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ORIGINAL ARTICLE

Studies on pre-treatment by compression for wood drying II: effects of compression ratio, compression direction and compression speed on the recovery rate and mechanical properties of wood

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Abstract As a follow-up report, the pre-treatment by compression for wood drying was systematically studied in terms of effects of compression ratio, compression direction and compression speed on the recovery rate (RR) and mechanical properties. The results showed: the RR decreased 0.18 and 0.20 % every 1 % compression ratio when the compression ratio was lower than or equal to 50 and 40 % for Poplar and Chinese fir, respectively, over this compression ratio, the RR decreased rapidly; the RR had the maximum value in tangential compression for Poplar, while had the minimum value in 45° compression for Chinese fir; the RR of specimens compressed at 3, 5 and 10 mm/min were bigger than those in 0.5 and 1 mm/min for Poplar. For Chinese fir, the RR difference among all the compression speed was quite small compared with that for Poplar. The RR at all conditions was no less than 73.3 and 79.7 % for Poplar and Chinese fir, respectively; The mechanical properties difference was not significant between the specimen compressed in different compression ratio, while was significant between the specimens compressed in different direction and different speed except the modulus of rupture (MOR) of Poplar between different compression direction. For Chinese fir, MOR and modulus of elasticity (MOE) in 45° compression specimen showed the maximum value. The mechanical properties at all conditions retained at least 83.1 and 88.1 % of MOR, 84.9 and 83.7 % of MOE for Poplar and Chinese fir, respectively. After all, the pre-treatment by compression for wood drying is viable in terms of RR and mechanical properties at all compression ratio, compression direction and compression speed we tested.

Keywords Pre-treatment · Compression · Recovery rate · Mechanical properties

Introduction

The previous report [1] showed that the moisture content (MC) could be very effectively reduced by means of pre-treatment by compression for wood drying. Unavoidable factors, including compression ratio, compression direction and compression speed, were systematically studied in terms of their effects on MC reduction. This study is obvious not enough because when talking about the compression of wood, the recovery rate (RR) is an unavoidable important factor affecting the volume of wood and therefore the value of wood. In addition, mechanical properties are among the most important properties in wood utilization, how the mechanical properties change after the treatment is one of top concerns. The effects of compression ratio, compression direction and compression speed on RR and mechanical properties are not clear. Therefore, the purpose of this study is to systematically study the effects of compression ratio, compression direction and compression speed on RR and mechanical properties, so that people will have a clear and enough information before practicing the pre-treatment technique in the wood industry.

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Materials and methods

Fifteen trees of 25-year-old Poplar (*Populus tomentosa*) plantation with the diameter at the breast height of 25 to 33 cm and the air-dried density of 0.43 g/cm^3, and 5 trees of 25-year-old Chinese fir (*Cunninghamia lanceolata*) plantation with the diameter at the breast height of 22–26 cm and the air-dried density of 0.36 g/cm^3, were collected from Guanxian County of Shandong Province and Suichuan County of Jiangxi Province, respectively. The specimens were prepared with the size of 30 mm (R/T) × 50 mm (T/R) × 100 mm (L) and tested in tangential compression, radial compression and 45° compression. The tangential (T) compression was carried on the vertical grain specimens with the compression direction parallel to the annual ring; the radial (R) compression was carried on the flat grain specimens with the compression direction perpendicular to the annual ring; and the 45° compression was carried on in-between tangential and radial specimens with the compression face having 45° with the annual ring. The 45° compression specimens were tested because in the industry practice, most boards are neither vertical nor flat grain boards, but the boards in-between vertical and flat grain.

To minimize the effects of specimens variation on the test results, all the specimens were oven-dried first so that the growth stress was released in some extent, and then vacuum pressure treated so that all the specimens were fully water-saturated having a similar MC. The compression speed at 0.5, 1, 3, 5 and 10 mm/min, and the compression ratio at 10, 20, 40, 50 and 60 % were easily, respectively, controlled by fully computer-controlled Instron 5582 Universal Test Machine. A special adapter was connected to the compression head to facilitate the compression.

