EFFECTS OF LASER DRILLING ON MECHANICAL PROPERTIES AND IMPREGNABILITY OF FIR AND SPRUCE WOOD*

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ABSTRACT

Fir (*Abies borisii regis*) and spruce (*Picea excelsa*) wood specimens, 2 × 2 cm in cross section and 34 cm long, were prepared with true radial and tangential surfaces. All lateral surfaces of the specimens were drilled by laser to a depth of 4 mm (1/5 of specimen thickness) with two drilling patterns (distance between holes 1 × 1 cm and 1 × 2 cm).). After drilling, the mechanical strength of wood (MOE, MOR, axial compression, toughness) was determined and compared with non-drilled controls. MOE was not affected by the laser drilling, MOR was significantly increased, axial compression was increased and toughness was decreased but not significantly. The overall results imply that strength properties do not decline by the laser drilling. Furthermore, wood specimens were impregnated with rape oil and CCB preservatives by applying vacuum (0.6 mmHg) and pressure (1,5 bars) for 15 minutes and 30 minutes, respectively. The results showed that both drilling patterns improved the retention and penetration of preservatives in fir and spruce wood specimens and, thus, are encouraging for further evaluating the drilling effects on the liquid permeability of these refractory to impregnation species. This effect was more pronounced in fir than in spruce wood.

Key words: fir/spruce wood, laser drilling, mechanical strength, impregnability, retention, penetration.

1. INTRODUCTION

Fir and spruce are wood productive forest species and, for this reason, very important in European market as well as worldwide. From fir and spruce wood, many products are produced such as poles, squared timber, sawn timber, glue laminated timber, cross laminated solid wood panels, laminated veneer lumber (LVL), etc. with extended applications in building constructions and other uses (Tsoumis 1991).

For a number of external applications, wood impregnation in closed cylinder under vacuum and pressure is a requirement, especially for species like fir and spruce which exhibit low natural durability of wood (class

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4 according to EN 460 1994). The success of the treatments requires a wood permeability that allows a sufficiently deep and homogenous distribution of the substances in the wood. However, fir and spruce wood is characterized as resistant to impregnation (Kakaras and Filippou 1996, Karastergiou et al. 2014) due to its anatomical characteristics and the extended pit aspiration that takes place during drying of wood (Richardson 1978).

Permeability of wood to gases and liquids represents a material property that is of great importance in the wood industry, influencing not only preservative impregnation, but also other industrial operations such as pulping and wood drying. The increase of permeability of the refractory to preservation forest species is one of the major technological challenges in wood science nowadays. Several techniques for the improvement of liquid permeability were researched over the years involving mechanical opening of the wood structure, steaming, solvent-exchange drying, critical point drying and biological treatments (Erwin and Zgraggen 1984, Ruddick 1986, Kakaras and Voulgaridis 1992, Lehringer et al. 2009). However, the above methods exhibit various problems in practice.

Laser-incising technology has shown high potential for liquid impregnation (Hattori 1995, Islam et al. 2007, 2008). The liquid-impregnation capability can be improved by creating deep pin holes in the body of the wood to provide additional intake points. It is also possible to customize the depth of penetration needed for a target property, which can be improved by the subsequent preservative treatment. However, incising technologies are often associated with carbonization and visible marks on the wood surface as well as with strength losses, which are considered to be disadvantageous for certain wood products (Richter 1989, Wang et al. 2013). The use of laser beams for creating surface microholes to a certain depth on wood surfaces may be an alternative method to improve the permeability of wood. The use of laser beams in wood industry is limited to cutting of wood of small thickness in the form of veneers, plywood and small thickness sawnwood (~ 5 cm) (Mc Millin and Harry 1971, Huber et al. 1982, Barnekow et al. 1989). Information on using laser beams for creating micro-holes on lateral surfaces of wood (laser incising or drilling) in order to increase the permeability for wood preservatives is limited; however the investigation of such laser treatments of wood may lead to a new application in wood preservation industry (Islam et al. 2009). Mechanical drilling of wood with needles of 2.8 mm in diameter caused a remarkable reduction in shear strength of wood (Junko and Takato 2003). However, results on the effects of laser drilling on mechanical properties of wood are lacking (Adamopoulos et al. 2014).

