9	-0.179	54	0.858
Radial	G, G+TM	16	135.2	28.0			
Tangential	MC20, MC20+TM	33	133.4	17.5	-2.689	46	0.010**
Radial	MC20, MC20+TM	15	146.4	9.9			
Tangential	G, MC20	36	140.1	14.0	-2.733	50	0.009**
Radial	G, MC20	16	151.5	13.4			
Tangential	G+TM, MC20+TM	37	127.4	21.7	-0.233	50	0.817
Radial	G+TM, MC20+TM	15	129.0	23.2			
Tangential	Reference	4	144.0	15.5	1.447	10	0.178
Radial	Reference	8	131.0	14.3			

Fang *et al.* (2011) concluded that too high temperature and long compression process time might lead to loss of mechanical properties of surface because of thermal degradation. Several studies indicate that thermal treatment may even increase MOE as a result of increased degree of crystallinity of the cellulose, whereas MOR, generally, decreases (*e.g.*, Millett & Gerhards 1972, Heräjärvi 2009, Widmann *et al.* 2012, see also: Hill 2006). The decrease in bending strength might be due to the hemicellulose degradation (Kass *et al.* 1970, LeVan *et al.* 1990, Kocaefe *et al.* 2008).

According to our results, compression compensates loss of mechanical properties caused by thermal degradation especially in case of aspen.

MOE and MOR of the compressed and thermally modified aspen were clearly lower than those of birch. Standard deviation in MOE and MOR was lower in birch boards than in aspen boards.

It is probable that the compression took place mostly in the lumens of earlywood. To improve the mechanical properties in greater extent would need the compression of latewood, as well. Birch and aspen had different behavior in terms of grain direction: in general, in case of birch, modification increased MOE and MOR in radial direction whereas in aspen the increase occurred in tangential direction. In birch, a possible reason for the greater response of radially sawn boards is the equal densification of both early wood and latewood layer during compression.

CONCLUSIONS

According to our results, in general, MOE increases and MOR decreases in the TMTM™ modification process. However, joint effect of initial moisture content, compression, thermal modification and species-specific mechanical properties are complex and effect of grain orientation on MOE and MOR in birch and aspen were divergent. Compression as a part of the TMTM™ method is a potential method to compensate the decreased strength of wood caused by thermal modification especially in aspen. Thus, combined compression and thermal treatment can maintain or improve several strength properties of wood while improving other mechanical properties as hardness and dimensional stability.

ACKNOWLEDGEMENTS

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The Garnica brick: a structural insulated sandwich panel based on modified poplar plywood and an XPS core

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Keywords: Poplar, plywood, construction, fire resistance, durability.

ABSTRACT

Garnica plywood has developed several product innovations. A new product development in their laboratory and R&D department is the fire retardant poplar plywood based on veneer impregnations and meeting European, American and industry standards. Similarly, a product range was developed called DURABLE, plywood resistant to fungi and insect attack.
The newest product range GARNICA BRICK are covering prefabricated structural panels which are highly insulated. The product GARNICA BRICK S.I.P. is consisting of 12 mm Poplar plywood, DURABLE treated + 30/60/100 mm XPS Extruded polystyrene + 12 mm Poplar plywood, DURABLE treated (Figure 1). This product is intended for demanding end uses like interaction with exterior climate. With more focus on the aesthetics and link to the interior climate the product GARNICA BRICK COVER consists of 10 mm Poplar plywood, DURABLE treated + 100 mm XPS / 100 mm wood fibre + 10 mm Poplar plywood + Interior decorative finish. A wide range of interior decorative finishes is available: natural or varnished wood veneers, MDO, HPL or plasterboard. These are highly insulating, resilient panels with decorative finishes for interiors. Finally there is also GARNICA BRICK DECO without poplar veneers with an enhanced durability and consisting of: 10 mm Poplar plywood + 30/60/100 mm XPS Extruded polystyrene + 10 mm Poplar plywood.

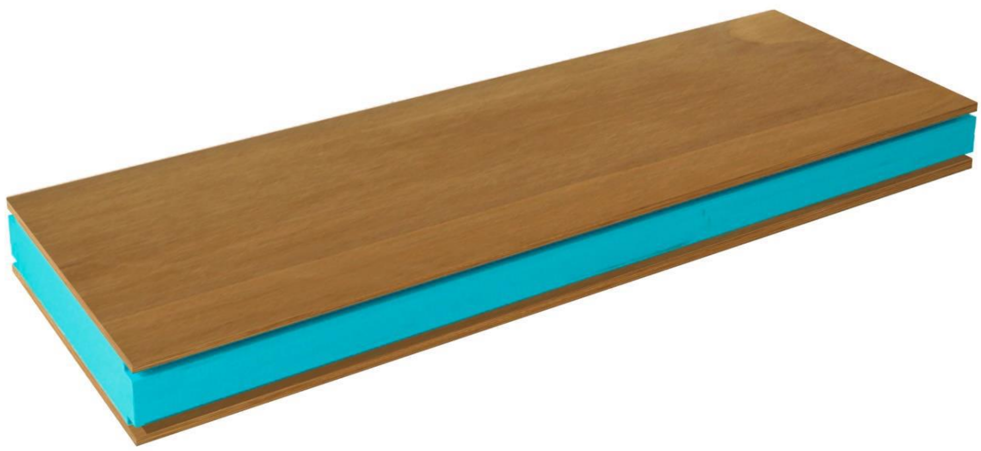

Figure 1: The GARNICA BRICK S.I.P.

Use of poplar for Wood-Polymer Composites manufacturing

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Keywords: Carbon fibre, mechanical properties, nanoparticle, physical properties, trembling aspen, wood-plastic composite, wood species.

ABSTRACT

Poplar (*Populus tremuloides* Michx) is abundant in Canada and its wood is highly valued for several applications in the wood industry including engineered wood products and pulp and paper. The use of aspen for these applications generates considerable quantities of residues suitable for wood polymer composites (WPC) manufacturing. However, the potential of this wood for this application is rarely explored. Thus, the objective of this study was to evaluate the potential of poplar fibres compared to fibres from other species for WPC manufacturing and to investigate the impact of carbon fibres and nanoparticles on the poplar WPC properties. The wood fibres were characterized for mass chemical composition and fibre morphology. WPC samples were formed by twin screw extrusion compounding, followed by injection moulding at fibre proportions ranging from 0% to 40%. Additives (carbon fibres, nanoparticles, compatibility agent) and fibres were mixed with the polymer in the extrusion step. Maleated polyethylene (MAPE) and maleated polypropylene (MAPP) were used as compatibility agent between wood fibres and high density polyethylene (HDPE) and polypropylene (PP), respectively. Compared to black spruce and white birch, poplar resulted in the best WPC physical and mechanical properties. This result is explained by the surface properties and physical characteristics of the poplar wood fibres. The addition of poplar fibres in the polymer matrix increased the bending modulus by up to 208% and the bending strength by up to 122%. The addition of carbon fibres in WPC formulations increased the bending modulus by up to 61% and the bending strength by up to 45%. However, the use of mineral nanoparticles had a negative effect on the performance of WPC. This result is explained by the bad dispersion of the nanoparticles in the composite.

INTRODUCTION

Trembling aspen (*Populus tremuloides michx*) is abundant in Canada and its wood is highly valued for structural engineered wood products such as oriented strand boards (OSB) and laminated veneer lumber (LVL). The use of poplar for these applications generates considerable quantities of small size residues from chipping, peeling, sanding,

etc. These residues are mainly used for energy but have good potential for wood-polymer composites (WPC) manufacturing. Thus, the objective of this study was to evaluate the potential of poplar fibres compared to fibres from other species for WPC manufacturing and to investigate the impact of carbon fibres and nanoparticles addition on the poplar WPC properties.

EXPERIMENTAL

Material collection and preparation

Five different fibres were sampled from industrial wood mills in the province of Quebec in eastern Canada: Poplar (trembling aspen*)*, black spruce and white birch wood fibres along with poplar and black spruce bark fibres were used. Prior to composite processing, fibres were air-dried to a moisture content of about 10% (dry basis). Fibres were then milled with a Wiley laboratory mill Model 4 and sieved with a Ro-Tap laboratory sieve shaker. The mill was mounted with a 2-mm opening sieve and the 150-710 µm opening fraction (100 to 25 US mesh) was kept from the sieve shaker. Finally, fibres were oven-dried at 80°C to approximately 3% moisture content.

Maleated polyethylene (MAPE) and maleated polypropylene (MAPP) were used as compatibility agent. Chopped carbon fibres (Panex, type-65) were supplied by Zoltek (Bridgeton, Missouri, USA). Its unpacked bulk density is 0.42 g/cm³, and the fibres are chopped at 6 mm in length. The tested proportions of carbon fibres in WPC were 0%, 3%, 6%, and 9%.

Three types of nanoparticles were used in this study: Aluminium oxide (Aeroxide Alu C805, highly dispersed hydrophilic fumed aluminium oxide treated with octylsilane), Silicate (Aeorosil R805, hydrophilic fumed silica treated with octylsilane), and montmorillonite (modified with quaternary ammonium, treated with methyl benzyl dehydrogenated tallow). The tested proportions of nanoparticles in WPC were 0%, 1%, 3%, and 5%.

High density polyethylene (HDPE) (DMDA-8907, Dow Chemical, USA) and polypropylene (PP) (4150H, Pinnacle Polymers, USA) were used as matrix. PP was used in carbon fibres WPC only. All other formulations are made with HDPE.

Fibre characterization

The mass chemical composition of fibres (cellulose, lignin, extractives, and ash) was measured using standard extraction methods for wood. The dried material was placed in an airtight container to homogenize the moisture content. Cellulose content was determined by Kürschner and Hoffer's nitric acid method (Browning 1967). Pentosan content was obtained according to ASTM D 1787. Lignin content was determined according to ASTM D 1106 (methoxyl group) with modification according to Rowell (2005). Ethanol-toluene extractives content was determined according to ASTM D 1107. Hot water extractives content was determined according to ASTM D 1110. Ash content was determined by combustion in a muffle furnace at 600°C according to ASTM D 1102 standard. Fibre length and width were measured using OPTEST fibre

quality analyzer. Each average length and width were obtained from three samples of 5 000 fibres each. Wood-plastic composite (WPC) processing and characterization
All composites were prepared in two stages: compounding for pelletizing followed by injection moulding. A counter-rotating intermeshing conical twin-screw extruder (Thermo Scientific HAAKE PolyLab OS Rheodrive 7 with Rheomex OS extruding module) was used for compounding all components (fibres, polymer, nanoparticles, additives). The screws were 30 mm in diameter at the large end and 340 mm long, and a 3-mm diameter die was used. Screw speed was 30 rpm and barrel and die temperature was 155°C. The extrudate was cooled in a water bath and ground into 3-mm long WPC pellets.

Samples were moulded for bending, and impact specimens with an Arburg 370 A (600 kN) injection moulding machine. Injection moulding parameters were 30°C mould temperature, 160 MPa injection pressure, 1.6 s injection time, 70 MPa holding pressure, 9 s holding time, 180°C barrel and nozzle temperature, and 17 s cooling time. All specimens were 3.18 mm thick. Bending and impact type specimens were 12.7 mm wide. Bending and impact specimens were 127 mm and 63.5 mm long, respectively.

WPC specimens were characterized according to ASTM D 1037 standard for water uptake and thickness swell (TS) of water-soaked samples. Measurements were repeated three times on bending type specimens. Three-point bending properties were measured according to ASTM D 790 standard with a span-to-depth ratio of 16:1 and at a speed of 1.4 mm/min. Unnotched cantilever Beam impact resistance was measured according to ASTM D 4812. Bending tests were repeated 6 times and impact tests were repeated 15 times.

RESULTS AND DISCUSSION

Wood fibres chemical composition and morphology

Table 1 presents the mass chemical composition of the different fibres. The cellulose contents found for the three wood species in the present study are in good agreement with previously reported values. Poplar wood has higher cellulose content than white birch wood, and hardwoods have higher cellulose content than softwoods. Cellulose is the structural component of wood and thus indicates the reinforcing potential for WPC. Bark generally has lower cellulose content than wood. As reported, the lignin content of spruce wood is higher than that of poplar and birch woods (Rowell 2005). There are also some variations of extractives content across wood species. Barks have the highest level of extractives (sum of ethanol-toluene and hot water extractives). The ash contents in Table 1 are typical for wood, and are due to the minerals present in wood cell walls and extractives (Rowell 2005). Bark showed ash contents in the range 1% to 5%. The higher ash content in bark than in wood is due to bark's higher inorganic content. Barks may also contain contamination with sand or dirt resulting from contact with the ground (e.g., after logging).

Table 1 shows the morphological characteristics of the fibres. Fibre aspect ratio (length/width) is presented in Table 1. Despite that fibres were milled and sieved with the same parameters, their aspect ratio varied slightly between 2.5 and 5.8. Poplar wood and spruce wood fibres are more slender with an aspect ratio of 5.8 while birch fibres

were the shortest with an aspect ratio of 2.5. As reported, the mechanical properties of WPC increased with increasing aspect ratio (Migneault *et al.* 2007). Thus, poplar and spruce wood are the best candidates for WPC manufacturing in terms of fibre morphology. These differences are explained by the fact that the different materials reacted differently to the milling and sieving processes; some wood species produce particles with a slender shape than others. The strength of the fibres in their axial direction is likely to produce long particles and high aspect ratio. This fibrous behaviour is usually promoted by a high cellulose content and a low micro fibril angle. It was also noted that particles can pass through the lengthwise direction in the sieve opening. These results show that the processing ability of the fibres is different and that the use of a sieve size as reference to fibre size can be misleading.

Table 1: Chemical composition and morphology of the different fibres used in WPC formulations

Fibre species/type	Cellulose [%]	Lignin [%]	Extractives* [%]	Ash [%]	Aspect ratio
Aspen wood	50.7	21.9	5.0	0.67	5.8
Birch wood	47.3	22.1	3.5	0.27	2.5
Spruce wood	43.0	27.0	5.0	0.3	5.8
Aspen bark	32.0	17.0	17.6	5.3	4.1
Spruce bark	33.5	16.4	20.3	1.6	4.6

* Sum of ethanol-toluene and hot water extractives.

Effect of wood species on WPC properties

The mechanical properties of the WPC are presented in Table 2. The addition of all fibre types resulted in a reinforcement of the HDPE matrix in terms of stiffness and strength. These results suggest good fibre dispersion and good fibre-matrix coupling. A great decrease of toughness compared to pure HDPE was observed with the addition of fibres, as expected. The highest reinforcement was observed with the poplar wood fibres, and the lowest reinforcement was observed with the bark fibres. Yemele *et al.* (2010) reported that bark is generally acts as filler rather than as reinforcement. Compared to all other composites, WPC with poplar fibres were the most dimensionally stable when immersed in water while those with birch fibres were the less stable (Table 2).

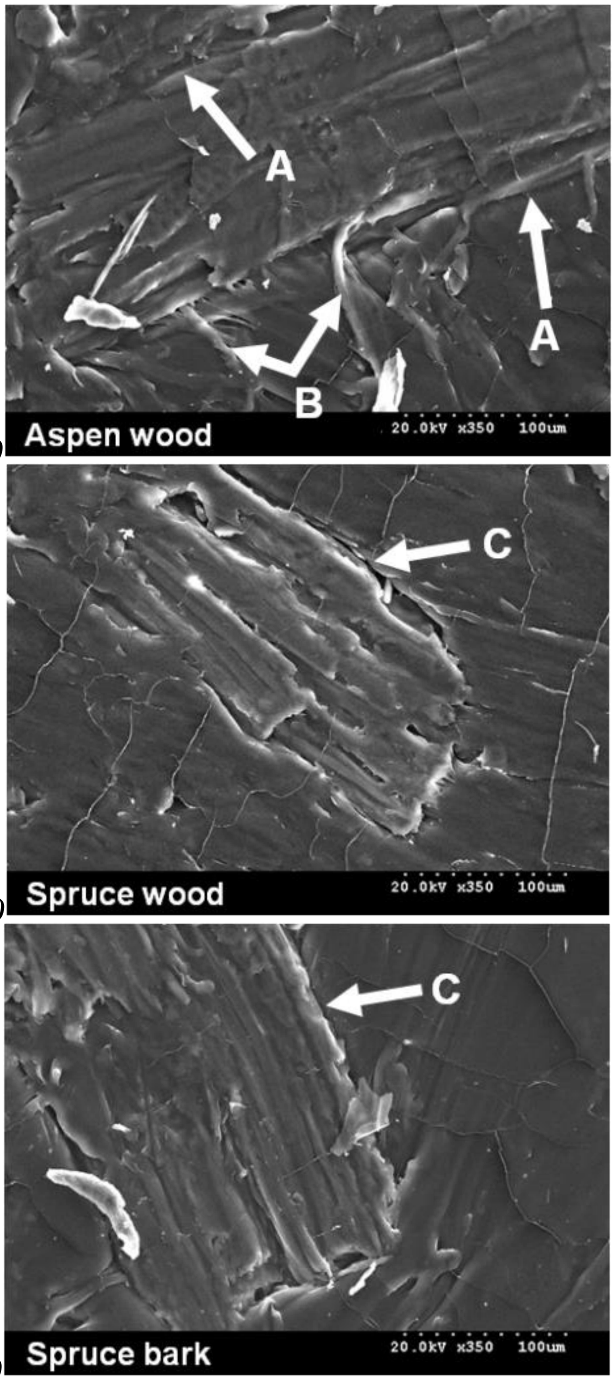
Table 2: Flexure, impact, and thickness swell of the WPC made with 40% of wood and bark fibres from different species

Fibre species/type	MOE [GPa]	MOR [MPa]	Impact energy [kJ/m²]	Thickness swell* [%]
Aspen wood	2.55	52.9	18.1	1.07
Birch wood	2.31	49.2	15.3	2.17
Spruce wood	2.45	46.9	11.7	1.27
Aspen bark	1.38	32.9	10.7	1.63
Spruce bark	1.42	33.7	9.4	2.15
None (HDPE)	0.56	19.9	-	-

* After 672 hours of water immersion

Scanning electron micrographs showed variations in wetting at the fibre-matrix interface among the different fibres investigated (Figure 1). For example, aspen fibres are completely wetted (Figure 1a) whereas spruce fibres are not in close contact with HDPE matrix (Figure 1b). Bark fibres are not completely wetted either (Figure 1c). Micrographs also showed variations in mechanical adhesion and interlocking at the

fibre-matrix interface among the different fibres investigated. Poplar fibres have macro-fibrils at the surface interlocking with the polymer matrix, thus increasing fibre reinforcement (noted B, Figure 1a). The wetting and interlocking phenomena suggest a superior stress transfer in the case of poplar wood fibres. This finding explains the better performance of this fibre type among the three wood fibres used in the present study.



a) *b)* *c)*

Figure 1: Scanning electron micrographs at 350x enlargement at the surface of the WPC samples made with a) aspen wood, b) spruce wood, and c) spruce bark (legend: A=close contact/good wetting, B=macro-fibrils, C=no close contact).

Effect of carbon fibres on WPC properties

The flexural modulus of elasticity (Figure 2) and strength (Figure 3) of carbon fibres reinforced PP increased with increasing carbon fibres content. This variation was attributed to the favourable interfacial properties of the carbon fibres combined with the effect of the coupling agent. In the absence of MAPP, the reinforcement of carbon fibres was much lower. The modulus of elasticity increased with increasing poplar fibre content with and without MAPP. This increase is due to the stiffness and uniform dispersion of the wood fibres. The WPCs with coupling agent showed a higher flexural strength than those without coupling agent because of the bonding effect of MAPP.

The variations in the flexural modulus of elasticity (Figure 2) and strength (Figure 3) of the hybrid composites increased with increasing carbon fibres content. This increase could also be explained by the desirable properties of carbon fibres and the effect of MAPP. An increase of up to 42% was observed with the addition of only 9% Carbon fibres with 20% wood content. In the absence of MAPP, the flexural strength of the hybrid composite dropped to 39.6 MPa. Therefore, the coupling agent improved the strength by 83%. Overall, the highest flexural strength and stiffness were reached with hybrid reinforcement.

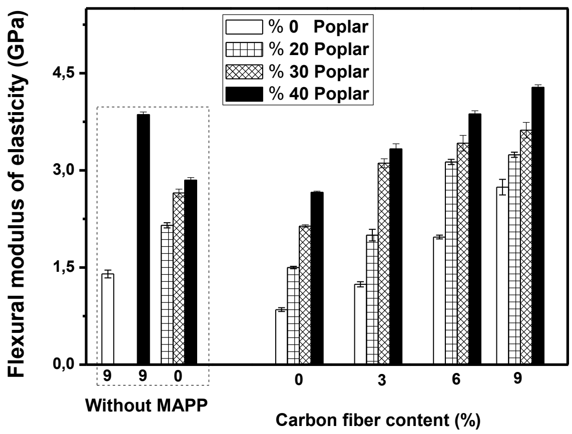


Figure 2: Effect of carbon fibre content on flexural modulus of elasticity of PP and composites

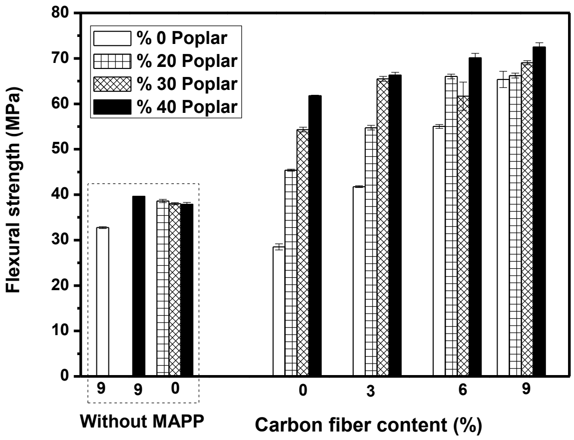


Figure 3: Effect of carbon fibre content on flexural strength of PP and composites

Impact of mineral nanoparticles addition on WPC properties

The mechanical properties of the WPC with added nanoparticles are presented in Table 3. The use of alumine and silicate nanoparticles reduced the mechanical properties of the WPCs compared to the formulations without nanoparticles. For all three nanocharge proportions used, the alumine had a negative effect on flexural and impact properties of the WPC. The garamite nanoparticles, however, slightly improved the flexural properties of the WPC. Unfortunately, all types and proportions of nanoparticles reduced the toughness and increased the water absorption of the WPCs. This result could be attributed to the nanoparticles agglomeration during processing and their bad dispersion in the composites.

Table 3: Flexure, impact, and thickness swell of the WPC made with poplar wood fibres and different types and proportions of nanoparticles.

Nanoparticle type and proportion [%]	MOE [GPa]	MOR [MPa]	Impact energy [kJ/m²]	Water absorption* [%]
Effect of nanoparticle type (at 40% poplar wood content)				
0%	2.54	52.8	18.2	1.64
5% Alumine	2.01	41.2	10.3	2.76
5% Silice	2.07	42.6	13.8	2.65
5% Garamite	2.82	57.8	9.4	3.28
Effect of nanoparticle proportion (at 20% poplar wood content)				
0%	1.40	38.7	22.5	0.81
1 % Alumine	1.38	24.8	14.9	1.26
3% Alumine	1.29	24.2	17.3	1.11
5% Alumine	1.25	23.5	17.5	1.00

* After 500 hours of water immersion

CONCLUSIONS

When compared to spruce wood, white birch wood, spruce bark and poplar bark, poplar wood produced WPC with significantly superior mechanical and physical properties. This result was explained mainly by its surface morphology and its compatibility with the polymer matrix. The addition of a small proportion of carbon fibres in combination with poplar fibres resulted in further increase of the mechanical properties of the WPC. The use of mineral nanoparticles had a negative or a low impact on the physical and mechanical properties of the WPC.