The thicknesses along the compression direction of specimens were measured, respectively, before compression and after the release of compression load when the specimens were fully recovered. The RR was calculated as following equation:

$$\mathrm{RR} = \frac{T_\mathrm{r} - T_\mathrm{c}}{T_0 - T_\mathrm{c}} \times 100\,\%$$

In which T_0 is thickness before compression (mm); T_c thickness after compression with compression load on (mm), controlled by testing machine; T_r is thickness after release of the compression load when the specimens were fully recovered (mm).

The specimens for mechanical properties tests were prepared with the size of 4 mm (T) × 10 mm (R) × 100 mm (L) after the compression was unloaded and the wood were recovered and air-dried. In this way (L/T ≧ 20), the size effect could be ignored. The specimens were conditioned at 20 °C and RH 65 % for a constant weight. The modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending were measured with the Instron 5852 Universal Testing Machine at the span of 80 mm and the load head radius of 5 mm.

Results and discussion

To limit the variation, all the specimens for studying the effects of compression ratio on RR and mechanical properties were radially compressed at the speed of 3 and 5 mm/min for Poplar and Chinese fir, respectively. In addition, all the specimens for studying the effects of compression direction and compression speed on RR and mechanical properties were compressed at a ratio of 60 and 40 % for Poplar and Chinese fir, respectively.

Effects of compression ratio, compression direction and compression speed on the RR

Wood RR at different compression ratio, compression direction and compression speed were shown in Fig. 1. It could be seen that the RR decreases with the increase of compression ratio while the RR at different compression direction and different compression speed had no clear patterns. Despite this, The RR at all conditions was no less than 73.3 and 79.7 % for Poplar and Chinese fir, respectively. In another word, the wood retained more than 84.0 and 92.0 % of original size. This concluded that the pre-treatment by compression for wood drying is viable in terms of RR at all compression ratio, compression direction and compression speed we tested. The wood volume has no or a slight loss after pre-treatment by compression, and therefore, the wood value based on volume has no or a slight loss after pre-treatment by compression.

Among the RR at all compression directions, for Poplar, the T compression showed the maximum value. This was attributed to that short radial pore multiple are main type of pore arrangement, the consecutive pore in radial direction would decrease the recovery in radial direction. For Chinese fir, the 45° compression showed the minimum value. This was attributed to, tracheids are always found in near rectangle shape, the microfibrils in the corner of the rectangle have sharp bend and have been used to this sharp bend, making the microfibrils at the corner more tolerant to the deformation.

For Poplar, the RR of specimens compressed at 0.5 and 1 mm/min was smaller than those in 3, 5 and 10 mm/min. For Chinese fir, the RR difference among all the compression speed was quite small compared with that for Poplar. Compression speed determines the compression time when the compression ratio is set for the same size

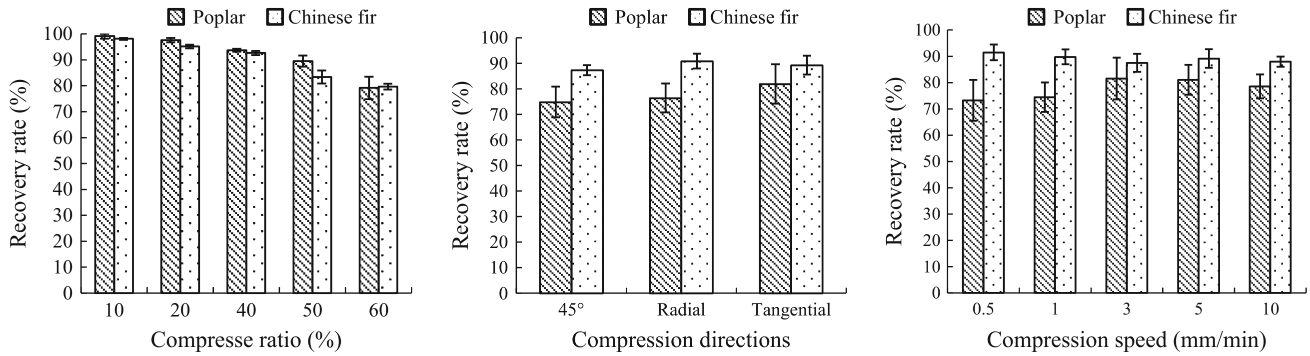

Fig. 1 Wood recovery rate at different compression ratio, compression direction and compression speed