In this work, the impact of a laser drilling process on mechanical properties of fir (Abies borisii regis Mattf.) and spruce (Picea excelsa Link) wood, and specifically static bending strength, axial compression and toughness and on their impregnability is investigated. This information is important to assess if the laser drilling process is a promising method to effectively improve the permeability of fir and spruce wood and to be applied in practice widening their uses in outdoor conditions.

2. MATERIALS AND METHODS

Defect-free sapwood specimens measuring 20 × 20 × 340 mm (Radial × Tangential × Longitudinal) were prepared from air-dried boards of fir (Abies borisii regis Mattf.) and spruce (Picea excelsa Link) of Greek origin.

Twenty specimen collectives were prepared per static bending and toughness. In each collective, three specimens were always taken in one longitudinal sequence to minimize the influence of natural property variation. As the specimens were subjected to two different laser drilling patterns and one control, this axial pairing provided a good comparability of the results. The wood specimens were adjusted to a manually operated XYZ positioning system and all their lateral surfaces were drilled by laser beams to a depth of 0.4 cm (1/5 of specimen thickness) at two drilling patterns, with distance between holes 1 × 1 cm and 1 × 2 cm.

Before testing, the specimens were conditioned and stored at 20 ºC and 65 % RH. Moduli of rupture (MOR) and elasticity (MOE) in static bending were determined by centre point loading of specimens over a 30 cm span according to DIN 52186 (1992) standard. Toughness tests were conducted on the pendulum impact testing machine PSd 150H (WPM Leipzig GmbH) at 24-cm span with centre loading of specimens according to DIN 52189 (1992) standard. Axial compression strength was determined on 6 cm long specimens cut from non-fractured positions of the static bending specimen collectives according to ISO 3787 (1976) standard. The static bending and axial compression tests were performed using a Shimadzu UH-A 300 kN testing machine.

After testing, ninety six (96) fir and spruce specimens measuring 20 × 20 × 150 mm (Radial × Tangential × Longitudinal) were prepared and divided to 12 groups (6 for each species). Four groups of specimens were laser-drilled in a pattern 1 x 1 cm (distances between holes), 4 groups were laser-drilled in a pattern 1 x 2 cm and the last 4 groups remained non-drilled as controls (see Table 1). The laser drilled wood specimens and controls were taken in a mode of axial pairing for each species and preservative, thus providing a good comparability of the results.

Laser-drilled and control specimens were impregnated with the full-cell method in a laboratory impregnation chamber by applying a vacuum of 600 mmHg for 15 minutes and pressure of 1,5 bars for 30 minutes. Two preservatives, an oil type (rape oil) and a water soluble (CCB of 3.2 % concentration) were used. A red pigment was added to rape oil in order to be visible into the mass of wood after the impregnation process.

After the completion of the impregnation process, retention (kg/m^3), penetration depth (mm) and impregnated area on cross sections (%) were determined. The determination of retention was based on samples' weight before and after impregnation and on their volume before impregnation. Penetration was measured in the three directions (radial, tangential, axial) and the impregnated area was determined on cross sections along the whole length of the wood samples.

3. RESULTS AND DISCUSSION

The effects of laser drilling on mechanical properties of fir and spruce wood are shown in Table 1 and Figures 1–2 (Adamopoulos et al. 2014).

MOR in static bending of both species was significantly increased by the laser drilling (Table 1, Figures 1–2). For fir, MOR was found to increase from 72.77 N/mm^2 in the non-drilled control specimens to 81.32 and 82.22 N/mm^2 for the 1 × 1 cm and 1 × 2 cm drilling patterns, respectively. For spruce, the respective mean MOR values were 70.57, 87.69, and 85.23 N/mm^2. Both drilling patterns had a statistical significant effect on the MOR of spruce, while in the case of fir significant differences were only noted for the larger drilling pattern 1 × 2 cm (ANOVA and

Tukey's HSD test at an error probability of α = 0.05).

The laser drilling did not affect the static bending MOE of both fir and spruce wood (Table 1, Figures 1–2). A slight numerical decrease for fir and also a slight increase was seen for spruce in the mean MOE values of the drilled specimens as compared to the non-drilled, but the differences were not statistically significant.

Axial compression of fir and spruce wood was significantly increased after laser drilling with a similar mode to MOR (Table 1, Figures 1–2). For fir, it was significantly increased from 36.25 N/mm^2 in controls to 44.41 N/mm^2 in the 1 × 1 cm drilling pattern and to 43.49 N/mm^2 in the 1 × 2 cm pattern. The increased mean axial compression values were 48.00 and 44.94 N/mm^2 for the two drilling patterns as compared to the mean of 37.78 N/mm^2 of the non-drilled spruce specimens. For both species, mean axial compression was statistically equal between the drilling patterns (ANOVA and Tukey's HSD test at P = 5 %).