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IPC Working Party on Harvesting and Utilization of Poplar and Willow Wood
2nd Conference on Engineered Wood Products based on Poplar/willow Wood
León, Spain, September 8th-10th 2016

Poplar and willow wood as source for veneer based products: possibilities and limitations

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Keywords: Poplar, willow, construction products, veneer, plywood, LVL.

ABSTRACT

Laminated veneer lumber (LVL) and plywood belong to the family of the engineered products, both based on reconstituting veneer sheets. Demand for engineered products is driven by many factors including diminishing old forests, new transformation technology and performance based building codes. Plywood and LVL products can be divided into two major groups. Structural products include all end-uses dealing with load-bearing applications (beams, I-joists, trusses, structural sheeting, rafters). These products are competing with large dimension timber, steel or concrete). Their main competitive factors are strength, weight, dimensional stability and price.

Non-structural products include all end-uses without specific load-bearing function (window joinery, door frames, furniture parts). Main competition lies in products as MDF, particleboard and plastics. Competitive factors here are appearance, machinability, dimensional stability and also price.

A group of more than 20 poplar clones and 10 willow clones was assessed on their veneer quality and to which extend they could be used for the production of plywood or LVL. More profound exploration of their wood properties (density, dimensional stability, tension wood occurrence…) allows to predict the potential yield of specific clones. Therefore, fitted distribution to measured wood properties and their higher moments (skewness and kurtosis) were needed. Moreover, it seems to be possible to rank clones at early age (6-8 years) to their potential use in veneer based products.

Laminated Veneer and Rubber Lumbers (LVRL): Manufacturing and physic-mechanical characteristics

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Keywords: Layered construction; poplar; railway sleeper; rubber.

ABSTRACT

Laminated lumber of wood veneers and rubber sheets (LVRL) were fabricated using a layered adhesive system comprised of polyaryl polymethylene isocyanate (PAPI) for wood-rubber inter-bonding and phenol formaldehyde (PF) resin for wood veneers. An optimized manufacturing process (rubber type: chloroprene rubber-CR; PAPI: 80g.m^{-2}; PF: 200g.m^{-2}; and silane: 9wt%) was acquired and then utilized to fabricate nine-ply LVRLs of five balanced constructions with two or three CR laminates. The physico-mechanical properties of the LVRLs were evaluated and the results showed that LVRLs have strong shear strength, sound dimensional stability, decent bending strength, and favorable damping performances. The newly-developed product is an interesting potential alternative to sawn log or concrete railway sleepers.

INTRODUCTION

Railways are now and have been historically an overwhelmingly popular channel for communication and transportation in many areas throughout the world, particularly densely populated countries such as China, Japan, and India. As of December 2014, railways in China spanned 112,000 kilometers in length, of which 14.3% are high-speed railways serving trains that operate at velocities over 250 kilometers per hour (Ministry of Transport of the People's Republic of China). Sleepers are the key component which fix and support railway tracks and distribute the loads delivered by moving trains. It is estimated that 12 to 16 million sleepers become old or decayed in North America annually and that in total, 21.5 billion sleepers in Russia must be renovated now. Most importantly, there are over 10 billion outdated sleepers awaiting replacement in China’s railway network.

Traditional railway sleepers are made of sawn logs from natural forests treated with preservatives. Wood, a natural viscoelastic material, has many inherent state-of-the-art advantages such as high strength-to-specific gravity ratio, excellent energy absorption, satisfactory durability (after proper pretreatment) and bio-degradability. Due to the dramatic reduction of the world’s forest resources, however, large-scale use of sawn log sleepers has gradually become unrealistic. To fulfill the increasing demands of high-speed railway services, a new source of sleepers with higher transportation loading capacity, longer lifetime, and lower ecological impact are a rather urgent necessity.

Concrete, which has very high strength and hardness, is often used for industrialized ballasted track sleepers. Due to their intrinsic inflexibility, however, concrete sleepers tend to crack when subjected to frequent impact loadings and repetitive thermal expansion effects. Concrete sleepers may also undergo erosion when exposed to moist

and/or acidic or alkaline weather conditions. Additionally, the production of cement and disposal of waste concrete sleepers may threaten the environment (Ramezanianpour *et al.* 2013).

By comparison, composite sleepers show superior toughness, durability, eco-friendliness, and suitability for large-scale production. Researchers and developers have been interested in composite sleepers dating back to the 1970s, when a novel synthetic sleeper made from fiber-reinforced foamed urethane (FFU) was applied successfully in Japan before spreading to other regions. This type of composite sleeper has been proven to have a sustainable usage period over 50 years (Koller 2015). In a recent study, Awad and Yusaf (2012) designed polyurethane fiber-glass composite railway sleepers through finite element (FE) and genetic algorithm (GA) methods. The same year, Manalo and Aravinthan (2012) built an innovative sandwich structure full-scale railway turnout sleeper using glue-laminated fiber composites comprised of glass fiber skins and modified phenolic core material; the products showed comparable mechanical properties with existing timber turnout sleepers. Considering the loading features of a railway track-sleeper system, elastic sleepers have also been of interest to many researchers. Miguel et al., for example, attempted to use end-of-life tire pads to bolster railway sleeper pads; the pads had controllable static and dynamic stiffness moduli with varying thickness and pretreatments, and showed remarkable load-distributing and anti-fatigue performance (Sol-Sanchez *et al.* 2014). Another study reported that elastic sleepers show favorable dynamic characteristics when applied to railway tracks within specified space between the top of the culvert and rail base (Gao *et al.* 2007). However, most synthetic polymer is not bio-degradable, which severely limits the application of polymer-based sleepers.

Wood composites possess many characteristics inherited from wood, such as excellent bio-degradability, energy absorption and damping performance. Many newly developed engineered wood composite products can be processed to fabricate railway sleepers. For example, Sun et al. investigated glass-fiber-enhanced composites of wood residues and bamboo pieces for sleepers, and analyzed the influence of phenol resin content on physical and mechanical properties (Xiao *et al.* 2014; Sun and Xiao 2011). Laminated composites of wood veneers (mainly from plantation forests) and rubber sheets can provide another solution for quality railway sleepers.

Studies in other fields on hybrid plywood composites have provided a wealth of valuable information and practical references; the fabrication of table tennis rackets is actually a great example (Manin *et al.* 2012, 2014; Liu *et al.* 2014). A table tennis racket is typically composed of three laminate layers, i.e., the bottom plate, rubber, and sponge. The primary concern of table tennis racket design is typically the impact load delivery performance of the rubber cover, which must be adaptive to the high speed and intense rotation of the ball. Relatively little attention, however, is typically given to the interfacial bonding between the rubber cover and wood base.

There have been notable recent studies conducted on the utilization of recycled rubber products in plywood manufacturing. One very popular research direction is blending waste tire rubber (WTR) powders in resin systems to optimize glue line elasticity. Ong *et al.* (2015) for example, used waste rubber powders (WRPs) as filler for melamine urea formaldehyde (MUF) to manufacture plywood. The WRPs were first treated with chemicals like nitric acid, hydrogen peroxide, and acetone, which benefited resin penetration in the WRPs and resulted in higher shear strength and lower formaldehyde emission in the plywood. Ashori *et al.* (2015) investigated a novel hybrid seven-layer plywood material composed of wood (beech and alder) veneers and rubber particles.

First, WTR particles were pre-pressed to a single laminate with methylene diisocyanate (MDI) resin and the layer was subsequently bonded to wood veneers, or, alternately, WTR particles were in-situ hot-pressed with wood veneers. The addition of rubber improved certain physical properties (e.g., water absorption, thickness swelling, sound absorption) of the manufactured panels, but degraded the mechanical properties (e.g., MOR, MOE, impact strength). The physical and mechanical performance of the plywood panels improved as resin content increased.
In summary, engineered wood composites represent an innovative approach to replacing outdated railway sleepers, as well as a push toward more eco-friendly wood materials even in an era of rightful concern over wood resource shortages. Wood/rubber plywood, a relatively new type of composite material, currently appears to be the most viable alternative. So far, poplar is the second largest plantation wood species used in the scale wood composition board industry in China. This study, therefore, attempted to build sound railway sleepers with wood-veneer/rubber-sheet laminated material by optimizing the interfacial bonding and physio-mechanical properties of the composite. Our results may provide useful information for manufacture of full-scale wood/rubber composite sleepers in the future.

EXPERIMENTAL

Materials

Poplar (*Populus deltoids Bartr. cv. 'Lux'*, I-69 poplar) was initially introduced to China from Italy in 1972, and subsequently planted widely throughout the southern region of China. The veneers (W) used to make LVRL were rotary-cut from I-69 poplar logs with diameter at breath height (DBH) of 30-35 centimeters. Veneers 1.8 mm in thickness were oven-dried to a moisture content of 12% and then cut into 500mm by 500mm pieces. The rubber sheets (R), 2mm in thickness, were specially supplied by Shanghai Mujing Rubber and Plastics Co. Ltd, and were cut to the same size as the poplar veneer pieces. Three types of rubber, acrylonitrile butadiene rubber (NBR), natural rubber (NR), and chloroprene rubber (CR), were selected to test their differential interfacial bonding with poplar veneers. Polyaryl polymethylene isocyanate (PAPI) resin was used as the W-R interfacial bonding agent, and phenol formaldehyde (PF) resin was used to bond the poplar veneers. The coupling agent applied to reinforce the interfacial bonding between wood veneers and rubber sheets was bis-(3-triethoxysilicyl propyl)-tetrasulfide (BTESPT), i.e., $(C_2H_5O)_3$-Si-$(CH_2)_3$-S_4 -$(CH_2)_3$-Si -$(C_2H_5O)_3$, commercially marked as KH69 (sulfur content above 22.5%).

Manufacturing process

The typical three-step technical route for LVRL manufacturing is shown in Figure 1. The first step was to establish an optimized interfacial bonding process between poplar veneers and the three kinds of rubber sheets (NBR, NR, and CR). PAPI resin was spread onto the rubber sheets at four loading levels (40, 60, 80, and 100 $g.m^{-2}$). Three-layer plywood segments (W-R-W) were paved and hot-pressed at 160^oC and 1.5MPa for 4 min using a 600mm x600mm single-opening hot-press. For the second step, a single-factorial experiment was conducted to study the influence of KH69 dosage (0, 3, 6, 9, and 12%, based on PAPI resin content,) on W-R interfacial bonding strength. The KH69 coupling agent was blended evenly in the PAPI resin before the glue was spread.

Finally, based on the process parameters determined through the above steps, five types of wood-rubber hybrid structures were designed to fabricate nine-layer LVRLs: R-7W-R, W-R-5W-R-W, 2W-R-3W-R-2W, W-R-2W-R-2W-R-W, and 2W-R-W-R-W-R-2W. Note that the poplar veneers were laid in a parallel direction in all the LVRLs.

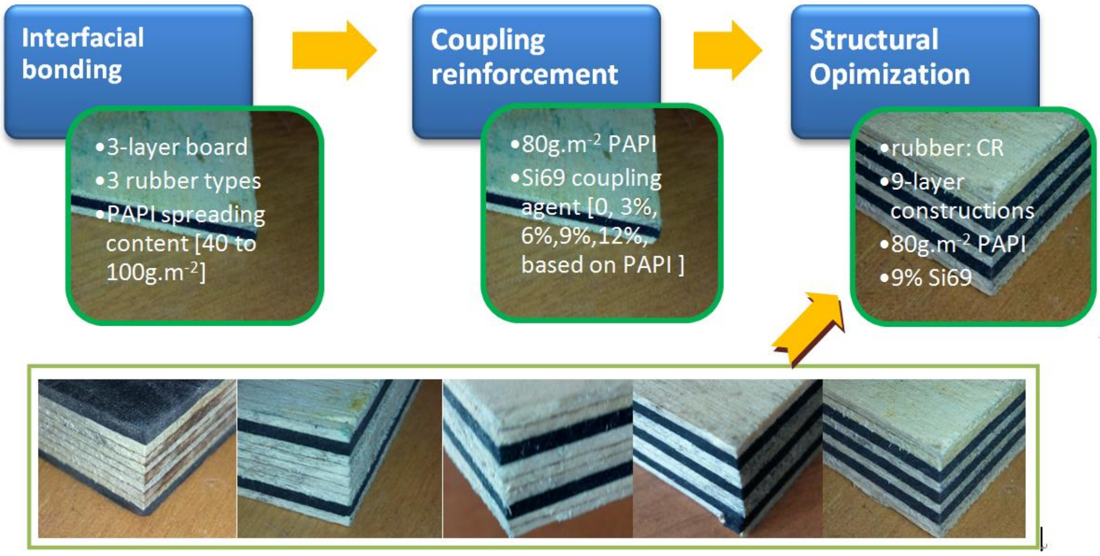

Figure 1: Three-step experimental technical route for manufacturing LVRLs

Properties evaluation

<u>Mechanical and physical properties</u>

All the boards were conditioned at room temperature (RT) for 48 hours before testing. Basic mechanical and physical properties, including wood/rubber glue line shear strength, static bending strength, MOR and MOE, and 24h-TS, were tested according to the Chinese national standard for wood-based panels, GB/T17657.

Glue line shear strength is a key index to evaluate the interfacial bonding between poplar veneers and rubber sheets. As shown in Figure 2, specimens were cut into segments 100mm in length and 25mm in width. Two narrow slots 25mm apart were sawn to test the selected W/W or W/R interfacial glue lines. The depth of sawn slots was dependent on the specific position of W/W or W/R interfacial glue lines in the laminated construction. After submersion in boiling water for 3 h, the specimens were subjected to a tensile load in the lengthwise direction at a speed of 2mm/min until failure occurred. Specimens for the static bending test were 50mm in width and length 20 times that of the thickness (span for centering loading) plus 50mm. A three-point static bending test was conducted to obtain MOR and MOE values, where a uniform moving rate of motion for the crosshead was set at 5mm/min. Both shear strength and bending performance values were tested using an Instron universal mechanical testing machine. A water soaking experiment was also conducted to test the dimensional stability of the LVRLs in moist conditions, in which specimens 50mmx50mm by thickness were submersed horizontally under 10mm of water at RT for 24 h. The thickness of the soaked specimens was then immediately measured upon removal of surface water to calculate the swelling rate.

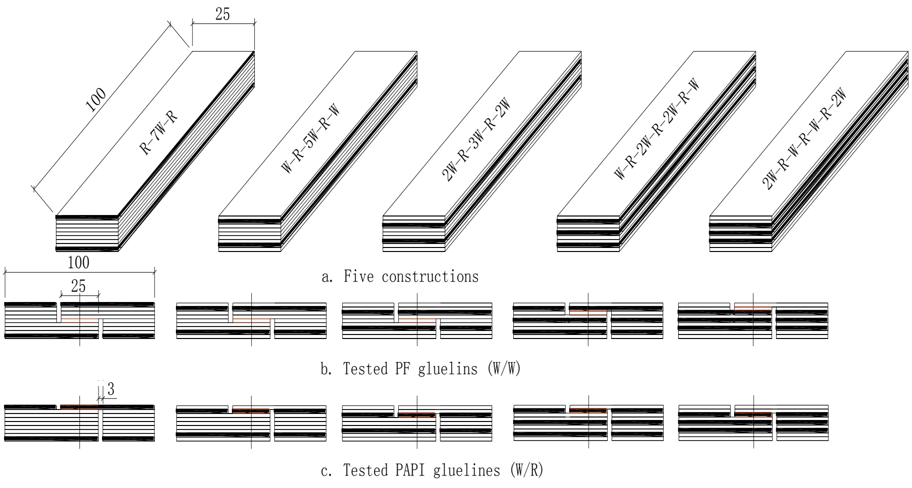

Figure 2: Schematic diagrams of shear strength testing specimens of five constructions, the slots are cut at a depth so that the designated glue line is exposed for tensile testing.

<u>Dimensional recoverability under repetitive compression loading</u>

LVRLs oriented to railway sleepers should have good dimensional recoverability under the frequent compression loads transmitted from passing trains. To reflect this quality, a five-cycle loading and unloading test was conducted using the Instron machine (Figure 3). Specimens 30mm x30mm by thickness were loaded in compression mode perpendicular to the surface at a loading rate of 3mm/min, and the ending compression load for every cycle was controlled at 5kN. The output load-deflection curve (L-D curve) was drawn to reveal the mechanical behavior of the specimens. The linear stage of each L-D curve can be described mathematically as L=f•D+c, where f is the slope reflecting the stiffness under compression.

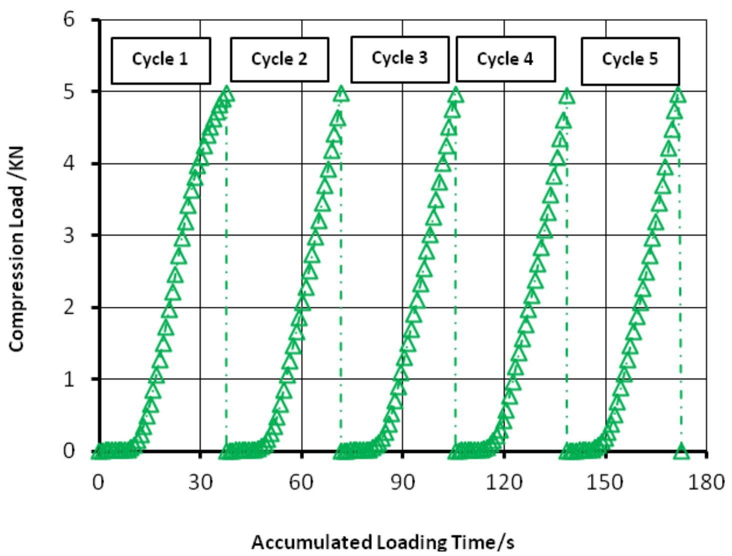

Figure 3: Schematic experimentation by five loading-unloading cycles to detect the recoverability of LVRLs imitating a railway sleeper under frequent transverse compressing by running trains.

Scanning electron microscope (SEM) analysis

A Philips scanning electron microscope (SEM-505) was used to characterize the micro-structure of wood-rubber interfacial glue lines. The scanning surfaces of the specimens were cut with a sharp blade, then the newly-cut surface was sprayed with Au particles before observation. Magnifications were adjusted as necessary.

Damping properties

A state-of-the-art forced vibration system (Figure 4) was installed in our lab to test the damping characteristics of the LVRLs. The system includes a rigid sample clamper, a hammer with a Nylon cap (signal source), an accelerometer, an FFT analyzer (Japan Onosokki, CF-7200A) and an amplifier. A bar-shaped specimen, 300mm x50mm by thickness, was steadily clamped at one end as a cantilever, then the accelerometer was glued on one side 50mm from the clamping end. The specimen was hit on another side along the half-width line to produce a transient stimulating signal. A similar study reported that chosen points have no significant influence on the final results (Zhang *et al.* 2005), so in this study, only one point was set 50mm from the free end. After hitting, the pressure sensor imbedded in the hammer captured and input the signals to the FFT analyzer along Channel 1 after amplification. The stimulated vibration signal was simultaneously captured and input to the FFT analyzer by the accelerometer along Channel 2. The output vibration attenuation waves from the FFT analyzer revealed the damping characteristics of the target material. Five repetitions were applied and averaged for each condition to form the final results. For the sake of comparison, laminated veneer lumber (LVL) specimens of the same size as the experimental specimens were tested as a control.

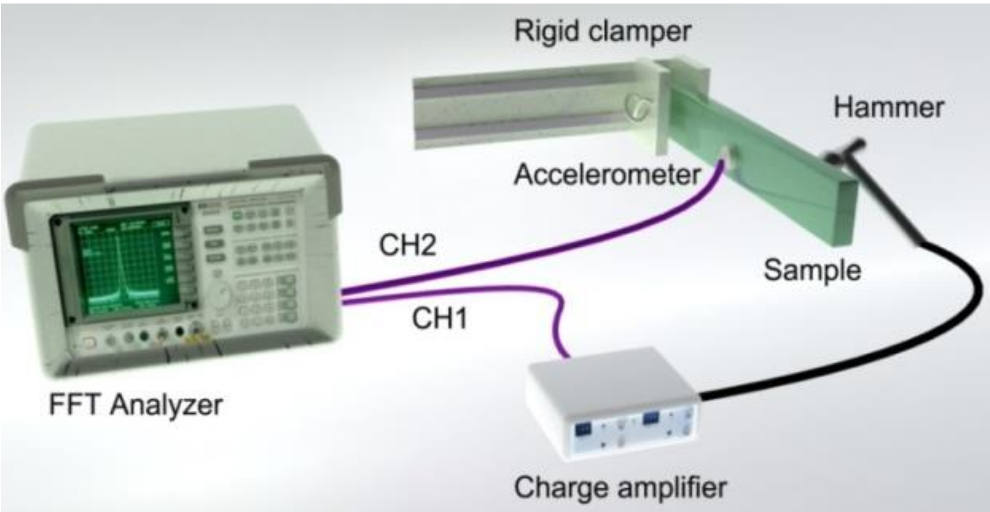

Figure 4: Schematic diagram of the modal vibration test system

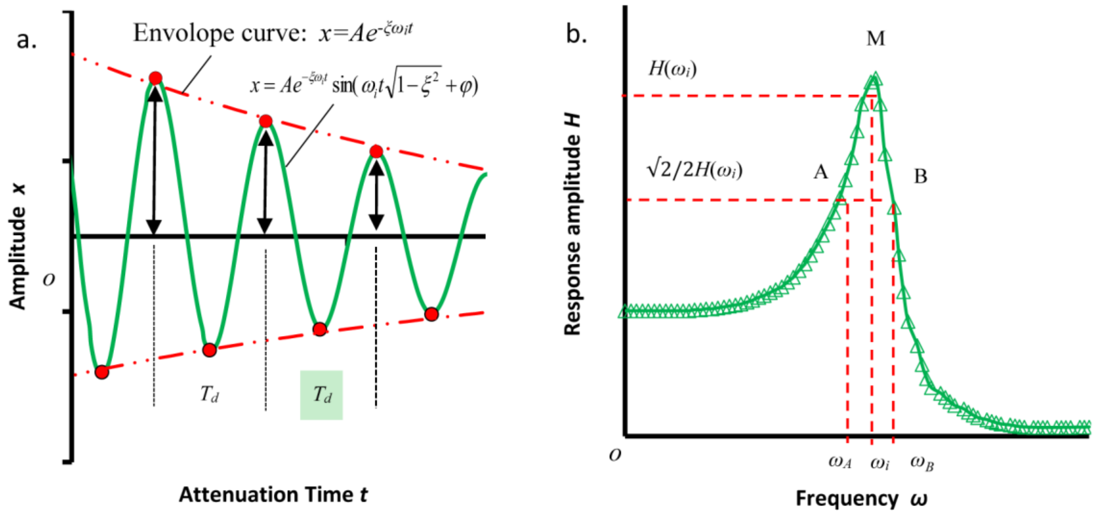

Figure 5. Schematic time- & frequency-domain vibration curves of a viscoelastic system stimulated by a transient signal. In Fig.5b, M stands for the maximum point in correspondence to the natural frequency ω_i, where resonance may occur; while A and B are the half-power points relating to frequencies ω_A and ω_B. Difference of ω_A and ω_B) can quantify the band width of damping of the tested material.

