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ENGINEERED WOOD FLOORING WITH A DENSIFIED SURFACE LAYER FOR HEAVY-DUTY USE

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High-density wood is required in wood flooring, especially in engineered wood flooring (EWF) designed for heavy-duty applications. However, high-density wood resources are limited and their cost is high. A densification treatment makes it possible for low- or moderate-density woods to replace harder species by modifying them into high-performance and high-value products, such as engineered wood flooring for heavy-duty applications. The general objective of this study was to develop a prototype of engineered wood flooring using sugar maple hygro-thermally densified surface layers. The results showed that thin sugar maple lumber densified at 200 °C under the combined effects of steam, heat, and pressure with a heat-resistant fabric had great potential for the manufacturing of engineered wood flooring for heavy-duty use. As a result of treatment, it acquired high density, improved mechanical properties, and it had a relatively high dimensional stability and an attractive color. Tests in conditioning rooms showed that the EWF with a densified sugar maple (*Acer saccharum* March.) surface layer presented the lowest amplitude distortion between the dry and humid conditions compared with the standard EWF (0.15 mm *vs.* 0.17mm and 0.25mm).

Keywords: Engineered wood flooring; Wood densification; Compression; Sugar maple

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INTRODUCTION

Species used in wood floor covering are limited by their density. Professional associations, such as the National Wood Flooring Association (NWFA) and flooring manufacturers rank wood species according to their Janka hardness. Common applications for wood flooring are related to residential building construction. Architects seldom specify wood flooring for commercial or high-traffic areas, and when they do, they prefer the high densities provided by tropical hardwoods or acrylate-impregnated wood (such as the Nydree™ product). North American species, such as hard maple and red oak, do not achieve the density levels required for these uses, even though they rank highly with the NWFA. Considering the limited resources and high cost, high-density wood is generally used as a surface layer in EWF construction. EWF substrate is usually made from plywood, HDF (High Density Fiberboard), or wood sticks. The use of wood sticks or HDF substrate normally imposes the need to use a backing layer.

A densification treatment makes it possible for low- or moderate-density woods to replace harder species by modifying them to meet the higher hardness requirements. Many wood densification processes have been developed to enhance mechanical properties and improve physical properties (Boonstra and Blomberg 2007; Fukuta *et al.* 2008; Gabrielli and Kamke 2008; Higashihara *et al.* 2000; Inoue *et al.* 1993a; Inoue *et al.*

1993b; Inoue *et al.* 2008; Ito *et al.* 1998b; Kamke 2006; Kollmann *et al.* 1975). These processes increase wood density by compressing wood to reduce its void volume, by impregnating the void volume with a chemical liquid that is then polymerized in the wood, or by combining compression and impregnation. However, unlike physical or mechanical compression, chemical impregnation affects the natural and recyclable character of wood, and is usually more expensive (Navi and Heger 2004). Mechanical compression processes have been reported for over a century (Fang *et al.* 2011c). However, compressed wood of this type is dimensionally unstable. Compression set recovery over time is often a problem following moisture absorption (Inoue *et al.* 1993a; Navi and Girardet 2000).

In order to improve dimensional stability, various densification processes combined with steam and heat have been attempted (Boonstra and Blomberg 2007; Gabrielli and Kamke 2008; Higashihara *et al.* 2000; Inoue *et al.* 1993a; Inoue *et al.* 2008; Ito *et al.* 1998a; Kamke 2006; Navi and Heger 2004). Some of these still cannot solve the dimensional stability problem. Other processes are lengthy or complex, and limited to batch processes. Furthermore, most deal with small wood specimens. Previous studies on aspen (*Populus tremuloides* Michx.) veneers (Fang *et al.* 2011a,b; Fang *et al.* 2012) describe a relatively simple densification process, and the resulting high-density wood also exhibits good physical and mechanical properties. The objective of this study was to develop an engineered wood flooring (EWF) product for heavy-duty applications, using a densified sawn surface layer of sugar maple (*Acer saccharum* March.). The physical and mechanical properties of the densified wood were also determined.

EXPERIMENTAL

Materials

Thinly-sawn strips of sugar maple (*Acer saccharum*) were obtained from LAUZON Distinctive Hardwood Flooring, Papineauville, Quebec. These components are typically used in EWF products. The nominal thickness of the strips was 3.5 mm. The length and width were 700 mm and 90 mm, respectively. They were conditioned to constant mass at 20 °C and 60% relative humidity (RH) before treatment.