specimen. Longer compression time resulted from lower compression speed allows longer time wood intermolecular rearrangement to reach a temporarily steady state during the compression when the wood was in water-saturated condition, causing the wood relaxation. This agrees that the RR of Poplar at 3, 5 and 10 mm/min was higher than that at 0.5 and 1 mm/min.

The fact that the compression ratio of Chinese fir (40 %) was 2/3 of that of Poplar (60 %) was the reason that the RR of the Chinese fir was higher than that of Poplar at different compression direction and compression speed (Fig. 1, center and right). In addition, the RR difference at different compression speed of Poplar was higher than that of Chinese fir. This was probably due to the relaxation time during compression of Poplar was 1.5 times of that of Chinese fir at the same compression speed. Moreover, it was probably due to much uneven structure of Poplar compared with Chinese fir, leading the RR of Poplar was more sensitive to compression speed than that of Chinese fir.

Before the compression, the MC of Poplar and Chinese fir was about 173 and 244 %, a fully water-saturated condition, the bound water was absorbed in wood cell and the free water was full of lumen of the vessel in Poplar and tracheid in Chinese fir. There were abundant interactions between the water molecules and wood molecule, wood was highly hygroplasticized by water as a plasticizer, which has a much lower glass transition temperature (T_g) compared with that of wood, and therefore, wood at fully water-saturated condition has a low T_g, and thereby wood was soften by water and was easily compressed.

The influences of MC on the softening temperature of wood constituents have been studied by many researchers. At dry conditions, the glass transition of hemicellulose has been observed over a rather broad range of temperatures, from 150 to 230 °C, that of lignin from 124 to 193 °C, that of cellulose around 230 °C [2]. At wet condition, data on the influence of MC on the glass transition temperature are conflicting: the transition temperature for lignin is reported lowered to 80–90 °C whereas hemicellulose is softened at room temperature [3]; the transition temperature were also reported 54–56 °C and 72–128 °C for hemicellulose and lignin, respectively, by Goring [4]; Cousins [5] has demonstrated that for isolated hemicelluloses, xylan and glucomannan from *Pinus radiata,* the mechanical properties show a typical glass–rubber behavior with increasing moisture uptake indicating a transition at about 30 % moisture content at 20 °C. However, cellulose is believed by many researchers that the transition temperature in wet condition was the same with that in dry condition, despite the fact that some research assumed that irregular zone of the cellulose microfibrils could be penetrated by water which then soften and drastically reduce the elastic modulus [6].

With the increase of compression ratio, the MC of wood decreased. When the compression ratio reached 60 %, the MC of Poplar and Chinese fir decreased to 65 and 68 %, respectively, much higher than the equilibrium moisture content, the water was supposed to be enough to hygroplastisize the wood, especially the wood matrix of lignin and hemicellulose. When the compression load was released, the microfibrils of cellulose, which owns a high transition temperature even in wet condition, would spring back and becoming the driving force to restore the wood to original size [7]. In the meantime, the softened wood matrix of hemicellulose and lignin facilitated the restoration in the wet condition. All these explained why the wood recovered to almost their original size.

The RR of Poplar was higher than that of Chinese fir at all compression ratio except that at 60 % (Fig. 1, left). This agrees the conclusions by Iida [7] that cellulose is the main driving force to spring back because the cellulose constituents in Poplar was higher than that of Chinese fir according to the former study [8]. Compression ratio at 60 % is an exception because the maximum compressible ratio for Poplar was 50.27 %, that for Chinese fir was 59.06 % based on the assumption that the lumen could be totally compressed [1].