Through the damping experiment and output time- and frequency-domain spectra, two characteristic parameters of LVL and LVRLs were acquired: the damping ratio (ξ) and the natural frequency of the viscoelastic system (ω_i). Theoretically, for a single-freedom viscoelastic system, the amplitude (x) of a free vibration attenuates with time (Fig.5a) and can be mathematically described by Eq.(1) :

$$x = Ae^{-\xi\omega_i t}\sin(\omega_i t\sqrt{1-\xi^2}+\varphi) \qquad [1]$$

where, A is the initial amplitude of vibration, t is vibration time, and φ is the phase difference angle. According to the time-domain spectrum, the logarithmic attenuation ratio (δ) of two adjacent vibration amplitudes (A_i, A_{i+1}) can be expressed as Eq.(2), where Td is the period of vibration defined as $Td=2\pi/\omega_i$ (Figure 5a).

$$\delta = \ln\eta = \ln\frac{A_i}{A_{i+1}} = \xi\omega_i T_d = \frac{2\pi\xi}{\sqrt{1-\xi^2}} \qquad [2]$$

More precisely, several continuous N periods are averaged to calculate δ, that is:

$$\delta = \frac{1}{N}\ln\frac{\mathrm{A_i}}{\mathrm{A_{i+N}}} = \xi\omega_i T_d = \frac{2\pi\xi}{\sqrt{1-\xi^2}} \qquad [3]$$

In this study, N=4. In the case of small damping ratios, ξ^2 approximately equals zero, so we found the value of damping ratio ξ as follows:

$$\xi = \frac{\delta}{2\pi} \qquad [4]$$

RESULTS AND DISCUSSIONS

Interfacial bonding properties between rubber sheet and poplar veneers

The bonding strength between rubber and wood materials is the most crucial factor in manufacturing wood-rubber composites successfully. Many previous studies have tried various resin systems for wood-rubber adhesion. Ismail *et al.* (2001), for example, attempted to use phenol formaldehyde (PF), silica gel, and resorcinol formaldehyde (RF) to glue oil palm wood flour and rubber powders to make composites. Their results indicated that a hybrid system of RF, silica gel, and hexamethylene tetramine (HMT) was best suited to bonding the materials. Isocyanate resins (e.g., diphenyl methane diisocyanate, MDI) have proven to be effective binders compared to traditional wood binders such as PF or urea formaldehyde (UF) at a designated spreading level. In particularly notable studies, Song (Song and Hwang 2001) and Zhao (Zhao *et al.* 2010). used isocyanate resin successfully to manufacture wood fiber/recycled tire rubber composites.

Table 1. Mechanical properties of three-layer plywood with various PAPI content and rubber types

Mechanical Properties	**Rubber Type**	**PAPI content /g.m^{-2}**			
		40	**60**	**80**	**100**
Shear Strength/Mpa	CR	0.63(0.08) [a]	0.84(0.15)	0.93(0.12)	0.89(0.09)
	NBR	0.67(0.03)	0.83(0.14)	0.91(0.10)	0.87(0.08)
	NR	0.62(0.05)	0.81(0.11)	0.87(0.08)	0.85(0.13)
MOR/MPa	CR	40.6(2.1)	46.5(2.4)	50.6(2.5)	50.3(4.6)
	NBR	38.8(3.3)	48.7(2.1)	47.6(5.1)	45.5(3.4)
	NR	41.5(3.7)	47.6(4.0)	49.7(3.9)	48.3(5.2)
MOE/MPa	CR	1645(155)	2100(158)	2395(231)	2265(212)
	NBR	1760(147)	2237(167)	2218(218)	2180(211)
	NR	1750(176)	2251(121)	2375(187)	1944(166)

[a] *Data in parentheses are standard deviation values at a repetition of 6.*

Table 1 present the mechanical properties of composite plywood with three types of rubber sheets and at four levels of PAPI content. All three tested mechanical properties (shear strength, MOR, and MOE) exhibited maximum values when PAPI content reached 80g.m^{-2} regardless of rubber type. At this resin content level, plywood with a CR sheet performed best, at 0.93MPashear strength, 50.6MPa MOR, and 2395MPa MOE.

To further characterize the impact of rubber type and resin content on plywood board properties, two-way ANOVA (MATLAB software version 7.0) was conducted for the data listed in Table 1. PAPI content had statistically significant influence on shear strength, bending strength, and modulus, at significance level (α) of 0.01(P values: 0.0001, 0.0014, and 0.0048), while rubber type only showed comparative significance on the shear strength and no evident influence on MOR or MOE (α=0.05; P values: 0.035, 0.2606, and 0.9667). For these reasons, PAPI resin content of 80g.m^{-2} and chloroprene rubber process were selected for subsequent experiments.

Interfacial bonding reinforcement with coupling agent

Silanes are a family of hydrophobic compounds that have been extensively used for interfacial adhesion reinforcement of filled rubber composites. The fillers may be inorganic, such as silica (Kaewsakul *et al.* 2015), fly ash (Maan *et al.* 2015), attapulgite clay (Tang *et al.* 2015), mica (Ismail *et al.* 2014), or organic compounds such as plant fibers (Wang *et al.* 2011; Pang and Ismail 2013). The introduction of silane can enhance filler-filler interaction, reduce compound viscosity, and lead to better compatibility between fillers and rubber matrices compared to composites without silane, but the contribution may be closely dependent on their specific functionalities. By using a silane coupling agent, fillers can be better dispersed to form a more homogenous filler-matrix network, which can delay crack growth in rubber composites under tensile, bending, or impact loads (Yao *et al.* 2015). BTESPT, or KH69, is an important member of the silane family commonly used in the rubber industry as a coupling, vulcanizing, and/or reinforcing agent for rubber-carbon hybrid matrices.

Table 2. Mechanical properties of three-layer W-R-W plywood as a function of KH69 content

Performance	**KH69 content （%）**				
	0	**3**	**6**	**9**	**12**
Shear strength/MPa	0.93(0.05)[a]	1.22(0.06)	1.45(0.11)	1.63(0.12)	1.51(0.09)
MOR/MPa	50.6(2.3)	56.8(2.8)	58.2(4.5)	62.5(5.1)	59.7(3.7)
MOE/MPa	2395(46)	2510(37)	2620(44)	2985(52)	2755(28)

[a] *Data in parentheses are standard deviation values at a repetition of 6.*

Table 2 shows variations in plywood composite board properties as KH69 coupling agent content increased. The mechanical properties of the board increased as silane content increased, reaching maximum values at 9 wt% silane content. Further increase of silane loading (to 12%) then caused the three tested properties to decline. Similar results were also observed in a study by Sae-oui's (Sae-oui *et al*. 2006). It is likely that excessive coupling agent content leads to plasticization effect.

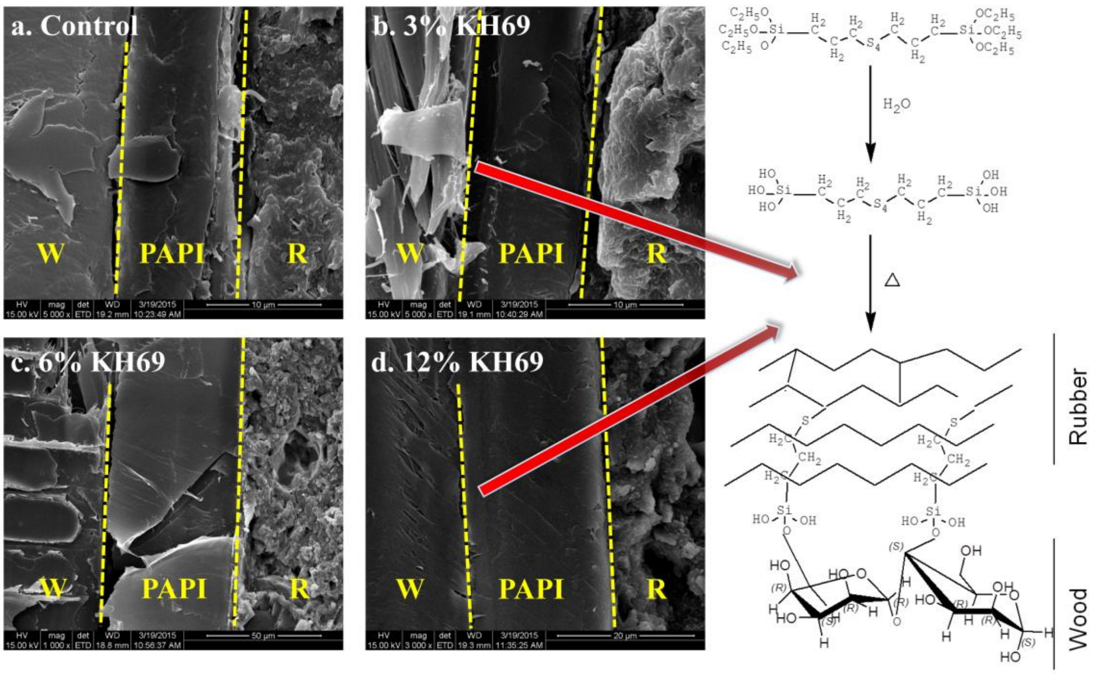

Figure 6: W/R Interfacial glue lines at various content of KH69 coupling agents (W-poplar veneer; PAPI-glue line; R-rubber sheet) and the coupling mechanism between wood and rubber.

Figure 6 depicts the micro-layered structure of rubber sheet-PAPI glue line-wood veneer samples, where it is clear that PAPI did successfully adhere the poplar veneer and rubber sheet, and the presence of BTESPT enhanced the interfacial compatibility. At magnification over 1000x, no evident fissures were observed between the cured PAPI resin layer and rubber sheet.

Board performance of five-layer constructions

Rubber substances typically have high hydrophobicity, high ductility (elongation at break is normally higher than 200%,) and relatively low strength (tensile strength is normally lower than 20MPa.) These inherent characteristics of rubber are mutually complementary to wood, so it can be expected that compositions of rubber and poplar veneers may show balanced properties between the two types of elements.

Table 3. Performance of nine-layer laminated lumbers

Board type	**Shear strength/MPa**		**24h TS/%**	**MOR/MPa**	**MOE/MPa**
	PF glue line	**PAPI glue line**			
Control (LVL)	1.3(0.09) [a]	—	7.8(0.65)	135(11.3)	13859(128)
R-7W-R	1.3(0.10)	1.6(0.14)	4.1(0.47)	42.6(4.4)	2965(30)
W/R/5W/R/W	1.4(0.09)	1.7(0.23)	3.8(0.33)	46.8(5.1)	3397(31)
2W/R/3W/R/2W	1.2(0.05)	1.5(0.07)	3.0(0.27)	45.3(2.3)	2988(28)
W/R/2W/R/2W/R/W	0.9(0.12)	1.5(0.16)	2.0(0.14)	47.1(4.3)	2730(19)
2W/R/W/R/W/R/2W	1.1(0.06)	1.4(0.11)	2.2(0.23)	47.5(3.1)	2714(22)

[a] *Data in parentheses are standard deviation values at a repetition of 6.*

Table 3 and Figure 7 compare the tested values of the five LVRLs and LVL. PAPI resin provided strong interfacial bonding between the rubber sheets and poplar veneers, which ensured the integratility of the LVRLs. In addition, rubber helped improve the LVRLs dimensional stability in the moist environment, which is quite important as far as LVRL use for railway sleepers. MOE is often used to simply judge the tenacity of a material - a relatively low MOE value may reflect toughening capacity. In this respect, the significantly lower MOE value of LVRLs compared to LVL proves that the LVRLs had better tenacity. In other words, LVRLs are much more suitable than LVL for use in railway sleepers to buffer the impact loads from passing trains.
One-way ANOVA analysis further revealed the significant influence (α=0.01) of five laminated constructions on 24h-TS, MOR, and MOE of the LVRLs. The LVRLs containing three rubber sheets showed altogether higher dimensional stability, stronger bending performance, and better toughening capacity than those without rubber sheets.
Both wood and rubber can absorb energy exerted by static or impact load through deformation, but their deforming behaviors differ. Wood is viscoelastic, so plastic deformation may occur under designed conditions such as static load above its yield limit (σ_s, where wood may gradually yield) static load applied for too long even below σ_s, or under impact load. In that case, the deformation of wood tends to be irrecoverable and wood gradually becomes denser, stronger, and stiffer. Hence, in designing solid wood railway sleepers, it is important to maintain maximum train loads lower than the yield limit of the selected wood species. Rubber, also called “elastomer” in the literature, behaves differently – it absorbs and releases exerted energy by pure elastic deformation and complete recovery. An elastic railway sleeper system established combining both wood and elastomers should, then, accommodate the intensity of the railway track system while ensuring that trains run smoothly.

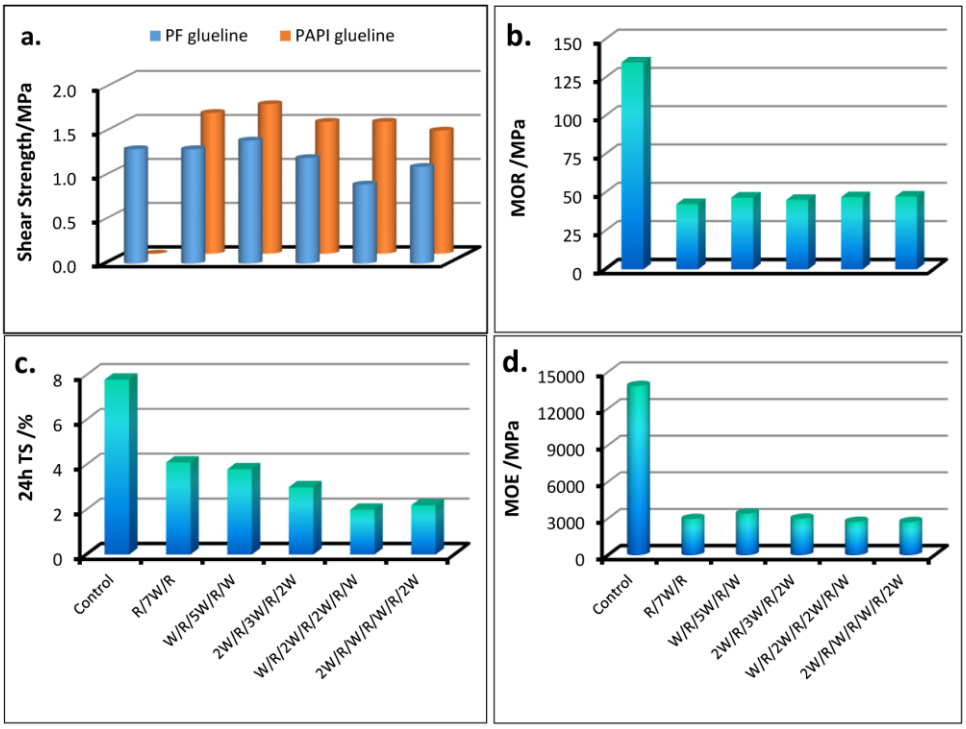

Figure 7: Mechanical properties and hydro-stability comparison between different laminated lumbers of wood veneers and rubber sheets.

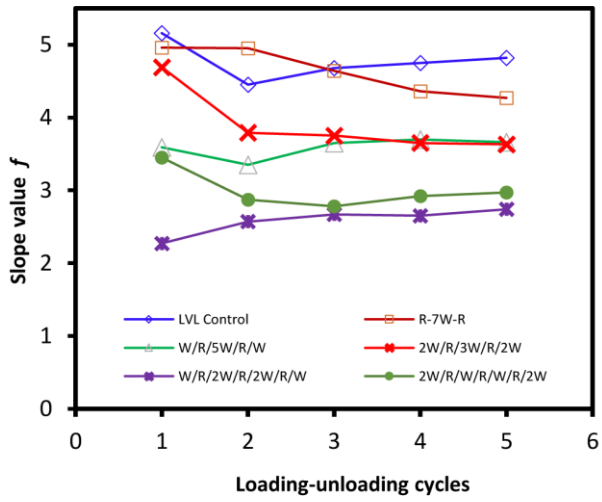

Figure 8: Change of LVRL stiffness under compression

Figure 8 depicts changes in f (slope of L-D curve at the elastic stage) for six types of lumber as a function of compression cycle times. LVL showed overwhelmingly higher f values than all the LVRLs, and continuously increasing f values after the first compression cycle. The poplar veneers, naturally, were gradually densified from surface to core layers with accumulated plastic deformation under transverse compression. The rubber laminates in the LVRLs, however, were highly elastic, so the compression may have been easily consumed through “proactive” deformation. Additionally, the rubber sheets successfully transferred and dispersed the compression load, preventing poplar veneer densification to some extent. As a result, the f values of all LVRLs were lower than that of LVL, and they tended to be steady (or change only slightly,) even after five cycles. Further analysis of tested specimens after five cycles of compression showed that LVL specimens became significantly thinner than they were initially, while LVRLs showed no evident change in thickness. This further proved the active role of rubber laminates in maintaining toughening and recovery effects in the LVRLs.

Damping properties

Full understanding of the response behaviors of a designated material is crucial to assess the applicability of the material to vibration-sensitive applications such as high-speed railways. Rubbery substances have good damping performance, and are commonly utilized in aviation, aerospace, navigation, submarine, or other large machinery applications where vibration attenuation is essential. Rubber sheets can be adhered to metal or engineering plastic substrates to form free or constrained damping constructions.

We glued rubber sheets to poplar veneers (which also show good damping performance), as laminated lumber materials, (actually layered damping structures based on wood substrates). Only the R-5W-R construction was a free damping structure; the other four LVRLs were constrained damping structures with surface poplar veneers as the restricted layers. The damping mechanism of these materials is fairly simple. When an LVRL receives an outer stimulating signal, both rubber sheets and wood veneers vibrate. Their vibrations are anisotropic, however, which facilitates micro-

interfacial friction and consumption of input energy. Figure 9 depicts this mechanism visually.

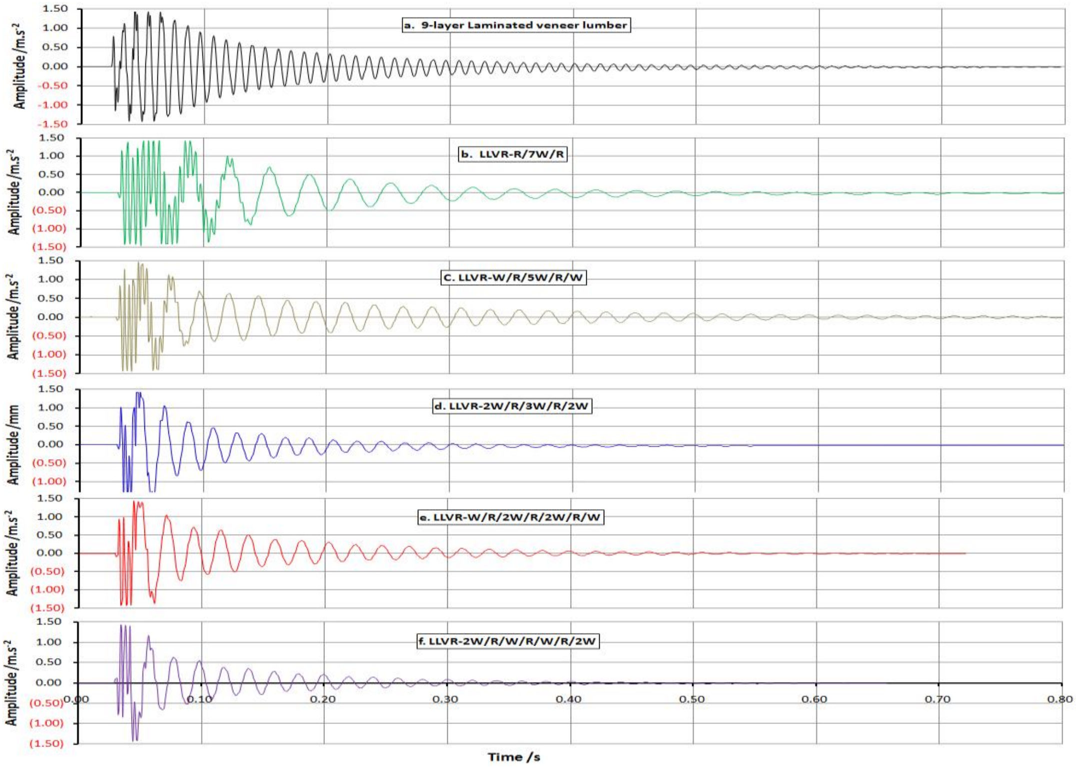

Figure 9: Time-domain spectra of LVL and LVRLs

The LVRLs with three rubber laminates showed a shorter attenuation time compared to other samples under a similar transient signal from an impacting hammer. LVL had the lowest damping ratio ξ (1.11) and LVRLs showed higher ξ values (1.47~2.65). Figure 10 shows where the vibration-response behavior of LVRL was controllable through adjusting the lamination parameters of rubber sheets, such as layers and paving position.

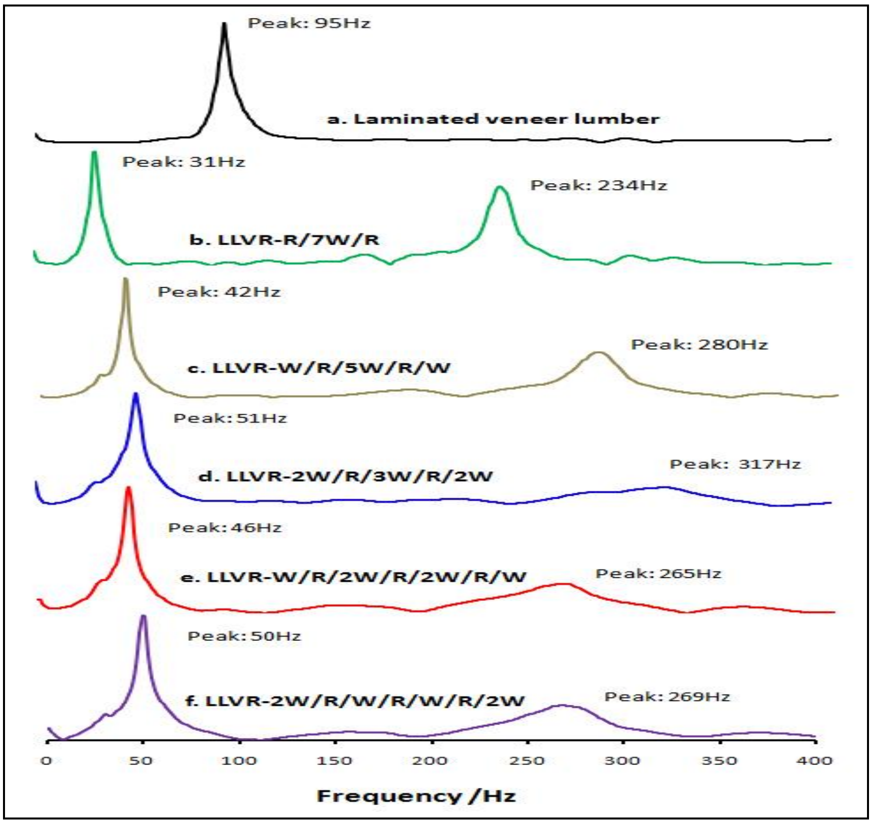

Figure 10: Frequency response spectrograms of LVL and LVRLs

The tested natural frequencies of five LVRLs were all within a low-frequency range, which is incongruous to most running vehicles; therefore, significant resonance is avoidable using LVRLs. LVL showed first-order natural frequency at 95Hz, reflecting the known vibration response characteristics of poplar wood veneers glued together with synthetic resins. Natural frequencies of wood are dependent upon many factors including wood species, density, hardness, moisture content, vibration directions, and others. So far, little is known about the vibration frequencies of planted poplar wood. We did refer to a study by Zhang et al. on the natural frequency of catalpa wood (density 0.453g/cm^3, moisture content 9%,) who found that the first-, second-, and third-order natural frequencies of catalpa are 40~42Hz, 108~109Hz, and 211~215Hz, respectively[15]. Interestingly, LVRLs showed two natural vibration frequencies at 31~51Hz and 234~317Hz due to the synergistic effect of wood veneers and rubber sheets. This phenomenon demonstrates that when receiving outer stimulating signals, wood and rubber laminates respond individually – in other words, the vibration of wood veneers and rubber sheets are asynchronized. This is the precondition for internal interfacial friction leading to energy consumption. We determined the displacement of natural frequency of wood veneers in lower-value domains (LVL: 95Hz; LVRLs: 31~51Hz), as poplar veneers in LVL showed more densification than the LVRLs.