Table 1: Mechanical strength of laser-drilled fir and spruce wood specimens, with two drilling patterns, 1 x 1 cm and 1 x 2 cm (n=20, mean values ± standard error. ns = not statistically significant differences. Values labeled with a different letter are statistically different at P = 5% (ANOVA and Tukey's HSD test).

Fir	**MOR**	**Axial Compression**	**Toughness**	**MOE**
Controls	**72.77** ^{a} (9.11)	**36.25** ^{a} (3.86)	**37.26** ^{ns} (13.39)	**8456**^{ns}(1623.89)
1x1	**81.32** ^{ab}(10.9)	**44.41** ^{b} (4.67)	**26.30** (12.58)	**8077** (1172.86)
1x2	**82.22** ^{b} (8.35)	**43.49** ^{b} (4.92)	**30.07** (10.14)	**8104** (1116.01)
Spruce	**MOR**	**Axial Compression**	**Toughness**	**MOE**
Controls	**70.57** ^{a}(11.29)	**37.78** ^{a} (4.98)	**33.01** ^{ns}(11.37)	**8729**^{ns} (1735.2)
1x1	**87.69** ^{b}(11.6)	**48.00** ^{b} (6.5)	**24.33** (9.25)	**9143** (1705.2)
1x2	**85.23** ^{b}(10.36)	**44.94** ^{b} (5.22)	**26.33** (10.08)	**8808** (1488.97)

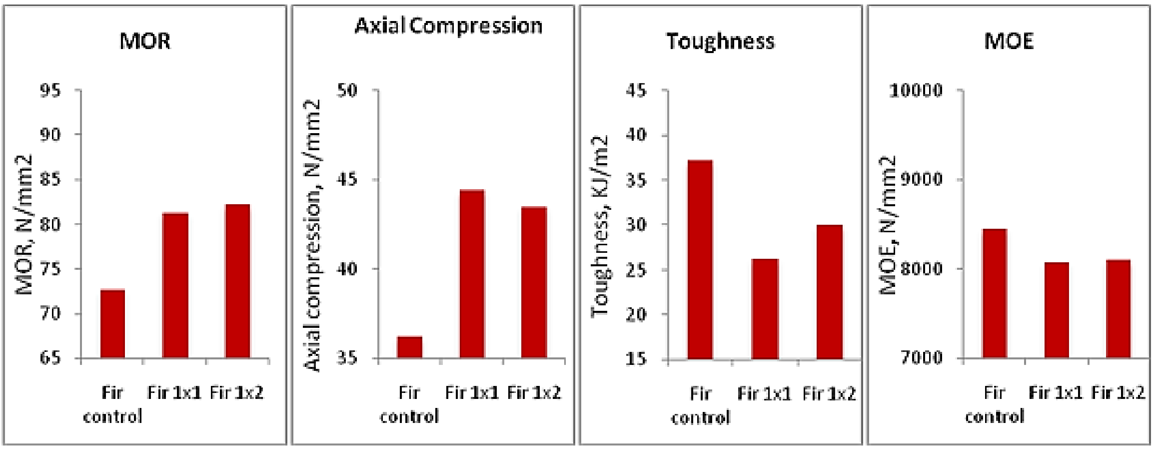

Figure 1: Mechanical strength of laser-drilled fir wood, with two drilling patterns, 1 x 1 cm and 1 x 2 cm.