Densification Treatment

The general densification process was described in previous work (Fang *et al.* 2012). Densification treatments were performed at 200 °C and 180 °C. After densification at 200 °C, the wood frequently carbonized. After numerous tests, it was found that separating the specimens from the hot platens with a thin steam-permeable material prevented carbonization and improved dimensional stability (see Results and Discussion). Finally, a special heat-resistant fabric made of Nomex® III A, manufactured by Dupont™, was used for maple densification at 200 °C. The theoretical compression ratio was 35%.

Physical and Mechanical Properties of the Densified Surface Layer

Oven-dry density was measured on both densified and non-densified (control) specimens.

After densification, the thickness of oven-dried specimens (T_C) was measured. The specimens were then saturated with water until their weight became stable. Following this, the specimens were oven-dried and their thickness (T_R) was measured again. Compression set recovery (R) was calculated as follows,

$$R = \frac{T_R - T_C}{T_O - T_C} \times 100\,(\%)$$

(1)

where T_O is the specimen thickness before densification at an equilibrium moisture content at 20 °C and 60% RH.

Equilibrium moisture content (EMC) at 20 °C and 60% RH, and saturated moisture content (SMC) were measured to determine the effect of the densification treatment on wood hygroscopicity. The SMC was measured after soaking to stable specimen weight at room temperature.

Specimen dimensions under oven-dry and water-saturated conditions were measured in the thickness, width, and length directions. Swelling in the wet condition was calculated from the expansion observed as a percentage of the initial oven-dry dimension. Swelling was calculated in thickness (compression direction), width, and length.

Wood color was measured with a portable spectrocolorimeter (Color-Guide 45/0, BYK Gardner) using a 10° standard observer and standard illuminant D65. CIE $L*a*b*$ color coordinates were calculated from the measured spectra. The $L*a*b*$ coordinates locate the color in a three-dimensional color space. The $L*$ coordinate is scaled so that 0 corresponds to black and 100 to white. Negative values for color coordinate $a*$ indicate green, and positive values indicate red; negative values for $b*$ indicate blue, and positive values indicate yellow.

Brinell hardness tests were conducted in the spirit of the European Standard EN 1534 (2000). Three-point static bending tests were also performed according to ASTM D 1037-96a Standard (1997) to provide modulus of elasticity (MOE) and ultimate strength in bending.

All the properties were measured on both densified and non-densified (control) specimens. Measurements were taken on 40 specimens for each treatment.

Engineered Wood Flooring Prototypes – Manufacturing and Performance

Determination of Adhesion Performance

The sugar maple test specimens were densified. Adhesion tests were performed on maple specimens densified at 200 °C with a heat-resistant fabric. Non-densified maple was also tested as control.

A block shear test was conducted, in conformance with the ASTM D 905-03 (2003) standard, to determine adhesion properties. Densified and non-densified (control) maple strips were assembled between two non-densified maple blocks with a type II PVA (polyvinyl acetate) adhesive and prepared as presented in Fig.1. Thirty specimens were prepared and tested for both the densified and control maple strips. The shear blocks were fabricated such that the applied load was parallel to the grain of wood.
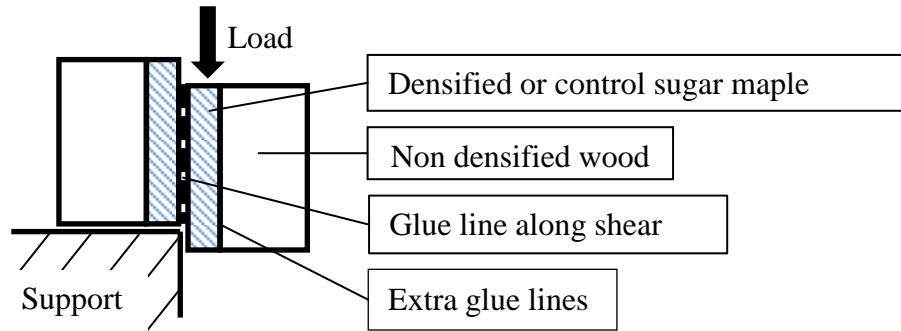
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Fig. 1 Set-up used to test the thin densified sugar maple strip in the spirit of ASTM D 905-03(2003)