CONCLUSIONS

Structural wood composites a promising potential alternative to traditional solid wood or concrete materials for use in fabricating railway sleepers, as they may benefit

resource conservation, environment protection, and transportation safety. The following conclusions are drawn:

1) By applying a layered gluing system of PAPI and PF resins, wood veneers and rubber sheets can be successfully laminated to create lumber materials.
2) CR shows the strongest bonding with wood veneers compared to NBR or NR, and wood-rubber interfacial adhesion can be further strengthened by adding KH69 silane.
3) An optimized process was established in this study for LVRL fabrication (rubber type CR, PAPI content of 80g.m^{-2}, and KH69 content of 9 wt%). The nine-ply LVRLs (containing two or three CR layers) of five balanced constructions showed outstanding physic-mechanical properties with prominent toughening and buffering performance compared to LVR samples.
4) As such, the material and processes proposed in this study are a favorable potential alternative to sawn logs or concrete for railway sleeper fabrication.

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Determination of poplar LVL effective modulus of elasticity by modelling peeling and evolution of raw material properties on cambial age basis

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Keywords: *Populus*, juvenile wood, mature wood, Laminated Veneer Lumber.

ABSTRACT

A model was designed to predict mechanical behaviour in the elastic domain of LVL panels based on the properties of raw wood material. This study aims to highlight how juvenile wood impacts the mechanical behaviour of LVL panels. An analytical mechanical model was designed to predict the modulus of elasticity of samples made from poplar LVL panels. The originality of the model resides in the integration of different models and interpolation from the literature dealing with the variation in wood properties along the radius of the log (specific gravity, Micro Fibril Angle, growth ring, specific modulus of elasticity) to predict the modulus of elasticity (MOE) of poplar veneers. The simulation of the peeling process leads to the production of various veneers from a mechanical perspective, which are randomly assembled. The model shows the influence of cambial age on LVL MOE, as is shown by the experimental results. It also highlights that the bending direction and veneer thickness have no influence on the average MOE, but affect MOE dispersion. This underlines also the influence of the peeling scenario on mechanical properties of the products.

INTRODUCTION

Laminated veneer lumber (LVL) is an engineering wood product made from veneer sheets glued together layer by layer to form panels or beams. Veneers are mainly obtained from a rotary peeling process. Peeling lines are computer-controlled, providing access to different types of data from the logs (Thibaut *et al.* 2016). Juvenile wood is the name given to wood created at the beginning of the radial growth, hence in a zone close to the pith. Juvenile wood usually has a lower density and less mechanical properties than mature wood. Its impact on LVL is difficult to apprehend experimentally (Burdurlu *et al.* 2007), due to many factors during timber growth cycles. The study focuses on poplar wood species which are typically used in peeling processes. This study is based on poplar wood properties in general, but principally on the measurements of Rahayu *et al.* (2015). The model developed is also based on numerous measured properties from the literature (Bao *et al.* 2001, Fang *et al.* 2006, Bjurhager *et al.* 2008, Bremaud *et al.* 2013, Hein *et al.* 2013). The aim is to obtain the behaviour of LVL structural elements from the pith to the bark of an average tree considering different peeling scenarios. In order to achieve this, a representative log is virtually peeled and veneer sheets are sorted according to their category: juvenile or mature wood. Finally, test specimens are

reconstituted from each group and simulation results are compared to experimental values from Rahayu *et al.* (2015).

MECHANICAL PROPERTY DEPENDENCY

The longitudinal elastic modulus of wood is influenced by many parameters from the micro to the macro scale, such as Micro Fibril Angle (MFA), density and humidity (Cousins 1976, Cave and Walker 1994, Evans *et al.* 2000, Evans and Ilic 2001). The material's humidity is not studied here because it is managed during manufacturing due to adhesive process requirements. MFA, annual growth ring width and specific gravity variations according to cambial age are taken into account in the model with experimental data of the literature. As described below, when authors didn't fit their measurements of the properties, a sigmoid function has been fitted on their values. Sigmoid functions allow both to smooth experimental data and provide monotonous curves which have an asymptotic behaviour at the boundary of the measurements.

Density

Wood density is an important quality attribute, related to many properties like stiffness and strength. Wood density is highly variable due to genetic, environmental, or silvicultural management. As a result, the specific gravity varies throughout the life of the tree. The following specific gravity data (Figure 1) come from Paillassa *et al.* (2013) where 14 cultivars were analysed.

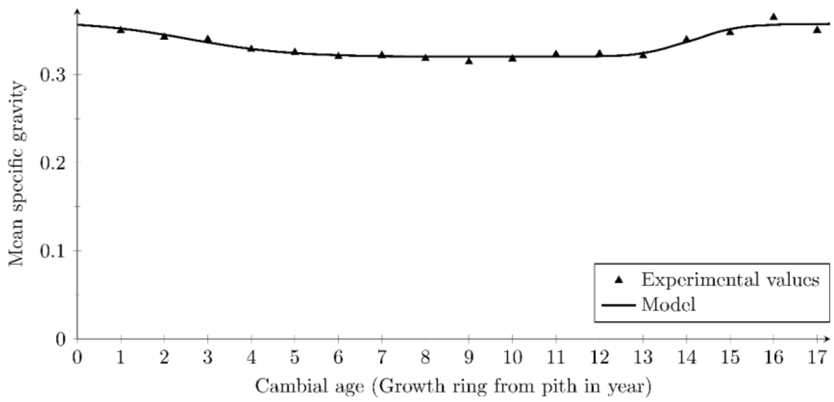

Figure 1: Variation in specific gravity with cambial age

Each cultivar was characterized using 3 logs of 7 meters long from 3 different trees. Cultivars had an average density of 330kg.m^{-3}. Wood density at 12% moisture content was calculated for each wood sample per cambial age. Fig. 1 shows the average specific gravity based on cambial age. For modelling purposes, a sum of sigmoid function (Eqn. 1) was fitted this experimental values:

$$\rho(C_a) = 319.99 + \frac{37.46}{1+e^{-1.848(C_a-14.11)}} + \frac{40.31}{1+e^{0.8703(C_a-2.574)}} \quad [1]$$

where specific gravity (ρ in kg.m^{-3}) is predicted from cambial age (C_a in years).
The fitted density variation profile observed in Figure. 1 is comparable to the results proposed by Senft and Bendtsen (1986) for poplar species (*Populus deltoides*). The specific gravity decreases during the very first years of the tree's life before

stabilization. Then it starts to increase from 10 to 16 years old. The density then seems to reach a new threshold, but the data available in the literature are limited for old poplars, entailing lower accuracy in this range. As observed for Larch, Douglas-fir and Scots Pine in literature (Karlman *et al.* 2005, Filipescu *et al.* 2013), the specific gravity reaches a horizontal asymptote after a few decades (17 years on average for the studied poplar cultivars), which is obtained thanks to sigmoid functions of Eqn. 1.

Micro fibril angle

MFA is an inherent property at the wood cell level. MFA variation can depend on cambial age (Cave and Walker 1994). Figure 2 shows the average MFA with respect to cambial age for seven poplar clones, obtained from an experimental study (Fang *et al*. 2006).

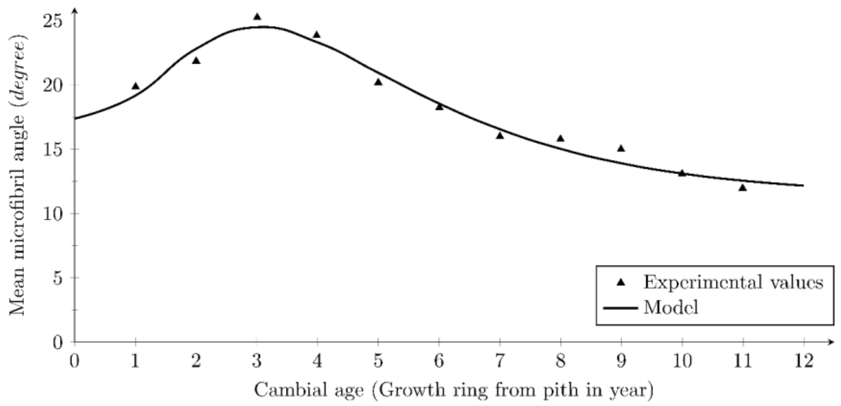

Figure 2: Variation in MFA with cambial age for seven poplar clones at breast height

A sum of sigmoid function (Eqn. 2) was fitted to the experimental values (extract from their article), for modelling purposes:

$$MFA(C_a) = 25.82 - \frac{40.30}{1+e^{-0.3947(C_a-2.187)}} + \frac{25.81}{1+e^{-1.202(C_a-1.542)}} \qquad [2]$$

Where the MFA (in degrees) is predicted from cambial age (C_a in years). After 12 years, the MFA fitted by the sigmoid function reaches a constant value.

Specific Modulus of Elasticity

According to Bremaud *et al.* (2013), there exists a strong relationship between the dynamic specific modulus of elasticity and the MFA. Here we use this relationship, which has been successfully tested for several softwood species (Bendtsen 1986, Reiterer *et al.* 1999, Sedighi-Gilani *et al.* 2005). Indeed, poplar is usually classified with softwoods in terms of its mechanical properties. A trigonometric function (Eqn. 3) was fitted by Bremaud *et al.* (2013) to their experimental values (Figure 4):

$$\frac{E}{\rho}(\mathrm{MFA}) = \frac{1}{0.03426\,\mathrm{Cos}[\mathrm{MFA}]^4 + 0.2053\,\mathrm{Cos}[\mathrm{MFA}]^2\mathrm{Sin}[\mathrm{MFA}]^2 + 0.6797\,\mathrm{Sin}[\mathrm{MFA}]^4} \qquad [3]$$

Where the specific modulus (E/ρ in MPa.m^2.kg^{-1}) is predicted from the MFA (in degrees).

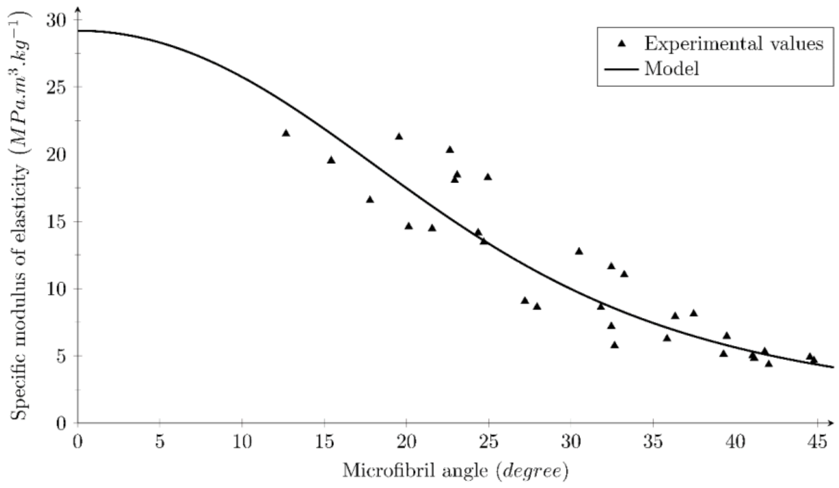

Figure 4: Variation in dynamic specific modulus of elasticity with micro fibril angle

Annual growth ring width

As well as specific gravity, environmental factors affect the width of each annual growth ring. The widths of the growth rings obtained in the study of Paillassa *et al.* (2013) are presented in Fig. 4 with respect to cambial age.

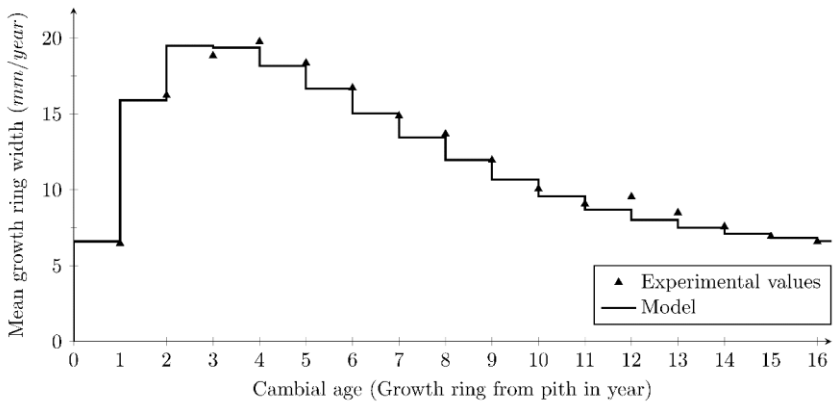

Figure 3: Variation in average growth ring width with respect to cambial age

A sigmoid function (Eqn. 4) was fitted to the experimental values for smoothing purposes:

$$w_{ring}(C_a) = -1.026 - \frac{18.77}{1+e^{-0.8475(C_a-6.727)}} + \frac{25.90}{1+e^{-1.696(C_a-1.285)}} \quad [4]$$

where the average annual growth ring width (w_{ring} in mm/year) is predicted from the cambial age (C_a in integer years). The average annual growth ring width is supposed to tend to a constant value after 16 years. This hypothesis for normal wood can be

observed for other species in literature (Adamopoulos *et al.* 2010, Guller *et al.* 2012, Campelo *et al.* 2015). Notice that for this study, the model will not be used for trees older than 16 years old. The radius based on cambial age is then deduced by integrating the annual growth ring width for each year of growth (Eqn. 4), with the assumption of a constant growth rate for a given year (cf. Figure 4). This enables us to link the equations based on cambial age to equations based on the log radius (r in mm) determined from the ring width ($\overline{w_{ring}}$ in mm.year^{-1}) by the following Eqn. 5:

$$r(C_a) = \int_0^{C_a} \overline{w_{ring}}(y)dy \qquad \text{with } \overline{w_{ring}}(y) = w_{ring}(C_a) \text{ for } y \in]C_a - 1, C_a] \qquad [5]$$

MODEL BUILDING

The model was developed using Wolfram Mathematica Software (2015). It consists of four different phases, schematized in Figure 5. The chosen width of the sheets is 500mm. The age threshold between mature and juvenile wood was chosen as 10.6 years. Each sheet is virtually subdivided into n_s subsamples of 20 mm width. Each group the sheets are assembled into n_l layers to represent a LVL panel of 21 mm thickness. Sheet thicknesses of 3 mm and 5.25 mm were used. All these values are chosen according to the experimental work of Rahayu *et al.* (2015). It is assumed that sheets can be randomly assembled upside down or not, and the layering is also randomised into a group. The panels are cut into test specimens of 20 mm in width. Then the effective modulus of elasticity of each test specimen is calculated from each layer's properties as described below.

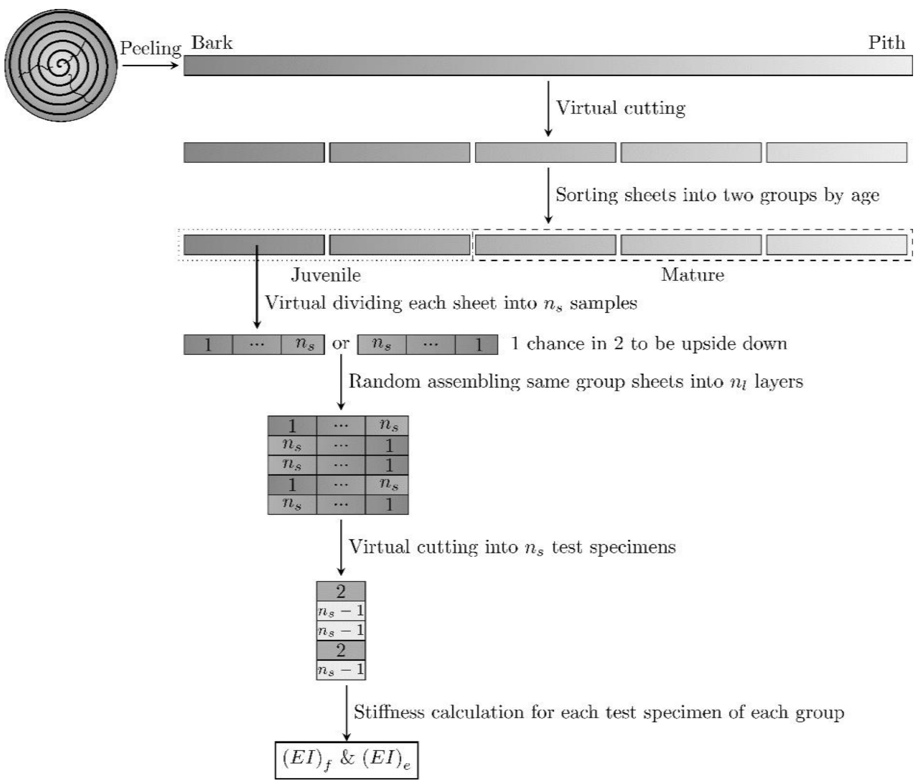

Figure 5: Virtual peeling and assembly process (shades of grey correspond to local cambial age of sheet)

Virtual peeling

The first step is to determine the maximum ribbon length depending on the log diameter. In cross-section, the peeling process corresponds to following a spiral curve (Figure 5). The equation of a spiral in polar coordinates is given by Eqn. 6, where r_s is the spiral radius (mm) with respect to the angle θ (in rad), r_i is the initial log radius (in mm) and t is the peeling thickness (in mm).

$$r_s(\theta) = r_i - t \cdot \frac{\theta}{2\pi} \quad [6]$$

The length of this curve can be calculated by the integration of Eqn. 6, which corresponds to the ribbon length. Second-order length is neglected due to linear variations in radius with respect to the angle. Thus the ribbon length from the core is determined by the following equation (7):

$$l(r_i, r_f, t) = \int_{2\pi \cdot \frac{r_f}{t}}^{2\pi \cdot \frac{r_i}{t}} \sqrt{\frac{\partial r_s(\theta,t)}{\partial \theta}^2 + r_s(\theta,t)^2}\, d\theta \quad [7]$$

Where l (in mm) is the ribbon length from the core and r_f (in mm) the final log radius. The integration domain depends on both the final and the initial log radius. Indeed, logs are not peeled up to the log centre; there remains a peeler core of r_f radius. Initial and final log radii were chosen to be respectively 200 and 35 mm for comparison purposes with the study of Rahayu *et al*. (2015).

Affectation of mechanical properties

Using the above equations (Eqn. 1 to 7) taken from the literature, it is then possible to determine the wood's modulus of elasticity along the peeling sheet by composing them (Eqn. 8) to obtain parametric coordinates on cambial age basis:

$$\begin{cases} l &= l\left(r_i(C_a, t), r_f, t\right) \\ E &= \frac{E}{\rho}\left(\mathrm{MFA}(C_a)\right) . \rho(C_a) \end{cases} \quad [8]$$

Where l (in mm) is the ribbon length from the core and E (in MPa) is the modulus of elasticity. These values are parametrized by the cambial age (Ca).

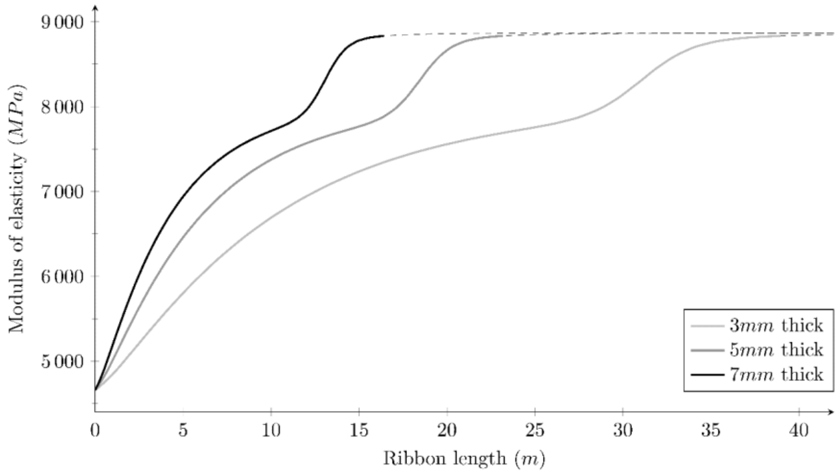

Figure 6: Examples of modulus of elasticity with respect to ribbon length for different peeling thicknesses (for an initial log radius of 200 mm and a kernel log radius of 35 mm)

In Figure 6, solid lines represent some examples for different peeling thicknesses showing the modulus of elasticity with respect to ribbon length for an initial log radius of 200 mm and a kernel log radius of 35 mm. Values beyond 200 mm radius are shown in dashed line in Figure 6. These values are almost constant due to the asymptotic behaviour of sigmoid curves, but they are not used in the model. However, if the model were used beyond 200 mm, the extrapolation would not produce outliners due to sigmoid function property.

Calculation of Flatwise and Edgewise modulus of elasticity

An effective modulus of elasticity is computed corresponding to the apparent modulus of elasticity for an equal and homogenous section. This modulus of elasticity depends on the loading direction (Burdurlu *et al.* 2007). In the model, the interface connection stiffness is considered higher than the material's raw stiffness. This is a prerogative in European standard (EN 14374) concerning LVL panels.