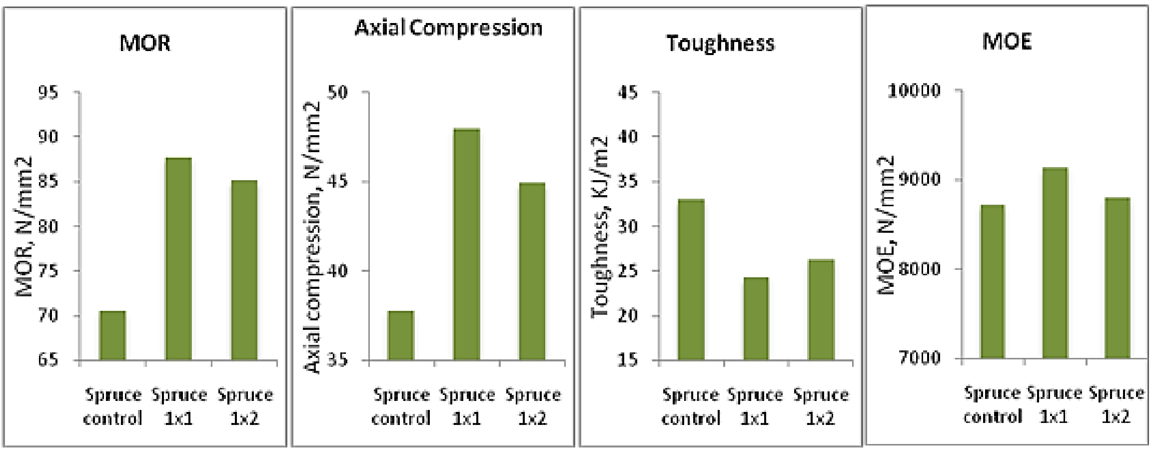

Figure 2: Mechanical strength of laser-drilled spruce wood, with two drilling patterns, 1 x 1 cm and 1 x 2 cm.

Toughness was found to decrease in the laser-drilled fir and spruce wood (Table 1, Figures 1–2). Mean toughness values reduced to almost equally levels for both drilling patterns in fir (26.30 – 30.07 KJ/m^2) and spruce (24.33 – 26.33 KJ/m2) from the initial values of the non-drilled controls (37.26 KJ/m^2 for fir and 33.01 KJ/m^2 for spruce). However, the differences were not statistically significant (ANOVA and Tukey's HSD test at P = 5 %) presumably due to the large deviation of the toughness values of the drilled specimens.

The substantial increase in static bending strength (MOR) and axial compression of fir and spruce after the laser drilling could be explained by fracture mechanics and stress concentration phenomena. It is well known that reduction caused by a crack in the area a force is applied, results in a localized increase in stress. A material can fail via a propagating crack, when a concentrated stress exceeds the material's theoretical cohesive strength (Anderson 2005). It seems that the holes produced by the laser beams are able to reduce the stress concentrations originating from cracks formed after loading of specimens. Obviously, the drilled holes cause a smaller stress concentration than the sharp end of cracks leading to a higher strength of the drilled-specimens. As MOE in static bending and toughness remained unchanged after the laser drilling, it can be concluded that the holes were not capable of altering neither the elasticity properties of the wood specimens nor their impact bending fracture behavior.

The effects of laser drilling on impregnability of fir and spruce wood specimens treated by rape oil and CCB preservative are given in Tables 2–4 and Fig. 3–5 (Voulgaridis et al. 2014).

Table 2 and Fig. 3 show the retention of preservative for each of the 12 groups of wood specimens. Retention either of rape oil or the CCB preservative was higher in laser-drilled than control wood specimens. Between the two drilling patterns, the retention of wood specimens drilled with the 1 x 1 cm pattern was higher than that of 1 x 2cm in most cases. Fir wood absorbed more preservative than spruce.

Table 2: Mean values of retention of rape oil and CCB preservative dry salt (kg/m3) of fir and spruce wood specimens with dimensions 2 x 2 x 15 cm (RxTxL), coated on cross sections*.

Wood species/ Preservative	Controls (Non-laser-drilled)	Laser-drilled (1 x 1cm)	Laser-drilled (1 x 2cm)
Fir/CCB (SD)-(min-max)	**11.22** (10.01)-(2.73-25.29)	**14.86** (9.46)-(4.34-26.03)	**15.02** (9.25)-(4.54-25.8)
Fir/Rape oil (SD)-(min-max)	**97.5** (89.0)-(30.6-290.2)	**288.6** (123.1)-(169.5-475.2)	**205.5** (165.1)-(39.4-462.4)
Spruce/CCB (SD)-(min-max)	**8.8** (3.99)-(3.96-17.1)	**12.72** (3.31)-(6.74-17.93)	**11.46** (5.65)-(5.91-21.9)
Spruce/Rape oil (SD)-(min-max)	**57.1** (23.3)-(25.8-89.7)	**117.9** (75.1)-(52.8-234.8)	**78.2** (32.4)-(44.6-118.7)