EWF Manufacturing

In order to determine the performance of the EWF made with a densified sugar maple surface layer, three types of EWF prototypes were manufactured. The substrate selected for all EWF constructions was a 9 mm-thick Russian plywood widely used in the EWF industry; 2.4 mm-thick densified maple (3.5 mm pre-densification thickness) was used as a surface layer. For the controls, non-densified 2.4 mm-thick (Control 1) and 3.5 mm-thick (Control 2) maple were also used as surface layer. Prior to gluing, all plywood panels and maple strips were conditioned to constant mass at 20 °C and 50% RH. The conditioned substrate and surface layers were then sanded (using a 100-120-150 grit sequence) to ensure uniform thickness and proper gluing surfaces. The surface layers and substrates were glued with type II PVA (polyvinyl acetate) adhesive in a cold-press. Press time was 60 minutes at 1.03 MPa. The EWF prototypes were constructed with the grain of the maple surface layer perpendicular to the longitudinal surface direction of the substrate panel. Because the PVA adhesive is water based, another conditioning period at 20 °C and 50% RH was required to ensure uniform moisture content across the test specimens. Following the machining of tongues and grooves, the surface layers were sanded to a final EWF strip thickness of 10.7 mm for densified maple and Control 1, and 12 mm for Control 2. This last control was introduced to compare the EWF performance with the same mass of densified and non-densified EWF sugar maple surface layer. Twenty EWF strips were prepared for each test series. All EWF strips were varnished at AkzoNobel facilities in Warwick, Québec, Canada using a high solid content UV coating.

Varnish Adhesion Properties

Direct pull-off tests were performed to determine the adhesion strength of varnish on densified and non-densified (control) maple. In these tests, an aluminum dolly was bonded to the coating film with epoxy adhesive. The applied force required to remove the varnish film from the densified and non-densified maple was measured. The break between the aluminium dolly and the varnish was considered to be a bonding failure, and the value obtained was not taken into account. These tests were performed according to ASTM D 4541-02(2002).

Hygro-mechanical Behaviour of EWF Prototypes

Cupping deformation over the EWF surface layer was used as a quantitative performance indicator. The method and the cycle used were the same as those used by Blanchet *et al.* (2003) and Barbuta *et al.* (2010). The EWF strips were glued onto 610 x

1220 mm Permabase™ cement panels with Bostik Best™ adhesive. The edges of the assemblies were sealed with silicone in order to limit edge effects. The strips were tested for 3 weeks at 20 ℃ and 20% RH and 3 weeks at 20 ℃ and 80% RH. The distortion was measured at 0, 1, 3, 4, 7, 14, and 21 days at each condition with a dial gauge over the width of the EWF strips. Cupping measurements were conducted with a gauge moving along a reference line located at one-third of the floor edge assembly. Measurement accuracy was assured by meticulous installation of the gauge in the same position on the EWF strip and the number of replications on each floor (12 replications). Measurement accuracy was within 0.01 mm. An analysis of variance (ANOVA) on the maximum cupping deformation amplitude between the two cycles was conducted to determine the performance of the EWF prototypes. This amplitude was determined by calculating the difference between the highest and the lowest cupping deformation values.

Statistical Analysis

A statistical analysis was performed with SPSS Statistics software. S-N-K tests of multiple comparisons were performed to discriminate the observations.

RESULTS AND DISCUSSION

Densification Treatment

Preliminary work has shown that sugar maple specimens are frequently carbonized after densification at 200 °C, but not at 180 °C. To prevent carbonization, a heat-resistant fabric was used for maple densification at 200 °C and no carbonization was found. This is due to increased steam distribution by the fabric. In view of the carbonization observed at 200 °C without the fabric, the following discussion will deal exclusively with the results obtained from maple densified at 200 °C with the fabric and at 180 °C without the fabric.