Edgewise

In an edgewise bending test, each layer can be considered as independent. Thus, the effective modulus of elasticity is determined by calculating the sum of the stiffness of each layer, as in the following Eqn. 9, according to Voigt principle:

$$(E)_e = \frac{\sum_{i=1}^{n_l} E_i I_i}{I_t} \quad \text{with: } \begin{cases} E_i & \text{Modulus of elasticity of the i}^{\text{th}} \text{ layer} & \text{MPa} \\ I_i & \text{Local inertia of the i}^{\text{th}} \text{ layer} & \text{mm}^4 \\ I_t & \text{Inertia of the homogeneous section} & \text{mm}^4 \\ n_l & \text{number of layer} & - \end{cases} \qquad [9]$$

Flatwise

In a flatwise bending test, the location of layers with different mechanical properties has influence on global properties, due to a different stress rate between border and central layers. The position of neutral section axis has first to be determined thanks to the following equation (10) (cf. Fig. 7):

$$z_0 = \frac{\sum_{i=1}^{n_l} z_{0,i} E_i S_i}{\sum_{i=1}^{n_l} E_i S_i} \quad \text{with: } \begin{cases} z_0 & \text{Distance from the neutral axis to an arbitrary reference} \quad \text{mm} \\ z_{0,i} & \text{Distance from the i}^{\text{th}} \text{ layer neutral axis to an arbitrary reference} \quad \text{mm} \\ z_i & \text{Distance from the i}^{\text{th}} \text{ layer neutral axis to the global neutral axis} \quad \text{mm} \end{cases}$$

[10]

Thus, the distance between each layer's neutral axis and the global neutral axis, z_i is deduced by equation (11). Then, the effective modulus of elasticity can be determined by the following Eqn. 12, according to Steiner's principle:

$$z_i = z_{0,i} - z_0 \qquad [11]$$

$$(E)_f = \frac{\sum_{i=1}^{n_l} E_i I_i + S_i z_i^2}{I_t} \quad \text{with: } \begin{cases} E_i & \text{Modulus of elasticity of the i}^{\text{th}} \text{ layer} \quad \text{MPa} \\ I_i & \text{Inertia of the i}^{\text{th}} \text{ layer} \quad \text{mm}^4 \\ I_t & \text{Inertia of the whole section} \quad \text{mm}^4 \\ S_i & \text{Section of the i}^{\text{th}} \text{ layer} \quad \text{mm}^2 \\ z_i & \text{Distance from the i}^{\text{th}} \text{ layer neutral axis to the neutral axis} \quad \text{mm} \end{cases}$$

[12]

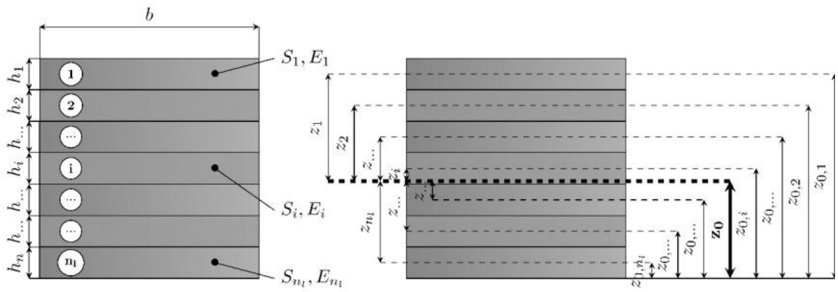

Fig. 7: Geometrical and mechanical properties of LVL in a specimen cross-section

Stochastic approach

As each virtual peeling process is based on a randomised assembly process, the process is repeated to identify and enhance a tendency. Indeed, there are several combinations of sheet arrangements after the primary cutting. These combinations are also increased by including the possibility to turn each sheet upside-down. For a given set of veneer sheets, the sheet positioning influences the flatwise modulus of elasticity, whereas it does not impact the edgewise modulus of elasticity. Consequently, a great number of processes have to be performed to obtain results close to experimental conditions. For the log size used, there are respectively 175 and 250 test specimens per log for respectively juvenile and mature groups. Due to the numerous ways to combine sheets from a set of 175 or 250 elements, a stochastic approach is chosen in order to obtain results within a reasonable computing time.

RESULTS

The model can be used to predict the effective elastic modulus of a parameterized LVL sample. It could be used with different scenarios but requires validation through a comparison with experimental data, which is done in the following.

Experimental results

A study of Rahayu *et al.* (2015) was carried out on ten different poplar species, where juvenile and mature wood LVL had their moduli of elasticity measured. A summary of the results is shown in Table 1. The dynamic MOE of LVL composed of juvenile wood appears to be significantly lower than that of mature wood, with a ratio of 0.858. The flatwise MOE is also slightly lower than the edgewise MOE, while there is no significant effect of veneer thickness. According to the authors, the differences in specific gravities are low and cannot alone explain these observations.

Table 1: effects of veneer thickness, maturity and sample position on MOE (Rahayu et al. 2015)

Group	n	Dynamic MOE [MPa]	Static MOE [MPa]	Density [kg.m^{-3}]
3 mm	1203	8707.18±1334.7	8201.54±1333.6	414.58±35.3
5.25 mm	604	8774.34±1551.6	8415.64±1516.1	394.91±39.7
Mature	905	9298.49±1373.7	8879.49±1336.6	408.25±37.3
Juvenile	902	8157.86±1204.8	7664.24±1185.6	401.26±38.4
Flatwise	949	8654.64±1401.8	8267.40±1419.1	407.91±37.8
Edgewise	858	8811.50±1418.1	8278.70±1381.4	408.11±38.2

Model results

Model was computed with the following parameters to fit the experimental set up presented by Rahayu *et al.* (2015): initial log radius: 200 mm; kernel log radius: 35 mm; sheet thicknesses: 3 and 5.25 mm; sheet length: 500 mm; test sample width: 20 mm; and juvenile cambial age limit: 10.6 years. Figure 8 shows the distribution of test samples with respect to the modulus of elasticity. Common statistical values are given in Table 2.

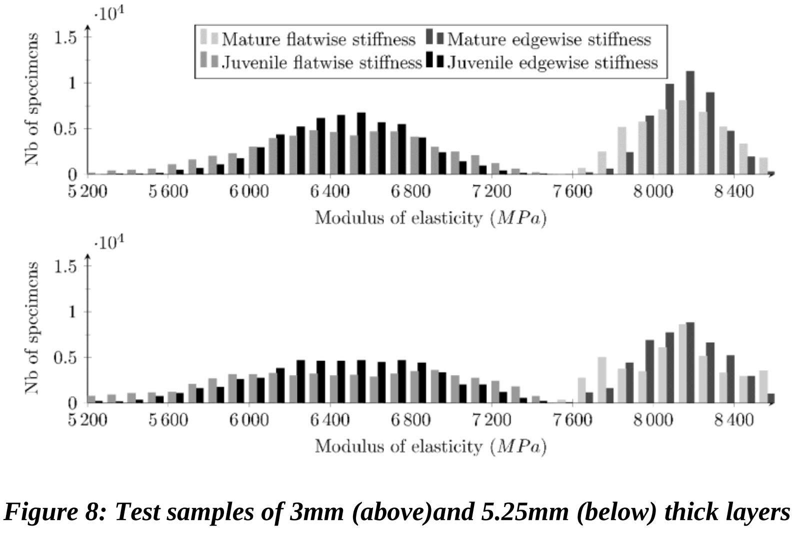

Figure 8: Test samples of 3mm (above)and 5.25mm (below) thick layers

Table 2: MOE (MPa) of juvenile and mature groups of LVL

Group	n	Min	Max	Average	STD	COV (%)
3mm	238,000	5171	8793	7271	931	12.80
5.25mm	238,000	4837	8819	7254	970	13.38
Juvenile	285,600	4837	7511	6461	449	6.96
Mature	190,400	7649	8819	8225	220	2.67
Edgewise	238,000	5075	8805	7269	927	12.75
Flatwise	238,000	4837	8819	7256	974	13.42

As expected in the light of the input parameters, mature groups have a higher average modulus of elasticity value (8225 ± 220 MPa) than juvenile groups (6461 ± 499 MPa) (cf. Table 2), which leads to a modulus of elasticity ratio of 0.79 between juvenile and mature groups. Each juvenile group has a higher dispersion than mature groups, which is shown by coefficients of variation from 5.03 up to 8.86% for juvenile groups and only from 1.94 to 3.35% for mature groups. The dispersion of modulus of elasticity is higher in a flatwise configuration than in an edgewise configuration, due to the greater influence of border layers in flatwise cases. Dispersion also increases between 3 mm and 5.25 mm LVL thicknesses because of the number of layers used. Indeed, the fewer layers there are, the greater influence they have. A comparison between experimental and model MOE values can be made thanks to Table 1 and Table 2, where the measurements are classified into groups according to whether the wood is juvenile or mature, and sheet thicknesses (3 and 5.25 mm). The comparison shows that modelled MOE are systematically lower than experimental ones, and that the standard deviation is higher for the experimental data. Juvenile LVL shows a significantly lower MOE in both the model and experimental results. No clear effect of the veneer thickness or the loading direction appears in the model, while in the experimental results there is no significant effect of veneer thickness, but a statistically significant effect of loading direction on the dynamic MOE exists. Nevertheless, this effect appears non-existent when looking at the static MOE, showing that this result has to be discussed (contrary to the effect of juvenility).

DISCUSSION

The model is based on the assumption that all poplar trees and cultivars behave in the same way in terms of growth, MFA variation and juvenile – mature transition, and thus the coefficient of variation (6.95 and 2.67%) is obviously lower than in the experimental results from (around 15% regardless of the group). The experimental ratio between the dynamic MOE of juvenile and mature wood is 0.876, which is higher than the model prediction (0.785). However, the results of Rahayu *et al.* (2015) present a higher coefficient of variation (Table 1). The study's ratio is included between 0.69 and 1.06 by considering both standard deviations of juvenile and mature modulus of elasticity. Therefore the results obtained with the model are closed to those from Rahayu *et al.* (2015). However, several reasons could have induced different ratios. Indeed, groups were made by visual observation of false heartwood but false heartwood does not necessarily correspond exactly to juvenile wood. From the modelling point of view, there is a lack of experimental input data for mature wood in the literature (Thibaut *et al.* 2016), entailing an assumption of steady parameters for extra dataset domain for raw

material properties. By doing so, the MOE of mature wood is bounded in the model, and the dispersion of LVL composed of mature wood is very low in comparison with experimental measurements. Thus the MOE can be underestimated, especially for mature wood, leading to the higher ratio between the juvenile and mature wood MOE observed in the model. Despite the observed differences between experimental and modelled MOE values, this study takes the stand of not modifying experimental values from the literature to obtain a first model without entering modifications. In this way, it is easier to understand the influence of each property's behaviour without any behaviour correction. The difference can rely on the relationship between the specific modulus and MFA (Figure 3) based on Bremaud *et al.* (2013). These experimental results show a significant dispersion in the ten to twenty degrees range. Furthermore, they were performed on a coniferous tree, which shows similar mechanical properties to *Populus*, but poplar has a different internal structural anatomy, like a broad-leaved tree. In Rahayu *et al.* (2015), the effect of thickness and bending direction cannot be concluded, since dynamic and static MOE give contrary results. Modelling shows no influence from either thickness or bending direction on the average MOE. However, compared to edgewise bending, the model shows an increase in standard deviation for flatwise bending, as well as for 5-layer LVL compared to 3-layer LVL. The results obtained by Rahayu *et al.* (2015) indicate that maturity is a source of variance of the effective modulus of elasticity after performing an ANOVA test on the dynamic and static test results; this variance also occurs with the model.

CONCLUSION

The paper proposes a model which is based on experimental measurements to create an average poplar log, which is used in a simulated peeling process. This study shows a correct mechanical behaviour prediction by model compared to experimentally behaviour from Rahayu *et al.* (2015). The model, featuring a stochastic approach, is also able to predict LVL behaviour according to veneer thickness and loading direction. Indeed, model results show no influence of these parameters on the average MOE. However, the model shows that dispersion is higher for flatwise than for edgewise bending. Greater veneer thickness also increases the dispersion. Model accuracy could be improved by leading a measurement campaign to determine a reliable specific modulus of elasticity for poplar cultivar. Indeed, this study relies on a softwood specific modulus of elasticity and could underestimate the specific MOE value on poplar with respect to specific gravity. From a practical perspective, this model could be used to highlight the necessity or not of sorting veneer sheets in an industrial process by showing the impact of juvenile wood in LVL products. It could also help to estimate the impact of a peeling strategy to build LVL billets as regards veneer thickness.

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Mechanical properties of Laminated Veneer Lumber made from 14 poplar cultivars

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ABSTRACT

In France, the veneer processing industry use only a very few number of different poplar cultivars. The major risk of such strategy is to face pest and diseases issues which would lead to a shortage of raw material or a significant loss in wood quality as it could be expected for I214 for light packaging. A project federating CNPF-IDF, FCBA, companies, ENSAM was built to evaluate the poplar quality of 14 cultivars. A large experimental campaign was performed to fully characterize (mechanically, physically) these new cultivars. This paper presents the mechanical results obtained for LVL. Non-destructive and destructive method were used to determine Modulus of Elasticity (MOE) and Modulus of Rupture (MOR). The results show that correlation between destructive and non-destructive test of the MOE is excellent (R^2=0.90, 1808 samples). In perfect agreement with solid wood observations performed by FCBA, some cultivars reveal high mechanicals properties (Lambro, Brenta, Taro, Alcinde, Soligo, Lena, Koster) and three cultivars (I214, A4A and Triplo) could be considered as unsuitable for structural applications. According to analysis of variance, there is a significant effect due to juvenility for each cultivar: difference of mean MOE and mean MOR between juvenile and mature LVL reach respectively +16% and +18.5% for an increase of density of less than 2%. The use of thick veneers appears not penalizing for mechanical LVL performances.

INTRODUCTION

In France, the veneer processing industry uses one poplar cultivar almost exclusively (I-214) for light packaging products. The major risk of such a strategy is to face a shortage of raw materials or a significant loss in wood quality due to pest and disease issues (El-Haouzali 2009). To be able to cope with a plague, the source of genetic material should be larger. Most new cultivars display a very interesting growth rate, which implies a large proportion of juvenile wood (Rowell *et al*. 2005) with assumed lower mechanical characteristic's. One of the most significant technical advantages of Laminated Veneer Lumber (LVL) is that specific performance characteristics can be considered in its design. By strategically placing selected veneer sheets within the composite, it is

possible to manufacture a wood-based product that has well-controlled physical and mechanical properties (Wang *et al*. 2003).
LVL presents the inconvenience of using a large amount of adhesive during its manufacturing. According to De Melo and Del Menezzi (2014), the adhesive is a component with significant technical and economic implications with regard to the utilization of wood products, and its cost can be half the product price.
Therefore, increasing veneer thickness can enable a decrease in adhesive use for these panels. Dynamic analysis is a simple and efficient way of characterizing the BING module of elasticity (MOE) of many materials, including wood (Brancheriau and Bailléres 2002; Bucur 2006). Using various species of wood, sample dimensions and growth conditions, several studies have shown a strong linear correlation between the dynamic and static modulus of elasticity (Biblis *et al*. 2004; El-Haouzali 2009). However, the use of such methods for estimating the MOE of engineered wood products, particularly LVL, has not been widely applied. In this study, the BING method was used to evaluate its efficiency in predicting the MOE of LVL.

This paper is largely inspired from (Rahayu *et al.* 2015). It manly analyses and discusses about:

- The use of vibrating method (BING) to predict LVL MOE even if made of thick veneers?
- The impact of juvenility on LVL mechanical properties
- Which are new poplar cultivars (from 14 new cultivars) suitable for structural applications of LVL
- The influence of using thick veneers on LVL mechanical properties

MATERIAL AND METHODS

This research was performed at LaBoMaP (Laboratoire Bourgogne des Matériaux et des Procédés), Ecole National Superieure d'Arts et Metiérs (ENSAM) Cluny, Bourgogne, France. Fourteen poplar cultivars named Brenta, Dvina, I-214, Koster, Lambro, Lena, Mella, Soligo, Taro, A4A, Alcinde, Polargo, Trichobel and Triplo were peeled using an instrumented lathe with forces gauges. Trees were between 13 and 17 years old (diameter logs were 35-45 cm). The total amount of logs was 56 logs (2 trees giving 4 logs from each cultivar) from three different sites. The length of logs was 60 cm (was cut from 260 cm from the bottom of the stem) (Figure 1). Trees information details are presented in Tables 1 and 2.
Logs were peeled by using 0° clearance angle, 1 m/s speed and with a moderate pressure rate of 10% to limit lath check growth and thickness variation (Lutz 1974; Feihl 1986, Marchal *et al*. 2009). For each tree, both logs, two types of 50x50 cm2 panels were manufactured (Figure 1):

- A panel made of supposed adult veneer (M) made from the most peripheral area of the ridge from sapwood for both logs.
- A panel made of juvenile veneer (J) composed with veneers from the most central part of the bolt (from false heartwood) for both logs.

Outerwood/corewood was distinguished by visual observations. False heartwood, which is situated in the centre of logs and is darker coloured, was assumed to be corewood. Sapwood, which is situated near bark, was assumed to be outerwood.

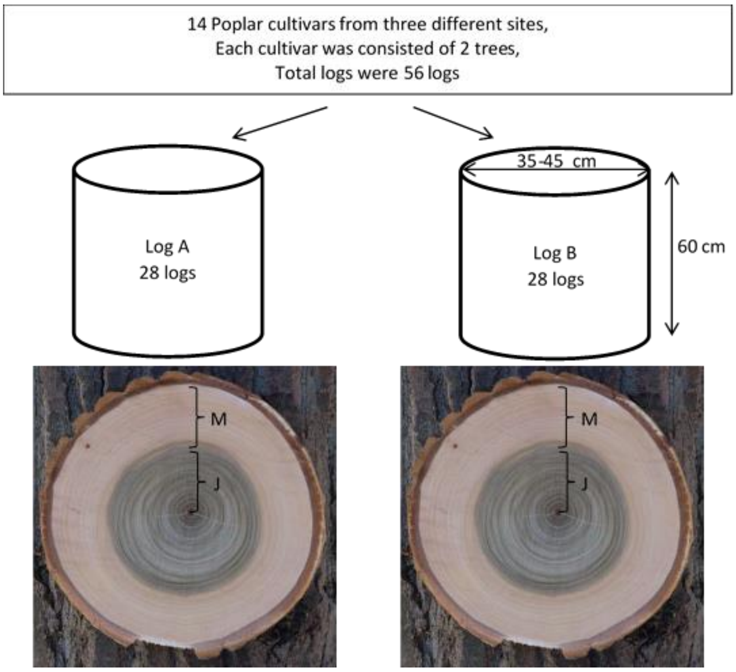

Figure 1: Samples Preparation

We assume that the peripheral area was composed not only with mature wood but also with "less juvenile" wood since the selected trees were too young to give enough full mature veneers. Thus, the most central part of the bolt was consisted of "more juvenile" wood. Indeed, most authors show that the transition between juvenile wood and mature wood is not abrupt and that wood properties evolve gradually (Lewark 1986; Maeglin 1987).

Table 1: Hybrid origin, taxonomy names, gender

No.	Cultivar	Originality	Taxonomy names	Gender
1	A4A	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Female
2	Brenta	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Female
3	I 214	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Female
4	Koster	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Male
5	Lambro	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Male
6	Mella	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Female
7	Polargo	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Female
8	Soligo	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Male
9	Taro	*P. canadensis xP. interamerican*	*Popolus sp. X Populus sp.*	Male
10	Triplo	*Euramerican*	*P. deltoids* Bartr. *x P. nigra* L	Male
11	Alcinde	*Populus deltoide*	*P. deltoids*	Male
12	Dvina	*Populus deltoide*	*P. deltoids*	Male
13	Lena	*Populus deltoide*	*P. deltoids*	Male
14	Trichobel	*Populus trichocarpa*	*Populus trichocarpa x Populus trichocarpa*	Male
15	Douglas fir	NC	*Pseudotsuga menzii*	NC
16	Sengon	NC	*Falcataria moluccana*	NC
17	Jabon	NC	*Antocephalus cadamba*	NC

Table 2: Tree samples information of 14 poplar new cultivars

Cultivar	Average value of proportion of false heartwood (%)	Tree reference	Veneer thickness	Growth Site	Age (years old)	Total length (m)	DBH (cm)	Diameter log (cm)
A4A	40	103	3 , 5.25mm	Bussy les Daours	13	23.5	41.4	38.4
		109	3, 5.25mm	Clarques	13	23.0	49.0	42.2
		119	3mm	Argenton	12	NC	44.6	39.0
Brenta	43	14	3 , 5.25mm	Sainte Hermine	18	33.0	50.3	45.8
		38	3mm	Saint Nicolas la Chapelle	18	32.0	43.3	38.1
I 214	40	26	3 , 5.25mm	Saint Nicolas la Chapelle	18	34.5	50.3	46.2
		71	3 , 5.25mm	La Réole	17	32.0	46.8	43.8
Koster	44	18	3 , 5.25mm	Sainte Hermine	18	33.0	51.6	47.3
		68	3 , 5.25mm	La Réole	17	32.0	50.3	43.7
Lambro	34	12	3 , 5.25mm	Sainte Hermine	18	30.8	52.9	44.0
		50	3 , 5.25mm	La Réole	17	34.0	47.1	50.0
Mella	45	23	3mm	Saint Nicolas la Chapelle	18	32.5	38.9	36.0
		54	3 , 5.25mm	La Réole	17	30.0	38.9	36.2
Polargo	37	107	3 , 5.25mm	Bussy les Daours	13	24.0	43.6	38.0
		122	3 , 5.25mm	Epieds	13	NC	NC	41.8
		124	3mm	Saint Jean d'Angely	13	NC	NC	40.2
Soligo	38	8	3 , 5.25mm	Sainte Hermine	18	33.3	54.5	51.4
		36	3mm	Saint Nicolas la Chapelle	18	32.5	48.4	42.1
		46	5.25mm	La Réole	17	34.0	56.4	52.5
Taro	52	20	3mm	Saint Nicolas la Chapelle	18	32.5	45.2	40.6
		65	5.25mm	La Réole	17	31.0	41.4	39.2
		81	3 , 5.25mm	Blanzay sur Boutonne	17	34.0	62.7	38.6
Triplo	38	91	3mm	Vervant	14	NC	46.8	41.0
		95	3 , 5.25mm	Saint Jean d'Angely	13	NC	NC	41.3
		100	3 , 5.25mm	Bussy les Daours	13	22.5	37.9	39.7
Alcinde	38	85	3 , 5.25mm	Le Busseau	19	NC	45.9	40.6
		89	3 , 5.25mm	Vervant	14	NC	46.2	40.9
		97	3mm	Saint Jean d'Angely	13	NC	NC	44.2
Dvina	55	3	3mm	Sainte Hermine	18	32.8	51.6	47.2
		42	5.25mm	Blanzay sur Boutonne	17	31.0	42.4	38.0
		60	3mm	La Réole	17	33.0	52.2	47.5
Lena	40	6	3 , 5.25mm	Sainte Hermine	18	33.7	57.6	51.0
		62	3 , 5.25mm	La Réole	17	33.0	52.2	49.0
Trichobel	42	83	3 , 5.25mm	Le Busseau	19	NC	46.8	40.9
		113	3mm	Long	14	31.0	42.7	42.4
		116	3 , 5.25mm	Vauchelle le Authis	22	34.5	45.5	46.7

Veneers were dried with a vacuum dryer to ensure a flat veneer surface (dried until they reached 8-10 % moisture content). Polyvinyl acetate (PVAc) was used as the adhesive. Veneers were selected randomly in each category (juvenile or mature) to avoid any layering effect. LVLs of seven layers of 3-mm veneer and four layers of 5.25-mm veneer were made, so that the target LVL thickness of 21 mm was achieved. Each board was cut into standardized test samples (EN 789), parallel to grain with a total of 1,808

samples. Density (D), MOE, MOR, Specific MOE (SMOE) and specific MOR (SMOR) were the observed parameters.