**For each group of wood specimens, 8 replicates were used.*

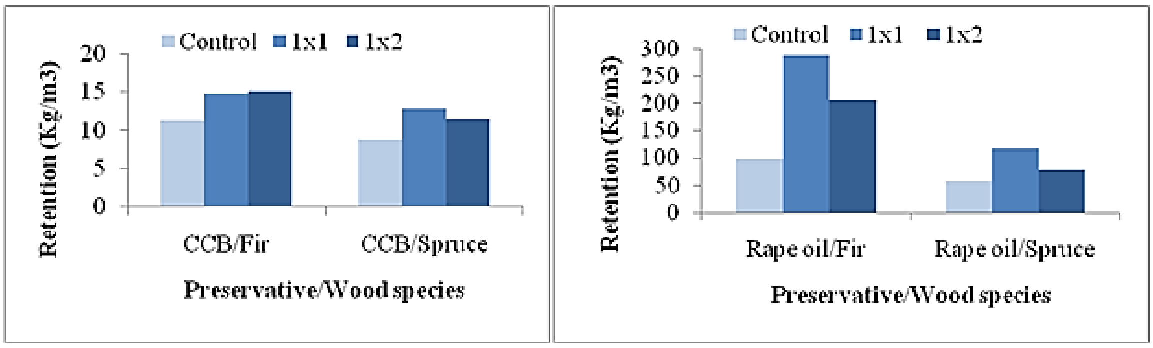

Figure 3: Mean retention values of rape oil and CCB preservative dry salt (kg/m^3) by laser drilled and non-drilled fir and spruce wood specimens, coated on cross sections.

Lateral (radial/tangential) penetration depth and impregnated area of non drilled wood specimens are shown in Table 3 and Fig. 4. Penetration depth and impregnated area (%) of CCB and rape oil were higher in fir than spruce wood either immediately after impregnation or after 7-day preservative diffusion in wood. In laser drilled wood specimens, the lateral penetration of CCB and rape oil immediately after impregnation was much higher (1.3 up to 5.6 times more) than that of non drilled wood specimens (Table 4, Fig. 5). It indicates that laser drilling of wood facilitates the penetration of preservatives in the three directions (Fig. 6).

Between the two drilling patterns the differences in penetration were not consistent (in fir penetration was slightly higher in the drilling pattern 1 x 2cm than in 1 x 1cm, while in spruce the reversal occurred in most cases. In most cases, penetration was found to be higher in fir than in spruce (Table 4).

Table 3: Penetration depth and impregnated area of non laser drilled wood*

Wood species	Preserva-tive	Penetration depth (mm)				Impregnated area (%)	
		Immediately after impregnation		After 7-day preservative diffusion		Immediately after impregnation	After 7-day preservative diffusion
		Radially	Tangentially	Radially	Tangential ly		
Spruce	CCB	**2.98** (2.27)	**3.07** (2.55)	**3.34** (2.24)	**3.24**(2.55)	**47.14** (18.43)	**52.67** (17.48)
	Rape oil	**1.75** (1.09)	**1.53** (1.89)	**7.04** (3.20)	**7.55**(2.87)	**27.66** (8.98)	**84.43** (20.35
Fir	CCB	**3.62** (4.59)	**4.53** (3.77)	**3.88** (4.35)	**4.66**(3.71)	**51.91** (32.44)	**55.05** (31.12)
	Rape oil	**1.36** (1.17)	**1.99** (1.47)	**7.04** (2.60)	**7.68**(2.04)	**32.31** (12.01)	**90.28** (8.57)