Although the wood showed a well RR after the pre-treatment by compression, the RR tends to decrease with the increase of compression ratio. Linear relationship between RR and compression ratio (Fig. 2) was found when the compression ratio was lower than or equal to 50 or 40 % for Poplar and Chinese fir, respectively, which suggested that the RR decreases 0.18 and 0.20 % every 1 % compression ratio for Poplar and Chinese fir, respectively. The RR decreases rapidly when the compression ratio was higher than 50 and 40 % for Poplar and Chinese fir, respectively.

Effects of compression ratio, compression direction and compression speed on the mechanical properties

Mechanical properties in static bending of pre-treated wood by compression at different compression ratio, different compression direction and different compression speed were shown in Fig. 3.

MOR and MOE in static bending did not show a clear pattern at different compression ratio (Fig. 3, upper), although the RR decreases with the increase of compression ratio. Higher compression ratio, in one hand, is more likely to risk the damage of wood in structure because of higher deformation and consequently the loss in strength; in the other hand, is always leaded a higher density resulted from a lower RR (Fig. 1), which is more likely to increase the strength. As a result, the effects of compression ratio on the mechanical properties are not obvious (Table 1).

Although the compression ratio is quite broad, the difference of the size along compression direction after recovery is quite small compared with the uncompressed specimens. Here, as an example, even at the highest compression ratio of 60 %, compressed under water-saturated condition, the Poplar and Chinese fir specimens recovered to 87.5 % and 91.9 % of their original size after the unload of the compression, suggesting the strength of microfibrils, the main driving force of restoration, were well functionally retained. This in some extent explains the mechanical properties between wood in quite broad compression ratio are not obvious.

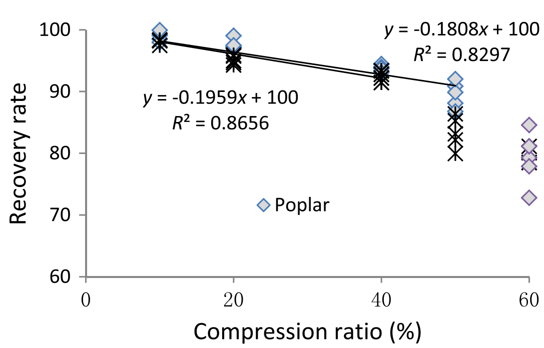

Fig. 2 Linear relations between the recovery rate and compression ratio when the compression ratio ≤50 % (Poplar) or ≤40 % (Chinese fir)

Despite the fact that MOE exited significant difference between the specimen compressed in different direction in both Poplar and Chinese fir, and MOR existed significant difference between the specimens compressed in different compression direction in Chinese fir (Table 1), the mechanical properties showed a slight loss or increase compared with the controlled specimens (Fig. 3, middle). For Chinese fir, MOR and MOE in 45° compression specimen showed the maximum value (77.31 MPa and 10.53 GPa), compared with that in tangential (66.44 MPa and 9.06 GPa) and radial (66.32 MPa and 8.98 GPa). During compression, suppose that all the lumen could be totally compressed, the opposite wood cell wall of the same cell is moved to the other cell wall along the compression direction. In 45° compression, the movable distance is the diagonal of the nearly rectangle shaped tracheid, which owns the maximum movable distance compared with T and R compression. The compression stress would not obviously increase until the corner of wood cell along compression direction contacts each other. In this way, wood cell wall was well protected. This is probably one reason that the mechanical properties in 45° compression specimen showed the maximum value. In addition, the highest density resulted from lowest RR at 45° compression compare with 2 other compression directions (Fig. 1) is one more reason that the specimens at 45° compression had a maximum mechanical value.

For the wood industry practice, well-retained RR (Fig. 2, center) and mechanical properties (Fig. 3, middle) mean that pre-treatment by compression for round wood in radial direction, for flat grain timber in radial direction, for vertical grain timber in tangential direction, for in-between vertical and flat grain timber in 45° direction are viable in terms of RR and mechanical properties.