Firstly, a dynamic test (BING) and then a static four-point bending test were performed for each sample (see Figure 2)

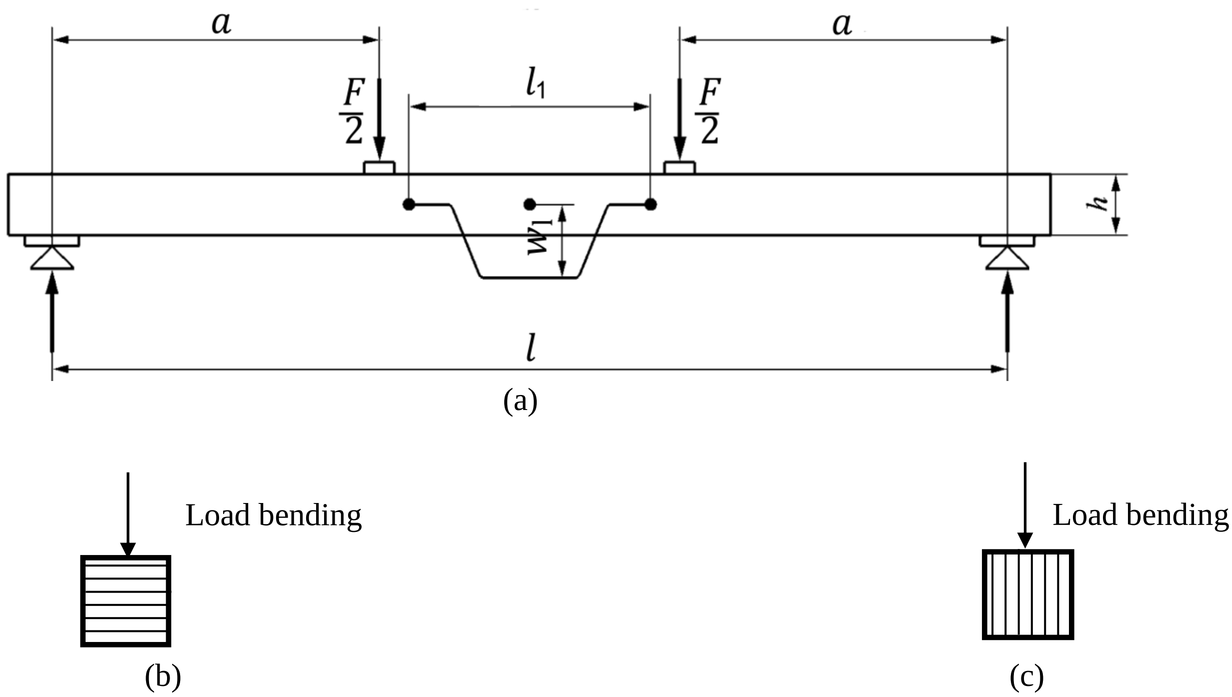

Figure 2: INSTRON for Destructive Test : Four point bending test (a); flatwise direction (b); and edgewise direction (c)

In order to estimate the dynamic MOE by a non-destructive test method, the BING bending vibration method was used. This is a fully automated system designed by CIRAD-Forêt following work by Bordonné (1989) and Hein *et al*. (2010). It is based on measuring and interpreting natural vibration frequencies from a wood piece subjected to impulse loading. The Timoshenko model was used. Thus, the dynamic MOE values were obtained through percussion bending perpendicular to the grain in two directions (flatwise (b) and edgewise (c)) for the 1808 samples.

Four-point bending tests were performed on an INSTRON universal testing machine (see Figure 2) to measure MOE (static) and Modulus of Rupture (MOR). Sample moisture content values were very uniform (8.5% ± 0.5) when destructive tests were performed. Specific MOE and specific MOR were obtained by dividing static MOE and MOR by the LVL density at (8.5% ± 0.5) moisture content.

The density of the wood and wood composite is one of the most important physical parameters and generally considered as the first predictor of strength properties (Kollmann and Cote 1968; Guitard 1987; Shukla and Kamden 2008). It was measured on anhydrous LVL samples.

The experimental results were statistically analysed using an analysis of variance (ANOVA, Table 3) to test the effects of veneer thickness (3 mm and 5.25 mm), poplar cultivars, maturity (juvenile and mature) and loading direction (edgewise and flatwise). Mean differences between levels of factors were determined using Duncan's Multiple Range Test (Table 4).

Table 3: Anova results of MOE static, MOE dynamic, MOR and density (P=0.05)

Source	MOE Timoshenko		MOE Instron		MOR		Density	
	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Veneer thickness (1)	0.54	**0.4614**	8.98	0.0028	92.31	<.0001	515.51	<.0001
Poplar cultivars (2)	226.05	<.0001	208.2	<.0001	117.63	<.0001	298.93	<.0001
1* 2	16.31	<.0001	13.53	<.0001	15.45	<.0001	14.45	<.0001
Maturity (3)	1052.63	<.0001	1164.17	<.0001	1125.67	<.0001	58.23	<.0001
1* 3	1.71	**0.191**	1.18	**0.2771**	3.36	**0.0668**	1.51	**0.2199**
2* 3	10.48	<.0001	7.89	<.0001	11.44	<.0001	15.82	<.0001
1* 2* 3	6.3	<.0001	6.88	<.0001	4.1	<.0001	2.53	0.0019
Sample position (4)	27.13	<.0001	0.01	**0.9435**	204.14	<.0001	0.12	**0.7307**
1 * 4	6.45	0.0112	0	**0.9724**	0.81	**0.3674**	0	**0.9554**
2 * 4	2.27	0.0057	1.72	**0.0517**	4.36	<.0001	0.08	**1**
1 * 2* 4	0.92	**0.5305**	0.94	**0.5072**	1.82	0.0351	0.1	**1**
3 * 4	0.16	**0.6903**	0	**0.9458**	5.07	0.0245	0.09	**0.7611**
1* 3* 4	1.55	**0.2135**	0.56	**0.455**	0.94	**0.3333**	0.24	**0.623**
2 * 3* 4	1.14	**0.3214**	0.63	**0.8268**	0.87	**0.5822**	0.09	**1**
1* 2* 3* 4	0.89	**0.5616**	1.2	**0.2761**	0.96	**0.4846**	0.14	**0.9999**

Table 4: Duncan multiple comparison test the effects of veneer thickness, cultivar, maturity and sample position on MOE dynamic, MOE static, MOR and density

Veneer Thickness

Source of variance	n	MOE dynamic	Moe static	MOR	Density
3mm	1203	8707.18A	8201.54B	51.40A	414.58A
5.25mm	604	8774.34A	8415.64A	49.58B	394.91B

Maturity

Source of variance	n	MOE dynamic	Moe static	MOR	Density
Mature	905	9298.49A	8879.95A	55.00A	408.25A
Juvenile	902	8157.86B	7664.24B	46.57B	401.26B

Sample Position

Source of variance	n	MOE dynamic	Moe static	MOR	Density
Flatwise	949	8654.64B	8267.40A	52.53A	407.91A
Edgewise	858	8811.50A	8278.70A	48.86B	408.11A

Cultivar

Source of variance	n	MOE dynamic	Moe static	MOR	Density
I-214	120	7039.62I	6712.90G	44.57E	354.97J
A4A	166	7539.84G	7140.15F	47.15D	384.26H
Triplo	158	7272.14H	6851.37G	45.28E	389.74G
Polargo	145	7916.65F	7410.27E	47.88D	395.48F
Dvina	114	8540.33E	8043.88D	44.94E	397.13F
Koster	120	8838.47D	8546.63C	53.98C	424.05D
Mella	115	8781.34D	8220.44D	47.66D	398.48F
Trichobel	154	9158.40C	8660.39C	46.59D	375.86I
Lena	120	9253.98C	8701.81C	55.76B	433.22C
Alcinde	128	9569.85B	9185.20B	57.98A	439.47B
Brenta	116	9760.09AB	9439.11A	56.31B	405.34E
Soligo	117	9897.93A	9197.90B	56.64AB	467.76A
Lambro	116	9754.91AB	9437.09A	57.98A	430.16C
Taro	118	9903.12A	9273.68AB	52.97C	442.44B

RESULTS

Density

The ANOVA (Table 3) shows that maturity, poplar cultivars and veneer thickness had significant influences on density ($p<0.01$). LVL density made from mature veneers (408 ± 37) kg/m3 is statistically significantly higher than LVL made from juvenile veneers (401 ± 37) kg/m3. This difference still is limited since it only represents less than 2.5% of increase The density of panels made from 3mm (415 ± 35) kg/m3 and 5.25mm veneer (395 ± 40) kg/m3 were close.

Modulus of Elasticity (MOE)

Figure 3 shows the correlation between static MOE and dynamic MOE for 1808 samples made of 3mm and 5.25mm thick veneers (LVL in flatwise and edgewise direction). The correlation is excellent ($r2 = 0.90$).

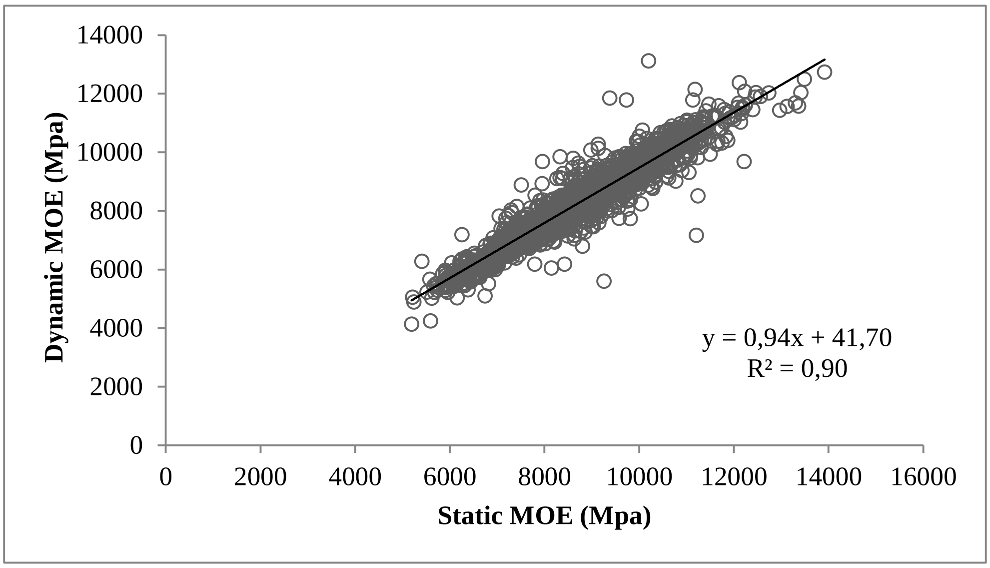

Figure 3: Dynamic MOE (Vibration) and Static MOE (4 point bending test) for LVL (1808 samples)

The ANOVA (Table 3), shows that maturity, cultivar and veneer thickness, had significant influences on static MOE ($p<0.01$). The Duncan multiple comparison test (Table 5) shows that MOE static value of mature LVL (8880 MPa) and juvenile LVL (7664 MPa) are statistically different. LVL made from mature veneer resulted higher static MOE value than juvenile veneer which confirms most of literature results.
The Duncan multiple comparison test (Table 4) shows that there is statistical difference between cultivars which is mostly attributed to wood density (from Table 2. R^2 between static MOE and density reach 0.6 whilst MOR and density reach 0.7). Brenta had the highest value of static MOE (9439 MPa), while I214 was the lowest (6713 MPa).
The Duncan multiple comparison test (Table 4) shows that MOE static value of 3mm and 5.25mm are statistically different. It is interesting to note that for such large number of samples, the effect of the veneer thickness on the stiffness (and it was also observed for MOR) was not negative since the average MOE increased from 8202 MPa for 3mm to 8416 MPa for the 5.25mm.

The ANOVA (Table 3), shows that sample position factor does not have significant effect on the static MOE. Mean flatwise static MOE value (8267 MPa) is not statistically different with edgewise mean MOE (8279 MPa).

Dynamic MOE

The ANOVA (Table 3), shows that all factors have significantly influenced dynamic MOE ($p<0.01$) except veneer thickness factor as for static MOE. LVL made from mature veneer (9298 MPa) resulted higher dynamic MOE value than juvenile veneer (8158 MPa).

Modulus of Rupture (MOR)

The ANOVA (Table 3), showed that all factors significantly influenced MOR ($p<0.01$). LVL made from mature veneer (55 MPa) resulted higher MOR value than juvenile veneer (47 MPa). According to Duncan multiple range (Table 4), Alcinde and Lambro had the same highest value of MOR (58 MPa), while Dvina, Triplo and I214 had the same value approximately (45 MPa) considered the lowest. The average value of MOR of LVL 5.25mm (49,6 MPa) and LVL 3 mm (51,4 MPa) were statistically different (Table 4). Flatwise position (52 MPa) gives higher MOR value than edgewise position (49 MPa). According to Duncan multiple ranges (Table 4), those values are statistically different.

Specific modulus of elasticity and specific modulus of rupture

Several researchers have used SMOR and SMOE to evaluate MOE and MOR results by taking into account the effect of density on flexural properties (Bao *et al*. 2001; Bal and Bektas 2012). As for MOE, the ANOVA (Table 3) showed that veneer thickness, poplar cultivars and maturity had significant effects on SMOE. For SMOR, only veneer thickness did not show any significant effect, while other factors did (comparable to MOR). The Duncan's test (Table 4) also showed that the statistical analyses between MOE and SMOE and between MOR and SMOR were similar, except for veneer thickness.

DISCUSSION

Density

Mature veneer (M) LVL D was significantly higher than juvenile veneer (J) LVL D. However, as mentioned before, this improvement did not exceed 2.5 % (see Table 5). Panel density is naturally more influenced by cultivar density itself. The thinner is the veneer, the more numerous are the glue bonds and the greater is the amount of glue used. Finally, LVLs made with thicker veneer were significantly lighter (5 %, on average) when each process parameter was constant (Table 5).

Table 5. The Increasing MOE and MOR Value of LVL Poplar from Juvenile to Mature

		MOE dynamic (MPa)	MOE static (MPa)	MOR (MPa)	Density kg/m^3
LVL 5.25mm	Mature	9431	9104	54	400
	Juvenile	8126	7736	45	390
gain in %		**+16.1**	**+17.7**	**+20.0**	**+2.6**
LVL 3mm	Mature	9233	8769	55	417
	Juvenile	8174	7628	47	412
gain in %		**+13.0**	**+15.0**	**+17.0**	**+1.2**

Modulus of elasticity

When grading poplar, the MOE, MOR and D of the set of samples are required. MOR is rarely the penalizing criterion for poplar mechanical grading compared to MOE or D. The excellent correlation presented in Figure. 3 indicates that BING is a reliable non-destructive instrument to help predicting LVL MOE of poplar even if made from 5-mm veneer. It was also shown that dynamicMOE (using Timoshenko approximation) was always slightly higher than static MOE, as observed many times in the literature (Kollmann and Côté 1968; Haines *et al*. 1996; El-Haouzali 2009). According to the authors, this point needs to be discussed, but the reason behind this trend may be the anisotropy and the heterogeneity of wood. For the rest of the paper, most of the conclusions and discussions dealing with MOE could be verified for both methods.

Static modulus of elasticity

The ANOVA and Duncan's multiple comparison test results were in agreement with observations in the literature regarding the effect of juvenile wood on solid wood and LVL stiffness (Kretschmann *et al*. 1993; Kretschmann 1997; Nazerian *et al*. 2011). It is interesting to note that for such a large number of samples, the effect of veneer thickness on stiffness was not negative since the average MOE increased from 8,202 MPa for 3 mm to 8,416 MPa for 5.25 mm (see Table 4). The ANOVA (Table 3) showed that the sample position factor did not have a significant effect on static MOE. MOE is measured in a zone of pure bending (local modulus EN408). This is why the MOE values between flatwise and edgewise positions were quite the same, contrary to the Bing measurements for which shear deformation occurred. Indeed, shear deformations are different since shear modulus differs due to wood orthotropy and slightly to lathe check orientation. This is also the expected reason why some differences in MOE can be seen in Table 4.

Modulus of rupture

The effect of lamination improved the tensile limit of these cultivars by about 20 %, on average, compared to solid wood (Rahayu *et al*. 2013). LVL made from mature veneer resulted in a higher MOR value than juvenile veneer. The average MOR values for 5.25 and 3-mm LVL were statistically different (Table 3) in line with the results of H'ng *et al*. (2010) who reported that LVL with thinner veneers (15 plies) had better mechanical performances compared to those of thicker veneers (11 plies). However, the improvement was still limited in that case and could be attributed mainly to the upgrading of lamination effects and, to a lesser degree, to the reduction in lathe check depth. This improvement was also limited because the material used was almost free of defects such as knots.

Specific modulus of elasticity and specific modulus of rupture

The veneer thickness, poplar cultivar and maturity factors had significant effects on SMOE, independently from D. Anatomical factors such as fiber length and microfibril angle also probably contributed to this effect. Further research is required to conclude. Veneer thickness showed a significant effect for MOR but not for SMOR. This shows that, in this context, the use of thick veneers is not penalizing for intrinsic LVL mechanical properties.

Structure application

The advantage of using veneers taken from the sapwood and therefore deemed more mature is obvious since mechanical properties were improved by 13 to 20 % for a comparable density (Table 5). This proves that there is an effect due to juvenility for each poplar cultivar. Therefore, users should consider juvenility in estimating LVL mechanical properties. Dynamic MOE, static MOE, MOR and density were lower for LVL made from juvenile veneers than for LVL made from mature veneers.
According to static MOE values of poplar cultivars and the results of Duncan's multiple comparison test (Table 4) for static MOE values, three categories were established. Taro, Lambro, Soligo, Brenta and Alcinde poplar cultivars could be considered as suitable for structural application (blue-coloured region in Table 4), whilst Lena, Trichobel, Mella, Koster and Dvina should be used with careful sample selection (red-coloured region). Polargo, Triplo, A4A and I214 should not be selected for such purposes (yellow-coloured region).

CONCLUSIONS

The resonance technique is a reliable tool for estimating LVL MOE and avoiding destructive tests. It is particularly useful for poplar. The advantage of using veneers from mature wood was proved with an improvement of 15 to 20 %, on average, for mechanical properties, with almost the same panel weight. This indicates that, for poplar, the selection of materials between veneers made from juvenile wood (corewood) and veneers made from mature wood (outerwood) can be relevant.
Five cultivars have a real potential for structural applications (Lambro, Soligo, Alcinde, Brenta and Taro), and some should be used with careful sample selection ('Lena', Trichobel, Mella, Koster and Dvina), while Polargo, A4A, 'I-214' and Triplo should be excluded.
The sample position, as regards the direction of load application, tallied with common knowledge available in the literature. Comparable MOE values were measured for edgewise or flatwise solicitation, but the MOR for flatwise was always a little higher. SMOR was also comparable for both thicknesses. Lastly, concerning this set of samples, the use of thicker veneers reduced the use of adhesive and simplified and accelerated the production of panels without altering their mechanical properties.

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Producing medium density fibreboard based on bamboo-willow

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Keywords: Bamboo-willow, fibre morphology, medium density fibreboard, micro-structure.

ABSTRACT

Bamboo-willow is a fast-grown tree and has a big potential to be used in producing medium density fibreboard (MDF). It is important to understand the micro-structural and physical properties of bamboo-willow in order to use it effectively. Meanwhile, the research on the relationship between fibre's morphology and the mechanical properties of MDF is limited. Fibres made of bamboo-willow were processed in three different temperature conditions and the morphology of fibres was investigated using electron microscope and high resolution fibre quality analyser (FQA). The results show that there is no obvious difference between earlywood and latewood of bamboo-willow. The difference between sapwood and heartwood is also not clear. The water contact angle on bamboo-willow is approximate 18.35º within two minutes. Compared with the condition at the temperature of 140 ℃ and 160 ℃, the fibres processed at room temperature (approximate 25 ℃) are longer and less curly, which could enhance the mechanical properties of MDF. Specifically, MDF produced with fibres that are processed at room temperature has higher modulus of rupture, modulus of elasticity, internal bond and less thickness swell caused by water adsorption. According to the findings of this paper, bamboo-willow is a valuable material for MDF production due to its relatively homogenous micro-structure and low contact angle. Carefully selecting the fibres based on their morphology can enhance the performance of MDF.

INTRODUCTION

Bamboo-willow has been widely cultivated in China because it grows fast and adapts to multiple climate situations. Specifically, bamboo-willow can grow well in saline-alkali land and be alive when submerging in water for two months. For the harvest of bamboo-willow, it becomes increasingly important to find a way to properly use it. It would be valuable if bamboo-willow could be used to partially replace wood harvested in the natural forest in the paper and wood-based panels industry. Researchers have studied the possibility of using bamboo-willow fibres to produce paper and found that the mechanical strength of bamboo-willow fibres is slightly lower than the mechanical strength of poplar fibres (Xue *et al.* 2009). However, few literature study how to use bamboo-willow to produce medium density fibreboard (MDF). Hence, the objective of this research is to study the properties of bamboo-willow and the physical and mechanical properties of MDF produced with fibres made of bamboo-willow. In this research, the micro-structure, contact angle and oven-dried density of

bamboo-willow were investigated. The influence of processing temperature on the morphology of bamboo-willow fibres was also studied. Finally, the relationship between morphology of fibres and MDF properties was explored.

EXPERIMENT

Material

Three-year-old bamboo-willow trees were used in this experiment, which were harvested in the Dongtai forest in JiangSu province of China.

Methods

<u>Micro-structure and water contact angle on bamboo-willow</u>

The micro-structure of the bamboo-willow was studied using electron microscope. In order to obtain the water contact angle on bamboo-willow, three specimens measuring 50×15×3 mm^3 were cut along radial cross section. Next, they were polished and then conditioned in conditioning room (25℃ and 65% relative humidity) for one week before testing. Demineralised water was dropped on the specimens and contact angle was recorded after 1, 5, 10, 15, 20, 30, 40, 60, 100, 120 seconds.

<u>Processing fibres and measuring their morphology</u>

The fibres were processed at three different temperatures, i.e., 140 ℃, 160 ℃ and room temperature (approximate 25 ℃), respectively. The length and width of fibres were measured using electron microscope. The curl index of the fibre was further analysed with high resolution fibre quality analyser (FQA). The average value of 50 fibres was used for data analysis. The relationship between actual length and projective length of the fibre is shown in Figure 1. Finally, curl index was calculated according to Eqn. 1.

$$\text{Curl Index} = (L/l) - 1 \qquad [1]$$

With L: actual length of the fibre; l: projective length of the fibre.

Figure 17: The relationship between actual length and projective length of the fibre. L= actual length; l= projective length

<u>MDF production and properties measurement</u>

Three different MDF panels were produced using bamboo-willow fibres processed in three different temperature conditions respectively. Urea formaldehyde adhesive was used in MDF production and the expected density of panels was 0.75 g/cm^3. One hot pressing approach was applied in all panels' production. The mechanical properties of

panels were measured based on the GB/T 17657-1999 (1999). Thickness swell was obtained by comparing the thickness of specimens in dry condition with that immersed in the demineralised water for 30 minutes.