Compression Set Recovery

Compression recovery over time following moisture absorption, also known as "shape memory effect" (Navi and Heger 2004), is often a problem in densified wood. A previous study (Fang *et al.* 2012) covering the effect of densification temperature on the compression set recovery of densified aspen and hybrid poplar veneers indicated that the higher the densification temperature, the lower the compression set recovery. A similar result was found in the present study. The average recoveries and standard deviations of maple densified at 180 °C (without fabric) and 200 °C (with fabric) were 30.5% ± 12.6 and 4.0% ± 3.3, respectively. Compared to the recovery levels observed at 200 °C (around 15%) by Fang *et al.* (2012), 4.0% recovery at 200 °C was very low. Such a low recovery is likely due to the contribution of the fabric used in the densification treatment, the mesh providing channels for uniform steam distribution over the maple surface. According to the mechanisms used to prevent compression set recovery (Fang *et al.* 2011a; Fang *et al.* 2012; Norimoto *et al.* 1993), the low recovery of maple densification with a fabric could be explained by hydrolysis of polysaccharides, especially hemicelluloses, due to increased steam distribution and penetration. A uniform steam distribution, especially during the post-treatment stage, can better relax stresses stored in the microfibrils and matrix during densification. Navi and Sandberg (2012) indicated that

hydrolysis of hemicelluoses during THM post-treatement plays an important role in the elimination of compresion recovery.

Effect of Densification on Wood Physical and Mechanical Properties

As a result of densification, the oven-dry density of the sugar maple strips increased significantly. The average oven-dry density and standard deviation of non-densified specimens were 712.7 ± 46.4 kg/m^3. They were 1020.0 ± 46.9 kg/m^3 and 1131.5 ± 64.5 kg/m^3, respectively, after densification at 180 °C and 200 °C.

The EMC at 20 °C and 60% RH, and saturation moisture content (SMC) values after water soaking were measured to determine wood hygroscopicity. The results are shown in Fig. 2. EMC decreased markedly after densification, especially at 200 °C. The EMCs of specimens densified at 200 °C averaged 5.9%, which was significantly lower than that of the controls and the specimens densified at 180 °C. The average SMC of the specimens densified at 200 °C was 57.8%, which was significantly lower than that of the controls and the specimens densified at 180 °C. The decrease in SMC after densification is related to wood porosity and cell wall hygroscopicity, as discussed in previous reports (Fang *et al.* 2011b; Fang *et al.* 2012).
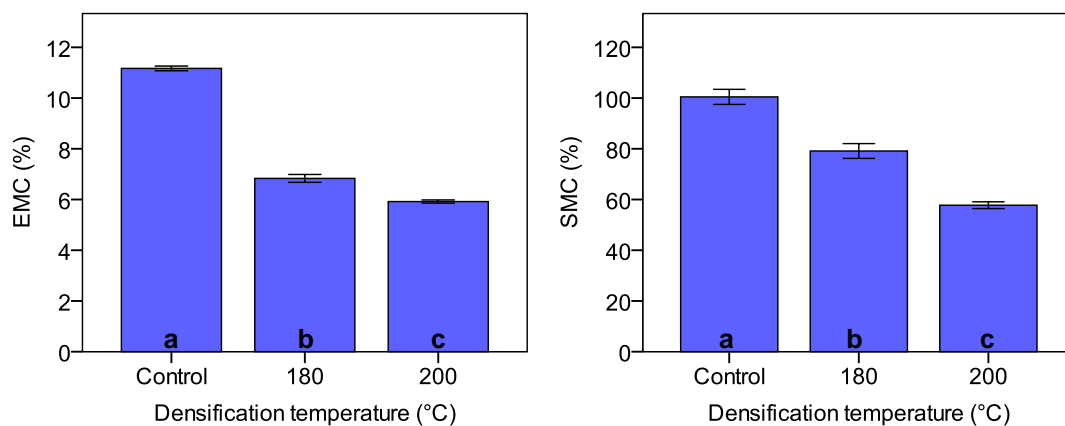