**Mean values of 42 measurements. Standard deviations in parentheses.*

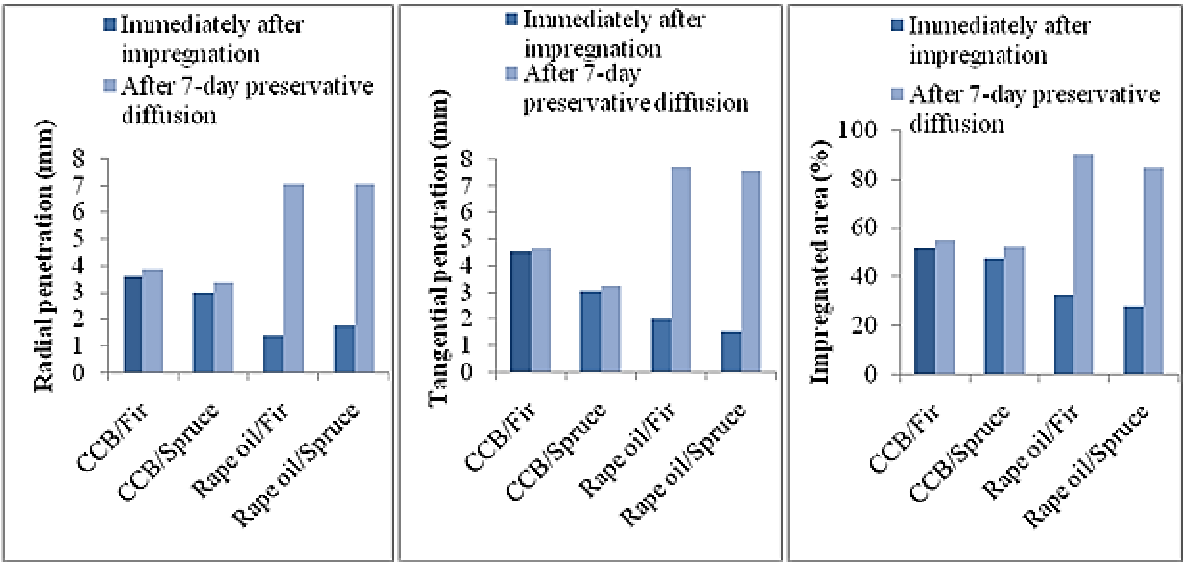

Figure 4: Penetration depth and impregnated area of non laser drilled wood.

Table 4: Penetration depth of laser drilled and non-drilled wood specimens*

Wood species	**Preserva-tive**	**Penetration depth (mm)**					
		Without laser drilling		**With laser drilling**			
				Drilling pattern 1 x 1		**Drilling pattern 1 x 2**	
		Radially	**Tangentially**	**Radially**	**Tangentially**	**Radially**	**Tangentially**
Spruce	CCB	**2.98** (2.27)	**3.07** (2.55)	**8.74** (1.65)	**7.60** (2.10)	**7.01** (1.37)	**7.39** (2.61)
	Rape oil	**1.75** (1.09)	**1.53** (1.89)	**3.30** (1.18)	**3.04** (2.85)	**3.39** (1.69)	**1.99** (1.64)
Fir	CCB	**3.62** (4.59)	**4.53** (3.77)	**7.92** (3.05)	**5.67** (3.89)	**9.21** (1.23)	**7.34** (2.20)
	Rape oil	**1.36** (1.17)	**1.99** (1.47)	**7.61** (2.76)	**3.85** (2.84)	**7.61** (3.22)	**3.52** (3.50)

**Mean values of 42 (non-laser drilled) and 16 (laser drilled) measurements. Standard deviations in parentheses.*

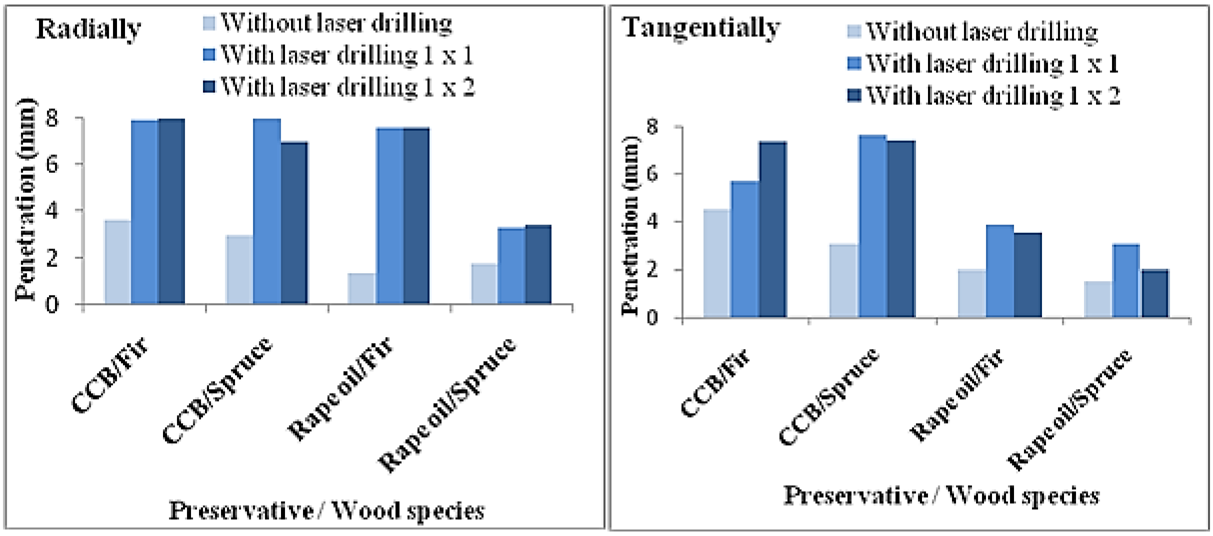

Figure 5: Penetration depth of laser drilled and non-drilled wood specimens.