RESULTS AND DISCUSSION

As a fast-grown wood species, it is logical that vessels in both earlywood and latewood of bamboo-willow are rather large (Figure 2). Generally speaking, the micro-structure difference between earlywood and latewood in bamboo-willow is not obvious. By inspecting the cross section of bamboo-willow using amplify lens, it was found that the difference between sapwood and heartwood is also not clear. The average oven-dried density of bamboo-willow is 0.359 g/cm^3. The low density and relatively homogeneous interior structure can simplify fibres' process. As such, bamboo-willow has a big potential to be a suitable raw material for MDF production.

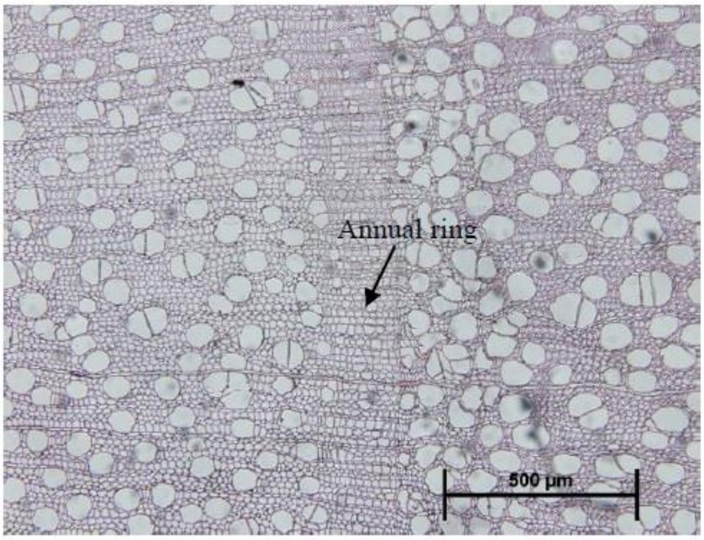

Figure 18: Cross-sectional detailed micro-structure of bamboo-willow obtained with electron microscope

Water contact angle on bamboo-willow is decreasing as time increases (Figure 3). After dropping water on bamboo-willow for two minutes, the contact angle decreased to lower than 20 degrees. The fast decrease of the water contact angle means that the bamboo-willow has a good wettability. It is an important factor for increasing the bond strength between fibres in MDF production (Ayrilmis and Winandy 2009).

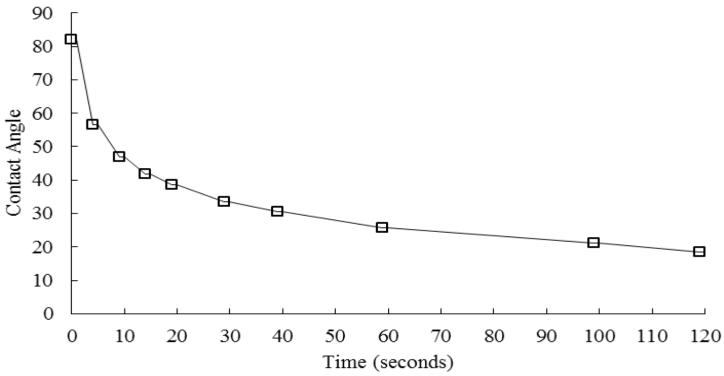

Figure 19: The relationship between wetting time and water contact angle on bamboo-willow

The image of the fibres was obtained using electron microscope and the morphology of these fibres was further analysed using FQA (Figure 4). The length and curl index of fibres decrease and increase respectively when process temperature increases (Table 1). High temperature could soften fibres and reduce their mechanical strength (Gerhards 1982), which probably cause the fibres to be short and curly.

Figure 20: The image of one fibre obtained with FQA

Table 1: The average length, width and curl index of fibres processed in three temperature conditions

Temperature(℃)	Length (mm)	Width (mm)	Curl index
25	0.42	0.026	0.0488
140	0.33	0.025	0.0488
160	0.3	0.025	0.0524

The mechanical strength of MDF is high when the fibres are processed at room temperature (approximate 25 °C) condition (Table 2). The large size of the fibre could be the reason of this phenomenon, which is consistent with the result that large wood fibres can increase the mechanical strength of MDF (Benthien *et al.* 2014). Researchers also found that large fibre size can increase the volumetric swelling of MDF after water absorption (Migneault *et al*. 2008). This phenomenon, however, is not obvious based on the findings of this research. It is possibly due to the low density of bamboo-willow because the volumetric swelling is positively correlated with the density of wood (Walker 1993). Although the fibres processed in the room temperature condition can

enhance the properties of MDF, using high temperature to process fibres is widely applied in the industry due to its high efficiency.

Table 2: The properties of MDF produced with fibres that are prepared in three different temperature conditions

Temperature(℃)	MOE[a] (MPa)	MOR[b] (MPa)	IB[c] (MPa)	TS[d] (%)
25	2895.32	34.07	0.56	12.7
140	2921.02	28.99	0.56	13.1
160	2495.32	24.77	0.51	14.3

[a]Modulus of elasticity1, [b]Modulus of rupture, [c]Internal bond, [d]Thickness swell

CONCLUSIONS

Bamboo-willow has a rather homogenous micro-structure. Specifically, the difference between earlywood and latewood is not obvious. Water contact angle on bamboo-willow decreases to lower than 20 degrees within two minutes. Compared with high temperature, fibres processed in the room temperature (approximate 25 °C) are larger and less curly. MDF produced with fibres that are processed in the room temperature condition has higher mechanical strength. Based on the aforementioned findings, we conclude that bamboo-willow is a suitable raw material for MDF production. To improve the performance of MDF, using fibres processed in the low temperature can be helpful. In order to widely use bamboo-willow in the MDF industry, optimised hot pressing parameters need to be exploded in the future.

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Enhanced potential of poplar and willow for engineered wood products

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Keywords: Poplar, willow, engineered wood products, market.

ABSTRACT

Fast growing tree species of the genera *Populus* and *Salix* are considered important to produce more wood in the future and hence selection and breeding of these deciduous trees has been since long a major part of sylvicultural and even agricultural frameworks. Furthermore, in many ways poplar trees can be considered having potential as best alternative for softwood species when relating to engineered wood products.
For traditional products like plywood, but also constructional timber, poplar or aspen are readily available. Aspen-OSB is an established product since decades in North-America. Specific strength and stiffness are surely interesting characteristics, but the ability to select quality trees with a major impact on production yield are for sure also an asset.
Today researchers are reassessing the potential of solid timber products using poplar wood. Dimensional stability and biological durability are improved using modern wood modification methods besides traditional treatments. In this respect both glulam and CLT (cross laminated timber) show major potential eventually also in combination with e.g. thermal modification.
The increased use of wood based panels (WBP) has a major impact on the use of poplar plywood not only for the furniture and interior application but also for construction and exterior end-uses. Even the need for more concrete formwork has impact on the production of plywood based on fast-growing poplar. Other wood based panels either based on residuals or smaller trees can profit from this lightweight hardwood resource. Alongside chip or particle based products also the pulping allows for an important additional input for both WBP and paper products.
Alongside softwood, the wood from poplar trees has proven to be a good alternative for packaging based on veneer or plywood products and even more when in contact with food.
In recent years the increased interest in bioenergy and even biorefineries has been the basis for assessing other sylvicutural methodologies like short rotation coppice (SRC). Hence selection and breeding of new poplar/willow clones can be focussing on enhanced quality for energy uses, material uses or both. Different engineered products might have different focus on certain properties but it remains critical that an integrated wood industry can rely on this wood resource with a broad spectrum excellence.
The tree and wood characteristics of domesticated poplars and willows have been part of intensive selection and breeding programs since long. The potential of these trees can be enhanced even more using fast fit-for purpose techniques based on modern genetic tools.

POPLAR ENGINEERED WOOD PRODUCTS

Engineered wood products can be interpreted in different ways. As defined in the Wood handbook of the Forest Products Laboratory (2010) it is less linked to the primary processing but more on the products. Engineered wood products (EWP) are made from lumber, veneers, strands of wood, or from other small wood elements that are bound together with structural resins to form lumber-like structural products. However, this limitation to lumber-like products (structural applications as sawn lumber e.g., girders, beams, headers, joists, studs, and columns) did not hinder the development of technologies to produce such structural elements starting with wood. So in this paper an overview is given of wood based composites and panel products, as well as glued structural products. The categorizing used by Forest Products Laboratory (2010) identifies 'wood based composites and panel products' as veneer and plywood, fibreboard, particleboard, OSB, wood–cement products and wood–plastic products.

In a broad sense, wood composites include a wide range of products, from composite panels, for example particleboard, hardboard, insulation board, medium-density fibreboard (MDF), oriented strand board and OSB, to composite lumber, for example laminated veneer lumber (LVL), laminated strand lumber (LSL), parallel strand lumber (PSL) and composite I-beams. In addition, mineral bonded wood composites, for example excelsior cement board, wood–cement particleboard, cement-bonded fibreboard, as well as wood–plastic composites, offer product opportunities for the utilization of poplars and willows (Balatinecz *et al.* 2014). Castro and Fragnelli (2006) underlined the new technologies and alternative uses for poplar wood.

The different engineered wood products are presented hereafter as data sheets. The definitions of the different products are primarily from FAO (2013) and secondary from CWC (2007). For modified wood the terminology is derived from Hill (2006). General statistics for each data sheet are valid for 2014 and based on FAO (2015). Extra data for wood products not detailed by FAO (2015) are based on other sources and sometimes estimated based on market trend reports.
Specific for poplar, aspen and willow some details are presented on the main specific optional or current uses. This is completed with a SWOT analysis mainly to discover new opportunities, and to manage and eliminate threats. A SWOT analysis is a useful technique for understanding your Strengths and Weaknesses, and for identifying both the Opportunities open to you and the Threats you face.

There are different ways to address engineered wood products and one straightforward way is based on the primary processing used. Sawn products are based on a different processing technology than veneer based wood products and additionally also processing to transfer wood into particles and fibres can be identified as separate technologies.

Sawn wood based products

Sawn wood is considered the most straightforward transformation to produce wood products. It can be used as such as an individual element or assembled into specific engineered wood products like trusses using mechanical connectors, like nail plates or

into glue-laminated timber (GLT) or glulam or more recently also in cross laminated timber (CLT).

SAWNWOOD - LUMBER – TIMBER	
Definition	SAWNWOOD Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness. It includes planks, beams, joists, boards, rafters, scantlings, laths, boxboards and "lumber", etc., in the following forms: unplaned, planed, end-jointed, etc. It excludes sleepers, wooden flooring, mouldings (sawnwood continuously shaped along any of its edges or faces, like tongued, grooved, rebated, V-jointed, beaded, moulded, rounded or the like) and sawnwood produced by resawing previously sawn pieces. LUMBER Lumber is a general term which includes boards, dimension lumber, and timber. The product is manufactured by sawing logs into rough size lumber or cants (square timbers) which are edged, resawn to final dimension and cut to length. TIMBER The term “timber” describes lumber which is 140 mm or more in its smallest dimension.
World production (2014)	Sawnwood (NC*): 126.6 million m³ Sawnwood (C): 312.1 million m³ *NC: non-coniferous, hardwood; C: coniferous, softwood
Main producer	Sawnwood (NC): PRChina: 37.9 million m³ Sawnwood (C): USA: 53.8 million m³
Specifics for poplar, aspen, willow,…	Poplar is well suited for the production of sawn wood (Hall *et al.* 1982). For example, sawmills in Canada and the USA have been manufacturing poplar lumber since at least the 1960s. But production volumes have remained low because of economic factors. Due to small log diameters and the high incidence of decay, the average cost of sawing aspen is generally higher than for other hardwoods, and is much higher than for softwoods (Balatinecz and Kretschman 2001). Poplar, aspen and willow sawn wood can be considered suitable hardwood alternatives for commodities now mainly produced from softwoods, also for structural applications. Structural use of hybrid poplar was indicated very clearly already in 1999 by Kretschmann and co-authors. Besides its use as structural timber, poplar sawn wood is used in several other applications. Pallets for transport are an important worldwide market. Packaging materials account for a significant amount of poplar wood usage. The presence of wet pockets, tension wood and lower dimensional stability have an impact on the potential to obtain quality dry timber (Fang *et al.* 2008). Nevertheless, there are options even to use high temperature drying (Vansteenkiste *et al.* 1997). The presence of tension wood (Jourez *et al.* 2003 and Badia *et al.* 2005, 2006) can be

	considered as a very important parameter influencing the suitability of sawn poplar wood for structural applications (De Boever *et al.* 2005, 2007). Today a lot of timber is graded before being used as structural material. Mechanical stress grading is more reliable for softwoods than for hardwoods like poplar. Visual grading systems have been developed specific both for poplar roundwood (FCBA 1994 and EN 1316-2 2002) and sawn products (EN 975-2 2004). The 1995 version of EN 336 on structural timber did mention poplar specifically in the sub-title: “Structural timber. Coniferous and poplar”. In North American aspen has been considered as an alternative construction lumber source already several decades ago (Hall *et al.* 1982), but the mechanical properties of fast growing poplar hybrids require a profound assessment anyhow (Hernandez *et al.* 2007). Furthermore, physical properties (Kellogg *et al.* 1985) and clonal differences have been considered key for the use of solid wood (Koubaa *et al.* 1998). The increased use of nail plate roof trusses (pre-assembled trussed rafter roof sections) could be a good option to use sawn poplar wood.
Strengths +	Solid sawn wood products have the lowest level of embodied energy; wood products requiring more processing steps (for example, plywood, engineered wood products, flake-based products) require more energy to produce but still require significantly less energy than their non-wood counterparts. Sawn wood is considered the wood product keeping the properties of wood as eminent natural composite as produced by photosynthesis in living trees, the main natural resource.
Weaknesses -	The conversion efficiency of logs to lumber rarely exceeds 45%, whereas the efficiency factor for composites can range from 50% up to 95%, depending on the type of product.
Opportunities !	Machine stress rated (MSR) lumber is softwood dimension lumber that has had its strength predicted by mechanical means rather than by relying on visual indicators. MSR lumber has traditionally been used for producing engineered wood products such as roof trusses and is now also commonly used in producing glue-laminated (glulam) beams, chords for wood I-beams and webs in stressed-skin panels. For poplar, aspen and willow timber this MSR approach will increase the potential considerably. Often this is key to work with standards like EN 338 (2009) on structural timber-strength classes and related standards EN 384 (2010) and EN 408 (2012). Eurocode 5 on design of timber structures is becoming key for the building sector regarding rules EN 1995-1-1 (2009), but also structural fire design EN 1995-1-2 (2006) and linked to more general Eurocode documents like EN 1998-1 (2004) on earthquake resistance.
Threats ?	Classic sawn and construction beams are traditional softwood products. The softwood experience and knowledge related to long term behaviour (rheology, creep, mechano-sorptive behaviour, fatigue,…) make it difficult for poplar and other hardwoods to provide with equivalent data for engineers and architects.

The most common building systems are timber frame structures based on light wood frame system (balloon frame structures evolved towards now prominent platform frame structures where lumber framing is stiffened with panels) and the post-and-beam building system combined with the use of mass timber or light wood frame floors.

Sawn wood, timber and lumber have limited dimensions related to the trees dimensions. This can be overcome by producing glued products. Glued laminated timber exist since long and more recently also CLT (cross laminated timber) has become popular. Glulam (GLT) is considered a 1D element (bar/trusses) while CLT is mainly used as 2D element (plate/slab). Sometimes the term mass timber is used to depict these engineered wood products. Mass timber construction uses large prefabricated wood members for wall, floor and roof construction. Some of these products include glued-laminated timber (glulam), cross laminated timber (CLT) and nail laminated lumber (NLT).

GLULAM & CLT (Cross Laminated Timber)	
Definition	GLULAM – GLT Glulam (glued-laminated timber) is a structural timber product manufactured by gluing together individual pieces of dimension lumber under controlled conditions. The attributes of this wood product account for its frequent use as an attractive architectural and structural building material. In the manufacture of glulam, the wood pieces are end jointed and arranged in horizontal layers or laminations. CROSS-LAMINATED TIMBER - CLT Cross-Laminated Timbers are large engineered wood panels manufactured by cross laminating lumber with adhesives or fasteners. CLT is produced with three to seven layers of lumber or planks stacked on one another at right angles and are either glued together in a hydraulic or vacuum press over their entire surface area or nailed together. Each layer is composed of softwood boards. Panel thickness is usually in the range of 50 mm to 300 mm but panels as thick as 500 mm can be produced. NAIL LAMINATED TIMBER – NLT NLT is created from dimensional lumber (2x4 up 2x12") stacked on edge and fastened together with nails. Plywood sheathing is often added to one top side to provide a structural diaphragm. As long as domestic CLT was not available in North America, traditional NLT was used and considered a competitive product. For more than a century, the use of NLT floor and wall assemblies have been utilized in the USA in buildings like warehouses where solid, sturdy floors were required.
World production (2014)	GLT (Glulam): 5 million m³ (2.7 Europa, 2.0 Asia, 0.3 North America, UNECE/FAO 2014) CLT: 0.6 million m³
Main producer	GLT production in Europe is heading for 4 million m³ annually. About 90% of CLT production worldwide is located in Europe, with a total production volume of 560 thousand m³ in 2014.
Specifics for poplar, aspen, willow,…	Poplar has been assessed as alternative for softwood to produce glulam, often combination with other hardwoods are investigated (Castro and Paganini 2003). A CLT product option is not yet fully assessed for poplar.
Strengths +	Structural glued-laminated timber (glulam) is one of the oldest glued engineered wood products. CLT started in the 90's at KLH in Austria. An increase of 10% on an annual basis

	shows potential for not only softwood species. Worldwide, the use of CLT as a building product is expected to grow at rates in the double digits. Within the next decade, therefore, CLT could become as important as glue-laminated timber, and it is likely to extend the limits of tall wooden buildings upwards (UNECE/FAO 2015).
Weaknesses -	The actual scope to use CLT as important component for tall buildings has triggered some concern related to the performance related to wood decay (Taylor *et al.* 2016).
Opportunities !	Hybrid CLT, e.g. beech and spruce (Aicher *et al.* 2016) was developed to overcome low rolling shear properties in cross layers (Ehrhart *et al.* 2015).
Threats ?	Often standards are developed based on softwood species and unfortunately there is a time lag for hardwoods, e.g. EN 14080 (2013) on GLT and EN 16351 (2014) on CLT.

Veneer based products

High quality trees are often processed beyond sawing using veneer production primary processing. Trees should primarily be straight, cylindrical and have a large diameter. Modern technology allows to process trees based on lower tree quality requirement but ease to peel or cut veneers is key especially for high volume products.

VENEER	
Definition	VENEER SHEETS Thin sheets of wood of uniform thickness, not exceeding 6 mm, rotary cut (i.e. peeled), sliced or sawn. It includes wood used for the manufacture of laminated construction material, furniture, veneer containers, etc. Production statistics should exclude veneer sheets used for plywood production within the same country.
World production (2014)	Veneer: 13.5 million m³
Main producer	PRChina: 3.0 million m³
Specifics for poplar, aspen, willow,…	The match industry as well as a segment of the packaging industry, for example for fruit and vegetable baskets and cheese boxes, also use poplar veneer. Finally, manufacturers of several small specialty products for the food and health care sectors also prefer poplar veneer, for example popsicle sticks, chopsticks, tongue depressors (Balatinecz *et al.* 2014) Rotary veneer peeling of poplar and aspen has been already early an important primary processing with focus on several specific products like packaging (often in contact with foods like cheese, fruit, vegetables,…), matches and as part of plywood production. Aesthetic quality is often not valued but can be useful for decorative products either using the whiteness, which can be combined with printing and colouring and even as sliced veneer there is a potential for these wood species. Rotary cut poplar veneers can be combined into multilaminar wood (MLW) to produce

	decorative materials and mimic fancy woods (Castro and Zanuttini 2004).
Strengths +	Veneer production is considered a high end primary processing of trees and it enables to transmit properties from the tree more directly in the products maximizing as such the natural resource potential.
Weaknesses -	Often veneer production is considered to be limited by the availability of suitable trees.
Opportunities !	Spindle-less lathes allow to produce veneer with up to 70 % yield and to process smaller trees.
Threats ?	Veneer based products are often considered to require adequate forest management to obtain quality trees. The related costs and the need to have active qualified forestry staff is sometimes not fully acknowledged by nature and forest services.

The main veneer based product is plywood, considered the highest quality wood based panel. Laminated veneer lumber (LVL) is a related veneer based product used primarily as a 1D engineered wood product.

PLYWOOD & LVL (Laminated Veneer Lumber)	
Definition	PLYWOOD A panel consisting of an assembly of veneer sheets bonded together with the direction of the grain in alternate plies generally at right angles. The veneer sheets are usually placed symmetrically on both sides of a central ply or core that may itself be made from a veneer sheet or another material. It includes veneer plywood (plywood manufactured by bonding together more than two veneer sheets, where the grain of alternate veneer sheets is crossed, generally at right angles); core plywood or blockboard (plywood with a solid core (i.e. the central layer, generally thicker than the other plies) that consists of narrow boards, blocks or strips of wood placed side by side, which may or may not be glued together); cellular board (plywood with a core of cellular construction); and composite plywood (plywood with the core or certain layers made of material other than solid wood or veneers). It excludes laminated construction materials (e.g. glulam), where the grain of the veneer sheets generally runs in the same direction. Non-coniferous (tropical) plywood is defined as having at least one face sheet of non-coniferous (tropical) wood. LAMINATED VENEER LUMBER - LVL Laminated veneer lumber (LVL) is manufactured by bonding thin wood veneers together under heat and pressure. Once it is fabricated into billets of various thicknesses and widths, it can be cut at the factory into stock for headers and beams, flanges for prefabricated wood I-joists, or for other specific uses. Veneer thicknesses range from 2.5mm to 4.8mm and common species are Douglas fir, larch, southern yellow pine and poplar.
World production (2014)	Plywood: 147.6 million m³ LVL: 4.6 million m³ (estimated)
Main producer	Plywood: PRChina: 104.0 million m³

	LVL: 1.7 million m³ in North America (UNECE/FAO 2015), however some estimation related to consumption indicate a total amount of 4.0 million m³ (estimated). Pollmeier (Germany) commenced production of beech LVL in 2014 and plans to produce 150.000–180.000 m³ of this product per year (UNECE/FAO 2014).
Specifics for poplar, aspen, willow,…	PLYWOOD Poplar wood is well suited for the manufacture of veneer and plywood, but veneer and plywood production requires logs of the highest quality. Poplar peeler logs need the least preconditioning of any species, because of the wood's low density, good machining characteristics and its high green MC (Balatinecz *et al.* 2014). The production of poplar plywood in North America has declined and been displaced by OSB. However, in Europe, and especially in China, the poplar plywood industry is thriving, largely because of the availability of good-quality peeler logs from plantations and good market demand (Balatinecz *et al.* 2014). Italy, on the other hand, has a long history of producing plywood for the furniture industry. These plywoods are lighter because the clone 'I-214' is used, which has a low intrinsic density. Also, very special boards with coloured veneers are produced, for example, for design furniture. Poplar veneer can also be used as core to make exotic plywood with (imported) decorative face veneers (Balatinecz *et al.* 2014) LAMINATED VENEER LUMBER - LVL Aspen (*Populus tremuloides*) is a relatively new substitute species in North America for LVL production. Compared to traditional Douglas fir and southern yellow pine, this species is relatively weak. (Wang and Dai 2005). Structural LVL must be manufactured with a waterproof adhesive. Its end uses cover both residential and non-residential construction in such applications as support beams, trusses, rafters and purlins. Non-structural LVL may be used in windows, door frames, stairs, furniture and fixtures and kitchen cabinets. Structural LVL consumption is concentrated in North America because of the strong tradition and preference for wood frame technology for residential construction. However, significant volumes are also used in Europe, primarily in architectural applications (Balatinecz *et al.* 2014). It is worthy to note that two LVL mills in Canada pioneered the manufacture of aspen LVL. The success of these mills demonstrate that poplars are very suitable for LVL production. The suitability of hybrid poplar for LVL has been evaluated in Canada (Knudson and Brunette 2002). There is a considerable interest to use low density hardwood species for the production of LVL (Shukla and Kamden 2008). Rahayu and co-authors (2015) underlined the potential of European poplar clones for LVL production.
Strengths +	Plywood is still assessed as a high quality product. Plywood exists since over 100 years, LVL is present since the 40's. In Europe Kerto LVL was initiated in the 70's. Due to the superior performance plywood and OSB are gaining popularity in a variety of areas, in structural and non-structural applications. LVL shows 10% higher yield than glulam/CLT and is more homogeneous. Most LVL in North America is used in new-home construction. In 2014, 73% of total consumption was used in beams and headers, rim boards and similar applications, and

	the balance was used in I-joist flanges (APA 2015). Standard applications for LVL are I-joists, posts, beams and headers, roof truss chords, wood-frame construction, panels and prefabricated building elements and hence key in the increased use of timber construction.
Weaknesses -	Considered low innovation because already since longer period available. Forestry needs to provide large-diameter trees and the stem form is critical.
Opportunities !	Both plywood and LVL are still the high quality products that can be obtained from fast growing trees. Although veneer-based products exist since very long there are still innovative products being developed, e.g. veneer-based I-beams called ultra high performance plywood (UHPP) (Grabner *et al.* 2014, 2016).
Threats ?	Main increase in volume can merely come from fast growing plantation trees.