Fig. 2. Equilibrium moisture content at 20 °C and 60% relative humidity (EMC) and saturated moisture content after water soaking (SMC) of non-densified (control) and densified sugar maple strips. Value bars with different letters indicate a significant difference at the 0.05 level. Error bars show 95% confidence intervals.
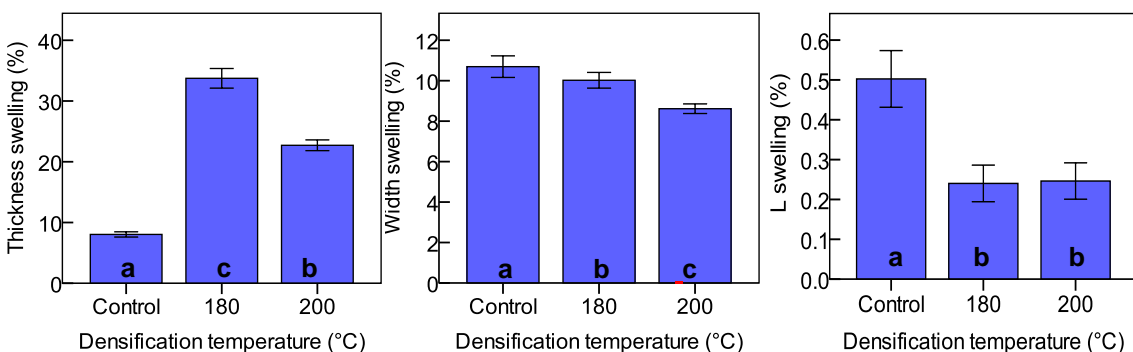

Fig. 3. Swelling in the thickness, width, and length (L) directions of non-densified (control) and densified sugar maple strips. Value bars with different letters indicate a significant difference at the 0.05 level. Error bars show 95% confidence intervals.

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Figure 3 shows swelling values from oven-dry to moisture-saturated conditions in thickness, width, and longitudinal directions for control (non-densified) and densified sugar maple. Very high thickness swelling (33.7%) was found for specimens densified at 180 °C. The average thickness swelling for specimens densified at 200 °C was 22.7%, which is significantly higher than that of the controls, but significantly lower than that of the specimens densified at 180 °C. The swelling of densified wood in compression (across the thickness) included reversible and irreversible swelling, reversible swelling being due to wood hygroscopicity, and irreversible swelling to compression set recovery. High thickness swelling may have been due to compression set recovery (Fang *et al.* 2011a). The lower compression set recovery for the specimens densified at 200 °C could explain the lower thickness swelling compared to that of specimens densified at 180 °C. Unlike thickness swelling, widthwise swelling decreased after densification. The swelling of specimens densified at 200 °C was significantly less than that of the controls and specimens densified at 180 °C. Reduced widthwise swelling might be caused by degradation of hydrophilic cell wall constituents, especially hemicelluloses during densification. Similar results were found for longitudinal swelling.

Color is an important characteristic for appearance products in general and for wood flooring in particular. Sugar maple darkened after densification and darkening intensity with increasing densification temperature. During hydrothermal treatment, the wood changes color, mainly because of the formation of colored degradation products from hemicelluloses and from extractive compounds (Navi and Sandberg 2012). After densification at 180 °C (Fig. 4), $L*$ decreased significantly, $a*$ increased significantly, and $b*$ increased slightly. Sugar maple became darker and more reddish after densification, especially at 200 °C. This is a generally desirable color in wood flooring.
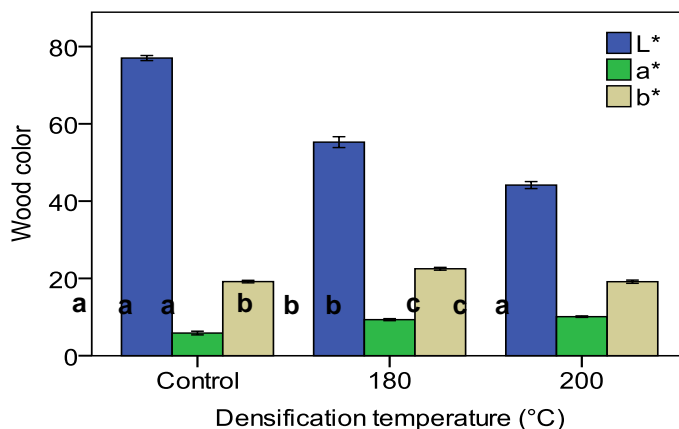

Fig. 4. Wood color change before (control) and after densification. Value bars with different letters indicate a significant difference at the 0.05 level. Error bars show 95% confidence intervals.