Despite the fact that MOR existed significant difference between specimen compressed in different speed at 0.01 level, and MOE at 0.05 level (Table 1), mechanical properties in static bending of both Poplar and Chinese fir at different compression speed were well retained compared with uncompressed control specimen (Fig. 3, lower). For Poplar, both MOR and MOE at 3, 5 and 10 mm/min compression speed were lower than those at 0.5 and 1 mm/min, this agrees that the RR of former were higher than the latter, resulting a lower density of former, and consequently lower mechanical properties of former (Table 2). For Chinese fir, both MOR and MOE at 3, 5 and 10 mm/min were higher than those at 0.5 and 1 mm/min, this agrees that the RR of former were lower than latter, resulting a higher density of former, and consequently

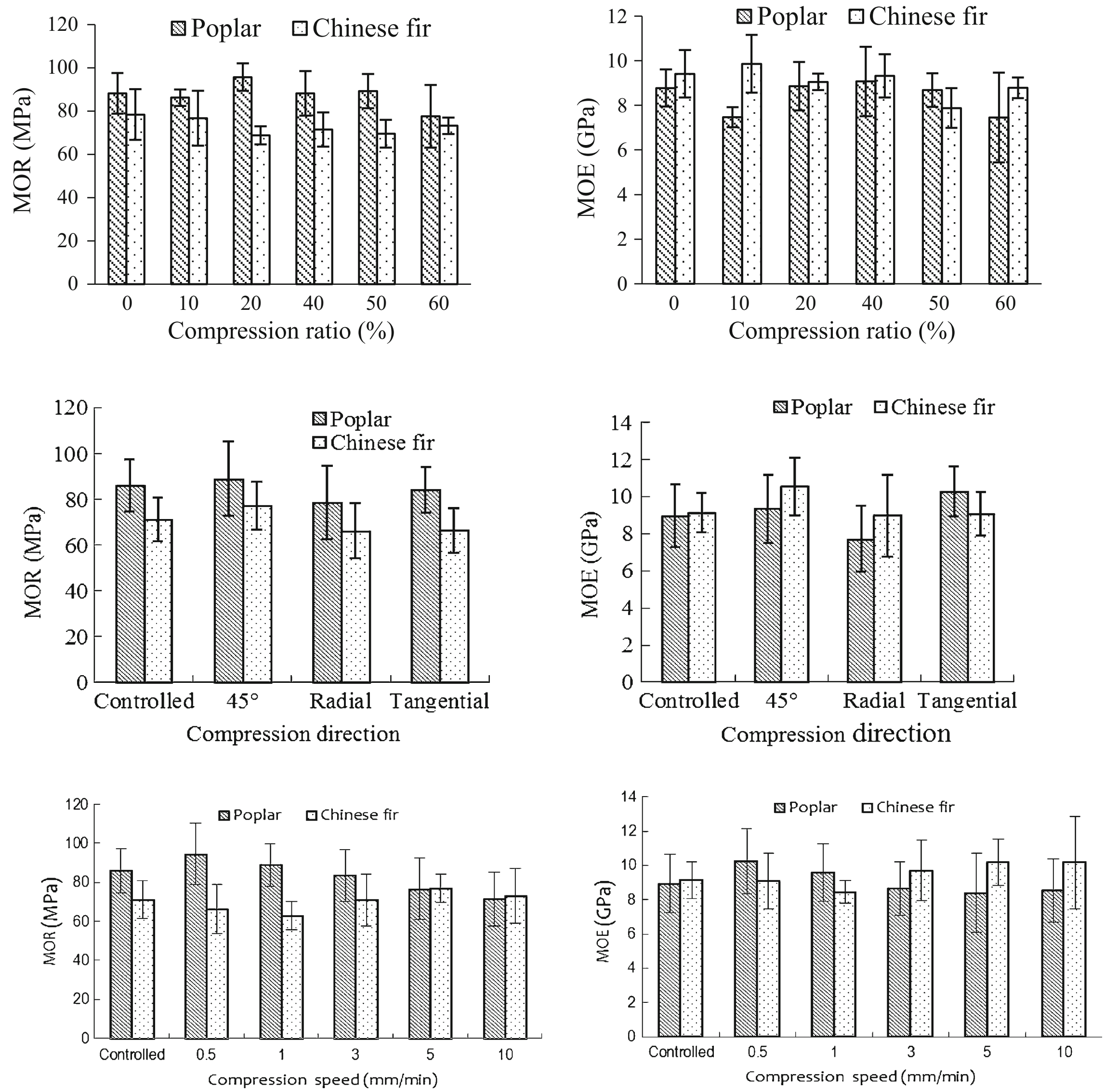

Fig. 3 Mechanical properties in static bending showing that they were well retained after the pre-treatment by compression at different compression ratio, different compression direction and different compression speed. *MOR* modulus of rupture, *MOE* modulus of elasticity

Table 1 *P* value of ANOVA on mechanical properties between different compression ratio, compression direction and compression speed

	Ratio		Direction		Speed	
	MOR	MOE	MOR	MOE	MOR	MOE
Poplar	0.122	0.162	0.071	0.000[a]	0.000[a]	0.053
Chinese fir	0.423	0.038	0.001[a]	0.003[a]	0.009[a]	0.030

MOR modulus of rupture, *MOE* modulus of elasticity

[a] Significant at 0.01 level

higher mechanical properties of former (Table 2). The compression speed had an effect on recovery rate, it might have an effect on the density profile along the compression direction as well. How the compression speed affects the density profile along compression direction, and consequently on the mechanical properties, need to be further studied.

According to Table 2, as a compromise between RR, mechanical properties and wood processing efficiency, 3 or 5 mm/min compression speed for Poplar and 5 or 10 mm/min compression speed for Chinese fir were recommended for wood industry practice.