Particle based products

Chipping of wood and recovered wood products as well as several other lignocellulosic resources can be used to produce wood based panels and related products by gluing particles. Particleboard is considered to be a general term while chipboard is considered to be non-structural and based on smaller particles while oriented strand board was developed to replace plywood as more structural panel. Consideration on structural use of wood based panels are compiled in the standard EN 13986 (2002).

PARTICLEBOARD – OSB (Oriented Strand Board)	
Definition	PARTICLE BOARD A panel manufactured from small pieces of wood or other lignocellulosic materials (e.g. chips, flakes, splinters, strands, shreds, shives, etc.) bonded together by the use of an organic binder together with one or more of the following agents: heat, pressure, humidity, a catalyst, etc. The particle board category is an aggregate category. It includes oriented strandboard (OSB), waferboard and flaxboard. It excludes wood wool and other particle boards bonded together with inorganic binders. ORIENTED STRANDBOARD - OSB A structural board in which layers of narrow wafers are layered alternately at right angles in order to give the board greater elastomechanical properties. The wafers, which resemble small pieces of veneer, are coated with e.g. waterproof phenolic resin glue, interleaved together in mats and then bonded together under heat and pressure. The resulting product is a solid, uniform building panel having high strength and water resistance.
World production (2014)	PB: 110.9 million m^3

Main producer	PB: PRChina: 20.6 million m³
Specifics for poplar, aspen, willow,…	Poplars and willows are well suited for the manufacture of particleboard, especially because of their good bonding characteristics and compressibility (Geimer and Crist, 1980). Some issues related to wooliness of particles from tension wood zones was discussed. The production and quality of hybrid poplar based OSB was confirmed by Zhou (1989 and 1990) as well as OSB based on willow by Tröger and Wegener (1999).
Strengths +	PB: Can also use residues, and recovered wood is being used increasingly in Europe. OSB: The quality and strength of composites are generally uniform and they do not exhibit common wood defects such as knots and splits found in lumber. Due to the superior performance plywood and OSB are gaining popularity in a variety of areas, in structural and non-structural applications.
Weaknesses -	Impact of moisture and time related mechanical properties limit the structural uses of particle based panels.
Opportunities !	Particle based panels are less dependent on softwoods and can introduce mixture with hardwoods and even full hardwood based production easily. Low VOC emissions are considered important for many wood products but a lot of attention is going to this topic for particleboard production sites. Poplar/aspen offer some advantages compared to pine (Paczkowski *et al.* 2013).
Threats ?	Although particleboard was originally linked to small assortments from managed forest and forest residues it has become more dependent on residuals form the wood industry and recovered wood. Although this is less valid for OSB the increased competition for resources with the bioenergy sector is having an impact.

Similarly as LVL shows similarity with plywood, also particleboard technology evolved in the production of beam-like products. Alongside the OSB (oriented strand board) and equivalent OSL (oriented strand lumber) and LSL (laminated strand lumber) using longer strands, veneer strips can be used to produce parallel strand lumber (PSL). Together with LVL (see above) these products are called composite lumber. When combining these lumber alike products with panels, for example OSB or plywood, generating I-shaped beams we can call all these products structural composite lumber (SCL).

STRUCTURAL COMPOSITE LUMBER	
Definition	STRUCTURAL COMPOSITE LUMBER - SCL An engineered wood product designed for structural use, SCL is manufactured from wood strands or veneers bonded with adhesives and created using a layering technique where the outcome is a block known as a billet. Similar to conventional sawn lumber and timber, SCL products are used for common structural applications and include laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL) and oriented strand lumber (OSL).

	LAMINATED STRAND LUMBER - LSL Laminated Strand Lumber (LSL) is the latest engineered wood product to come onto the market. This revolutionary product is used for a broad range of applications including rim board, millwork and window, door and garage door headers, as well as for many industrial uses. New uses for this product are still evolving, including the use of LSL for vertical members in commercial applications where the framing member heights are long, and the wind loads are substantial. LSL resembles oriented strand board in appearance because like OSB, LSL is made from long strands coming from fast-growing aspen or poplar. However, unlike OSB, the strands are arranged parallel to the longitudinal axis of the member. Like other engineered wood products like LVL and PSL, LSL offers predictable strength, outstanding weatherability and dimensional stability that minimizes twist and shrinkage. ORIENTED STRAND LUMBER - OSL Oriented strand lumber (OSL) is made from flaked wood strands with a high length-to-thickness ratio. The manufacture of OSL also represents the efficient utilization of wood resources because it makes use of strands from fast-growing and underutilized species. The strands are oriented and combined with an adhesive to form a large mat or billet and then pressed. OSL is used in a variety of applications such as studs, beams, headers, rim boards and millwork components. The strands used in OSL are shorter than that used in LSL. Both LSL and OSL offer good fastener-holding strength. PARALLEL STRAND LUMBER - PSL Parallel strand lumber (PSL) is a high strength structural composite lumber product manufactured by gluing strands of wood together under pressure. It is a proprietary product marketed under the trade name Parallam®. Because it is a glued-manufactured product, PSL can be made in long lengths but it is usually limited to 20 m by transportation constraints. I-JOISTS Prefabricated wood I-joists are made by gluing solid sawn lumber or laminated veneer lumber (LVL) flanges to a plywood or oriented strandboard (OSB) panel web to produce a dimensionally stable light-weight member with known engineering properties.
World production (2014)	Proportional to the LVL production the different structural composite lumber products are produced in lower volumes but their engineering aspect is considerable. I-beams: 200 million linear meters in North America (UNECE/FAO 2014)
Main producer	North America (USA and Canada) as main producer and exporter.
Specifics for poplar, aspen, willow,…	PSL: Chen *et al.* (1994) reported that hybrid poplar was suitable for the manufacture of PSL. A product, by the name of 'Scrimber', which is somewhat similar to PSL (original PSL product, 'Parallam', was developed by McMillan-Bloedel during the 1970s), was developed in Australia during the 1970s, and this technology was later 'resurrected' in the USA under the brand name 'TimTek'. A similar product has also been developed in Japan by the name of SST ('Super Strength Timber') for the utilization of small-diameter plantation materials (Suzuki 2005). Both SST and TimTek claim very high yields (over 85%) of finished product. These technologies may offer new opportunities for composite lumber production from small-diameter, short rotation poplars and willows (Balatinecz *et al.* 2014). LSL: This is a typical North-American product is primarily made from long strands

	coming from fast-growing aspen or poplar. I-JOIST: There is a potential opportunity for the utilization of poplars in I-joists, where both the web and the flange may be made of poplar, for example poplar OSB and poplar LVL. Since hybrid poplars are suitable for the production of both OSB and LVL (Hua *et al.* 1994), they could also be used in the manufacture of I-joists via OSB and LVL (Balatinecz *et al.* 2014). One issue which needs to be evaluated is the stress rating of hybrid poplar I-joists, based on actual products, because of the lower density and structural strength of these materials.
Strengths +	With its ability to be manufactured using small, fast-grow and underutilized trees, SCL represents an efficient use of wood resources as it helps to meet the challenge of increasing demand for quality structural lumber. As part of the engineered wood products family, SCL has been successfully used in a variety of areas used as headers and beams, truss chords, I-Joist flanges, columns and studs and other applications. Structural composite lumber is a growing segment of the engineered wood products industry and specifications are available (APA 2016).
Weaknesses -	PSL and LSL are manufactured primarily by a single company, and production volumes are low compared with other EWP. OSL is in production at a single plant converted from OSB production: uses are expected to be the same as for solid sawn lumber and glulam, such as posts, beams, headers, rim boards and structural framing lumber (UNECE/FAO 2015). The company Weyerhauser, which is producing TimberStrand® LSL, Microllam® LVL, and untreated Parallam® PSL, indicated in their TJ-9000 specifier’s guide that these products are intended for dry-use applications. Moisture dynamics of such products are of importance (Cai *et al.* 1997).
Opportunities !	Structural composite lumber production and use has to grow beyond its origin in North-America. At least some products are not just focussed on softwoods.
Threats ?	The proportion of glue included and the technology and energy aspects of the production process has an impact on competitiveness of SCL products.

Fibre based products and hybrid products

Fibre based products are not the first product range to consider when discussing structural applications. Nevertheless, a range of wood products are based on primary processing technology similar to the pulp and paper sector. Under the heading fibreboard traditional products are hardboard and softboard (or insulation board) while the dry-process product introduced more recently is referred to as medium density fibreboard (MDF). Especially for fibreboard the density (specific gravity) is an important classification factor (Figure 1).

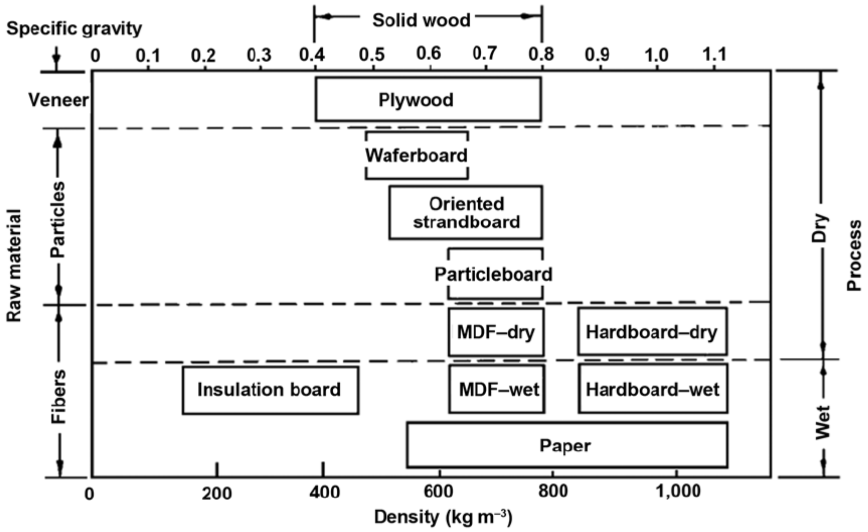

Figure 1: Classification of wood composite panels by particle size, density, and process (Suchsland and Woodson 1986).

FIBREBOARD	
Definition	FIBREBOARD A panel manufactured from fibres of wood or other lignocellulosic materials with the primary bond deriving from the felting of the fibres and their inherent adhesive properties (although bonding materials and/or additives may be added in the manufacturing process). It includes fibreboard panels that are flat-pressed and moulded fibreboard products. It is an aggregate comprising hardboard, medium density fibreboard (MDF) and other fibreboard. HARDBOARD Wet-process fibreboard of a density exceeding 0.8 g/cm^3. It excludes similar products made from pieces of wood, wood flour or other lignocellulosic material where additional binders are required to make the panel; and panels made of gypsum or other mineral material. MEDIUM DENSITY FIBREBOARD - MDF This is a dry-process fibreboard. When density exceeds 0.8 g/cm^3, it may also be referred to as "high density fibreboard" (HDF). MDF production was introduced based on continuous chipboard production technology and requires glue as binder for the fibres. INSULATING BOARD Wet-process fibreboard of a density not exceeding 0.5 g/cm^3. Alternatively identified as softboard.
World production (2014)	Hardboard: 12.3 million m^3 MDF: 93.5 million m^3 Insulation board: 9.9 million m^3

Main producer	Hardboard: PRChina: 6.1 million m³ MDF: PRChina: 56.8 million m³ Insulation board: USA: 4.9 million m³
Specifics for poplar, aspen, willow,…	Fibre material of willow and poplar wood is very suitable for the production of all different types of fibreboard (Scheithauer, 1999). The feedstock material usually comes from residues, such as planer shavings, sawdust and wood chips. The raw material is considered very suitable to be converted to fibres by thermomechanical pulping (Balatinecz *et al.* 2014).
Strengths +	Pulping primary processing is largely independent of the tree diameter or volume and variability in wood properties within a tree can easily be handled as technical fibres are mixed.
Weaknesses -	Most fibreboards are sheathing products and beam like elements are considered inadequate for structural applications.
Opportunities !	The value added for pulp based wood products is higher than when converting biomass into energy but very similar production systems like short rotation coppice could be used to control supply – demand.
Threats ?	Wood fibres can be used to improve performance of man-made products like plastics and mineral based panels sometimes merely as filler giving little credit to the complexity of wood as a natural composite.

Although fibreboards are less prominent as engineered wood products the hybrid product with cement or plastic has become important products for the building sector. Wood-cement products are considered high quality products as performance of these mineral bonded composites is enhanced considerably compared to pure cement or board.

WOOD-CEMENT PRODUCTS (mineral-bonded wood composites)	
Definition	Cement-bonded wood composites are strands, particles, excelsior or fibres of wood mixed together with cement (usually Portland cement) and manufactured into panels, tiles, slabs, blocks, bricks and other products used in the construction industry (Balatinecz *et al.* 2014) Cement boards are made of mixtures of cement, water and either reinforcing fibres or particles. The resulting mix is formed into sheets or continuous mats, stacked (and/or pressed), dried and trimmed to size. There are four distinct categories according to Saunders and Davidson (2014): fibre cement board (FCB), wood wool cement board (WWCB), cement bonded particle board (CBPB) and wood strand cement board (WSCB).
World production (2014)	Estimated production of fibre cement board is 26 million tons. Wood cement board often contain approx. ¼ wood. Market is expected to grow more than 4 % on annual basis.
Specifics for poplar, aspen,	Some researchers are looking for specific opportunities for poplar (Ashori *et al.* 2011).

willow,…	
Strengths +	Wood–cement composites benefit from the positive attributes of each component material, resulting in a more desirable end product. Cement contributes high compressive strength, excellent fire resistance, enhanced durability and dimensional stability. Wood fibres and particles, on the other hand, add improved flexural strength, fracture toughness, lower density and superior thermal- and sound-insulation properties (Balatinecz *et al.* 2014). Wood-cement boards, fibre-cement boards, gypsum fibreboards, and gypsum particleboards are now manufactured in various parts of the world (Frybort *et al.* 2008). Because of the mineralization of the fibres, the boards possess high resistance to bio-degradation and fire.
Weaknesses -	Fibre and particle based wood-cement boards are twice as heavy as gypsum-based board systems and more expensive. Though fibre cement board can be cut with a saw, the dust can be considered toxic to breathe, so installers must wear masks.
Opportunities !	Exist since over 60 years. Fibre cement's ability to mimic the appearance of wood while offering greater durability will boost demand in siding applications.
Threats ?	There are limited indications that wood species are important for compatibility (Na *et al.* 2014) although the impact of extractives has been considered (Nazerian *et al.* 2011).

The hybrid products between wood and plastic are mainly produced through co-extrusion with the main objective to lower the temperature impact of the plastic component and to increase the moisture protection of the wood component. These so-called wood plastic composites are very popular as decking and cladding commodities but sometimes also used as post or fence component.

WOOD-PLASTIC COMPOSITES	
Definition	Wood–plastic composites (WPCs) are intimate mixtures of wood fibres or particles dispersed and encased in a polymer matrix. Both thermoplastic and thermoset polymers are used in industry (Balatinecz *et al.* 2014).
World production (2014)	WPC: 2.5 million m³ or 3.0 million tons estimated (50% is wood) This market is expected to grow some 10 % on annual basis.
Main producer	Approximately half of the worldwide production is located in North America.
Specifics for poplar, aspen, willow,…	WPCs can also use poplars and willows as feedstock materials (Balatinecz and Sain 2007).
Strengths +	The fact that Wood–plastic composites (WPCs) are durable and suitable for many long-term applications, are easily reused and recycled, contain no harmful substances and can be manufactured into a wide range of consumer and industrial products with relatively low energy consumption gives these materials a strong competitive position

	in the marketplace when material choices are made (Balatinecz *et al.* 2014).
Weaknesses -	Durability and long service life are not fully guaranteed without additional protection against decay (Defoirdt *et al.* 2010).
Opportunities !	Besides wood also natural fibres can be used to produce combined product with a potential for structural uses. The use of bio-based resins in future will enhance potential of combining decay control of the wood component through steering moisture dynamics with an improved end-of-life concept through full biodegradability.
Threats ?	The wood resource for wood plastic composites is suitable for the very competitive production of pellets for bioenergy.

Treated engineered wood products

Durability or material resistance against decay is considered an important weakness of wood and wood products. Related to the use class there will be a difference in hazard or risk that performance will not lead to a desired service life. Wood preservation has been since long a key method to increase the potential in this respect. Alongside biocidal treatments other wood protecting systems are possible and to enhance also properties like dimensional stability several wood modification methods have been developed over the last decades. Also treatments with fire retardants show several similarities in technology used.

TREATED WOOD & MODIFIED WOOD	
Definition	PRESERVATIVE-TREATED WOOD Preservative-treated wood is wood which has been surface coated (non-pressure treated wood), where the application of preservative is by brushing, spraying or dipping the piece) or impregnated by means of pressure with chemicals (Pressure Treated Wood) which improves resistance to damage from decay and insect attack. MODIFIED WOOD (Hill, 2006) Wood modification involves the action of a chemical, biological or physical agent upon the material, resulting in a desired property enhancement during the service life of the modified wood. The modified wood should itself be nontoxic under service conditions and, furthermore, there should be no release of any toxic substances during service, or at end of life following disposal or recycling of the modified wood. If the modification is intended for improved resistance to biological attack, then the mode of action should be nonbiocidal. Chemical modification of wood is defined as the reaction of a chemical reagent with the wood polymeric constituents, resulting in the formation of a covalent bond between the reagent and the wood substrate. Commercial processes available are acetylation and furfurylation. The thermal modification of wood is defined as the application of heat to wood in order to bring about a desired improvement in the performance of the material. Of all the various wood modification processes that have been studied, thermal modification

	is by far the most advanced commercially. Thermal modification is invariably performed between the temperatures of 180°C and 260°C, with temperatures lower than 140°C resulting in only slight changes in material properties and higher temperatures than 260°C resulting in unacceptable degradation to the substrate. THERMALLY MODIFIED TIMBER – TMT (CEN/TS 15679 2007) Wood at which the composition of the cell wall material and its physical properties are modified by the exposure of temperature higher than 160°C and conditions of reduced oxygen availability. The wood is altered in such way that at least some of the wood properties are permanently affected through the cross section of the timber. FIRE-RETARDANT-TREATED WOOD (FRTW) Fire-retardant-treated wood is wood which has been impregnated with fire-retardant chemicals in solution under high pressure.
Production worldwide (2014)	The pressure-treated wood industry is producing approximately 16.5 million m³ of preserved wood per year. In Europe the wood preserving industry produces around 6.5 million m³ of pressure-treated wood per year. Modified wood production can be estimated at about 250 000 m³ in total, of which 60 000 m³ is chemical wood modification (acetylation, furfurylation,…).
Main producer	USA is the main producer of pressure treated wood. Europe is the main producer of modified wood.
Specifics for poplar, aspen, willow,…	Poplar and poplar products like plywood are not durable and hence treatment has been assessed (Cooper 1976; De Boever *et al.* 2008). Treatability of poplar, aspen and willow can be considered rather straightforward but still requires some technicalities due to difficult to impregnate transition zones (Murphy *et al.* 1991; Van Acker *et al.* 1990; Van Acker and Stevens 1995). Poplar is a very good wood species to obtain enhanced quality in very good products based on both thermal and chemical wood modification and different treating and modification processes can be used adequately (Fraanje 1998). Also plywood can be considered non-durable and protective treatments can be necessary to comply with service life expectations in harsher environments (Zannutini *et al.* 2003; De Smet and Van Acker 2006; Van Acker 2008) However, when considering also the moisture dynamics some plywood products can perform quite well in outdoor conditions without ground contact (Van den Bulcke *et al.* 2011, Li *et al.* 2016).
Strengths +	Durable and stable wood species are only to a limited extent available and treatments focussing on increasing these properties either by vacuum-pressure treatment using biocides, other protective measures or by fit-for purpose wood modification allow to use a wider scope of forest resources, e.g. fast grown plantation timber for higher end applications.
Weaknesses -	Inevitably when requiring a treatment or modification one points out that wood as such has some minor properties related to service life and stability both mainly linked to moisture impact.

Opportunities !	Wood protection and modification can increase the potential use of poplar and poplar products considerably. Some Garnica plywood products developed recently are good examples (Sufrategui *et al.* 2016).
Threats ?	Architects and engineers involved in construction with wood often prefer to avoid treatments with chemicals.

CONCLUSIONS

More wood is consumed every year in the United States than all metals and all plastics combined. Wood is a renewable resource and it is infinitely renewable as long as the forests from which it is obtained are managed sustainably.

Wood has to be considered a serious alternative when building today and Engineered Wood Products (EWP) will definitely become an increasingly more important part in this. EWP have some main advantages: (1) Fast: short building time, often 30% faster, (2) Light: very good strength-stiffness ratio and (3) Green: sustainable especially when using bioenergy.

Green building activities are said to double every 3 years and this is very positive for wood in construction. Also the trend to build taller buildings with wood products can be used as a stimulus for engineered wood products.

Although many engineered wood products originate from developments based on softwoods, there are many parameters indicating that poplar, aspen and willow have the potential to increase production volumes in this context. Taking into account the genetic improvements, the experience in plantation production systems and the adequate option for processing this resource allows for a bright future of the poplar, aspen and willow forestry - wood industry chain.

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