Improving mechanical properties is a primary goal of the densification treatment. The results obtained for Brinell hardness, bending strength, and MOE are shown in Fig. 5. For wood flooring, especially EWF designed for heavy-duty applications, hardness is a critical indicator. In this study, the Brinell hardness of the densified sugar maple strips was about twice that of the controls. A significant change in hardness due to densification has also been reported for different densification processes (Fang *et al.* 2012; Kamke 2006). The increase in hardness is generally linked to the increased density. In this

research, however, a decrease in hardness with increasing densification temperature was observed. This can be explained by the more advanced degradation of the matrix (hemicelluloses and lignin) due to the higher temperatures (Fang *et al.* 2012). The increased hardness observed in densified sugar maple remained comparable to that of Jatoba (*Hymenaea courbaril* L.), a species frequently used for high-grade wood floors. Similar results were found for bending strength (Fig. 5); bending strength increased significantly after densification. MOE also increased significantly after densification.
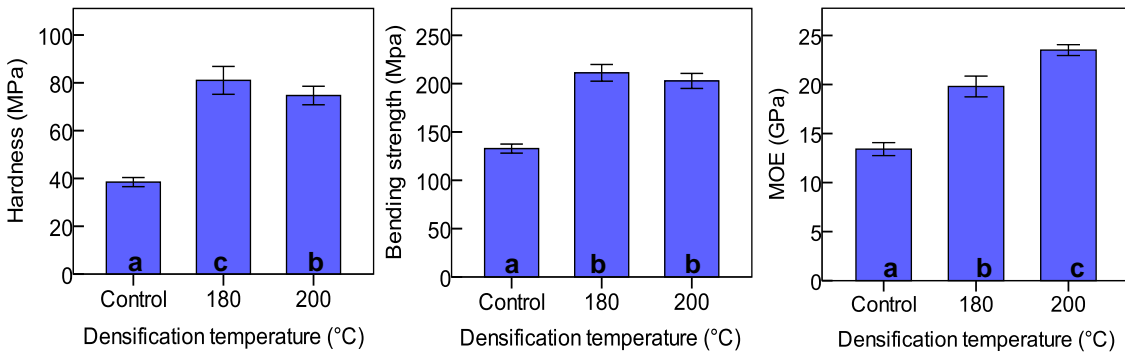

Fig. 5. Brinell hardness, bending strength and MOE of non-densified (control) and densified sugar maple strips. Value bars with different letters indicate a significant difference at the 0.05 level. Error bars show 95% confidence intervals.

Adhesion Performance

Table 1 shows the results of shear stress tests. The F-value (47.38) obtained from the ANOVA shows that the difference between densified and control specimens was significant at the 0.01 level. The maximum shear stress of the densified specimens was 27% lower than that of the non-densified specimens. This result is explained by the fact that it was more difficult for the glue to penetrate the densified surface of sugar maple. The densification treatment changed the wood structure through the effect of temperature and pressure, which affected mainly the mechanical adhesion by reducing the inter-locking surface or mechanical adhesion. The treatment could also change other wood properties such as diffusion, absorption, and chemical structure, which directly impact the penetration of the adhesive and adhesion performance. However, densified specimens showed markedly less variance than the controls.

Table 1. Results of Shear Stress Tests

	Mean shear stress (MPa)	Standard deviation	Coefficient of variation (%)
Control	17.9	2.5	13.9
Densified (200°C)	13.1	1.1	8.4

Varnishing Performance

Table 2 presents the mean pull-off stresses obtained from the control and densified specimens. The mean pull-off stress of densified specimens was 19% lower than that of non-densified specimens. The ANOVA shows that the difference between densified and non-densified specimens was significant at the 0.01 probability level with an F-value of 28.70. As with the shear tests for adhesion performance (Table 1), the densified specimens showed less variance than the controls. The reduced pull-off stress

of the densified specimens is caused by the dense surface, which reduced varnish penetration. However, no standards specify the pull-off resistance needed for high solid content coating for flooring, and the pull-off strength observed might be enough for EWF, and a more in-depth investigation should be conducted in the future.