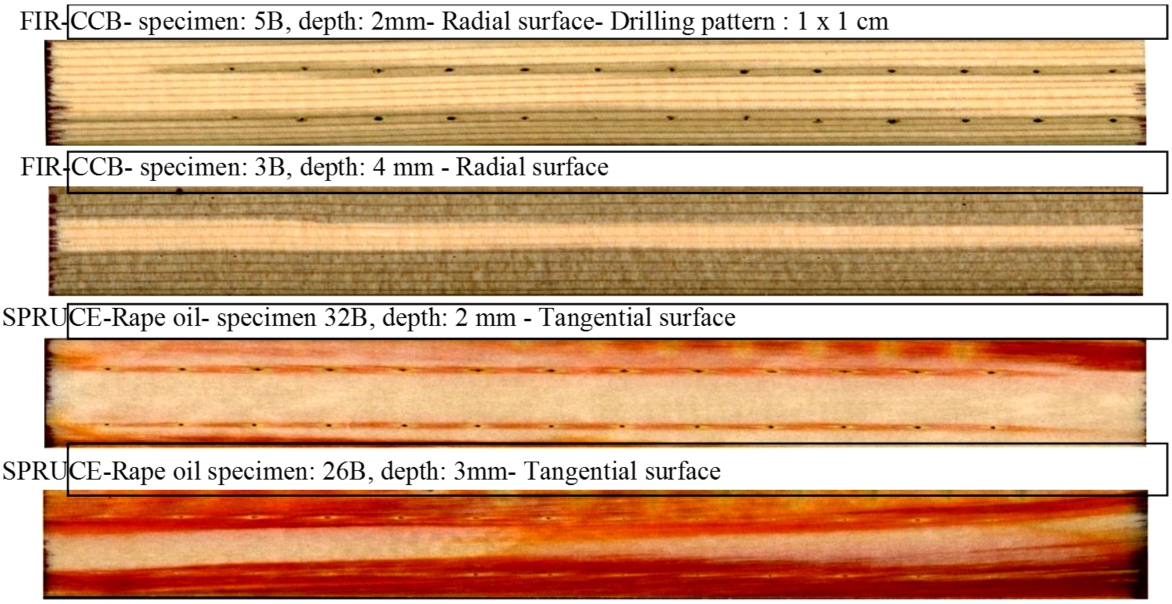

Figure 6: Axial and transverse penetration of CCB and rape oil in fir and spruce laser drilled wood specimens.

4. CONCLUSIONS

It can be concluded that the two drilling patterns 1×1 cm and 1×2 cm created by laser beams on all lateral surfaces of fir and spruce wood specimens at 0.4 mm depth did not impact negatively major mechanical properties of wood. MOE in static bending and toughness remained unchanged, while MOR and axial compression were even increased by the laser drilling. This is a positive indication allowing further experimentation on the effects of laser drilling on the impregnability of fir and spruce wood.

Lateral (radial/tangential) penetration of rape oil and CCB preservative in non drilled wood specimens, immediately after impregnation, ranges in fir between 3.62 (R)–4.53(T) mm (CCB) and 1.36 (R)–1.99 (T) mm (rape oil) and in spruce between 2.98 (R) –3.07 (T) mm (CCB) and 1.75 (R)–1.53 (T) mm (rape oil). After 7 days, diffusion increased the penetration depth about 7 % for CCB and 385–500 % for rape oil. Fir wood appeared to be more permeable than spruce wood. The differences between radial and tangential penetration were small.

Laser drilling of fir and spruce wood specimens facilitated the penetration of preservatives and improved the impregnability of both CCB and rape oil tested. This facilitation occurred in all directions (radial/tangential/axial) from the position of each hole. Between the two drilling patterns (1 x 1cm and 1 x 2 cm), the penetration differences were small and inconsistent in both species.

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