Table 2. Results of Pull-off Tests

Substrate	Mean pull-off stress (MPa)	Standard deviation	Coefficient of variance (%)
Control	2.74	0.27	11.6
Densified (200°C)	2.23	0.26	9.9

Hygro-mechanical Behaviour of EWF Prototypes

Figure 6 shows the mean EWF strip distortions observed according to time and hygro-thermal conditions. By comparison with Controls 1 and 2, EWF made with densified maple clearly exhibited the smallest cupping distortion. The average values of maximum deformation amplitude between the two conditions were calculated to be 0.15 mm, 0.17 mm, and 0.25 mm for EWF made with densified sugar maple, Control 1, and Control 2, respectively. The distortion measured in EWF made with densified maple was significantly lower than that of Controls 1 and 2 at the 0.05 probability level. The EWF made with densified specimens showed the best dimensional stability. In the EWF industry, 0.25 mm is a commonly used reference to determine acceptability in terms of distortion between dry and wet conditions (Blanchet *et al.* 2003). All EWF constructions tested in this study yielded a distortion level representing only 60% of this deformation maximum, which suggests that the densification treatment of the sugar maple at 200 °C had a significantly positive effect on the performance of EWF.
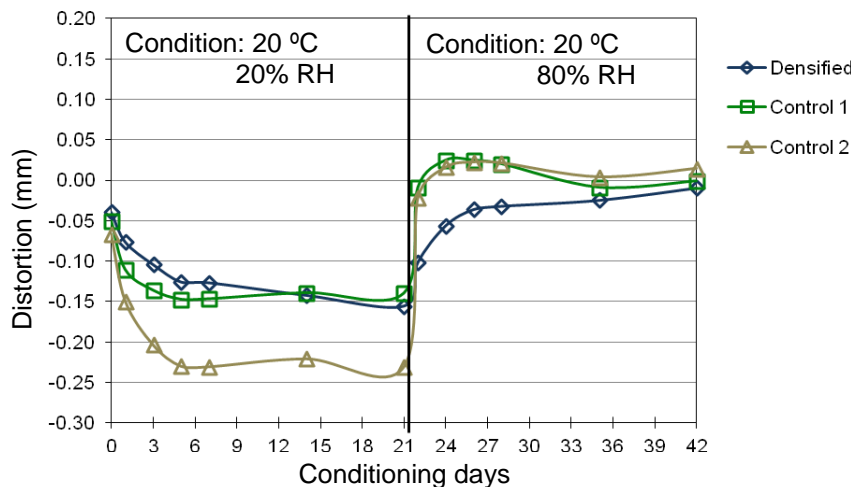

Fig. 6. Average EWF distortion as a function of conditioning time and hygro-thermal conditions

EWF distortion is mainly caused by surface layer shrinking and swelling in the width direction to moisture absorption and desorption at different RH levels while the substrate does not change at the same rate. It was found that widthwise swelling in specimens densified at 200 °C was significantly less than in the controls (Fig. 3). Furthermore, hygroscopicity was found to be lower in densified specimens (Fig. 2), and

the rate of moisture absorption and desorption was lower for the densified specimens than for the non-densified ones, resulting in reduced shrinkage of the surface for a given RH change. All these facts explain the lower cupping distortion of EWF made with a surface layer of densified maple.

On the other hand, a lower shrinkage or swelling in width direction will not only reduce the EWF cupping deformation but also the stress transmitted by the surface layer to the substrate through the bond line. In this case, a more stable widthwise EWF surface layer will compensate the loss of the adhesion properties of the densified maple.

CONCLUSIONS

From the results obtained in this study, the following main conclusions can be drawn:

1. The use of a heat-resistant fabric during pressing in the densification process resulted in uniform distribution of steam and gases over the wood strips and prevented densified wood carbonization.

2. Densified sugar maple showed higher density, lower hygroscopicity, lower swelling in the width and length directions, higher swelling in the thickness (compression) direction, higher hardness, improved bending strength, and increased MOE as compared with non-densified controls. It also offered a desirable color. The hardness of the densified sugar maple was about twice that of the controls.

3. Densification of sugar maple at 200 °C yielded better results than at 180 °C, provided that a permeable fabric layer was placed between the press hot platens and the wood specimen.

4. Average distortion measurements in the EWF prototypes made with densified sugar maple proved significantly lower than with the non-densified controls.

5. Thin sugar maple wood densified under the combined effects of steam, heat, and pressure appeared to be highly justifiable in the manufacturing of engineered wood flooring intended for heavy-duty applications (*i.e.* commercial, *etc.*) due to its very high density and mechanical properties, relatively good dimensional stability, and pleasant appearance.

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