Among all the specimens compressed at different compression ratio, different compression direction and different compression speed, compared with the controlled specimens, for Poplar, the mechanical properties retained at least 83.1 and 84.9 % for MOR and MOE, respectively; for Chinese fir, retained at least 88.1 and 83.7 % for MOR and MOE, respectively (Fig. 3). In some cases, the

Table 2 The recovery rate, MOE and MOR at different compression speed

Speed (mm/min)	*N*	Recovery rate			MOR			MOE		
		Mean (%)	SD (%)	RET (%)	Mean (MPa)	SD (MPa)	RET (%)	Mean (GPa)	SD (GPa)	RET (%)
Poplar										
Controlled	14			100.0	86.0	11.2	100.0	9.0	1.7	100.0
0.5	15	73.3	7.8	73.3	94.5	15.7	109.9	10.2	1.9	114.4
1	15	74.4	5.6	74.4	88.9	11.0	103.4	9.6	1.7	107.2
3	15	81.5	8.0	81.5	83.7	13.3	97.4	8.7	1.6	96.7
5	15	81.0	5.7	81.0	76.6	15.8	89.1	8.4	2.3	93.8
10	15	78.5	4.6	78.5	71.5	13.7	83.1	8.5	1.8	95.3
Chinese fir										
Controlled	15			100.0	71.3	9.6	100.0	9.1	1.1	100.0
0.5	15	91.5	3.0	91.5	66.4	12.4	93.0	9.1	1.6	99.4
1	15	89.8	2.8	89.8	62.9	7.2	88.1	8.5	0.7	92.5
3	15	87.5	3.4	87.5	70.9	13.2	99.5	9.7	1.7	106.4
5	15	89.1	3.5	89.1	76.9	7.1	107.8	10.2	1.4	111.4
10	15	88.0	1.9	88.0	73.1	13.9	102.5	10.2	2.7	111.3

MOR modulus of rupture, *MOE* modulus of elasticity, *N* number of specimens tested, *SD* standard deviation, *RET* retained compared with the controlled specimens

mechanical properties were higher than that of controlled specimens due to the densification resulted from lowered RR. It suggested that the mechanical properties had a slight loss or increase after the compression treatment under high moisture condition. Therefore, the pre-treatment by compression for wood drying is viable in terms of mechanical properties.

As mentioned before, all the pre-treatment by compression were in water-saturated condition, and the MC after compression were more than 65 % for both tree species. In such a wet condition, the wood owns the remarkable deformability resembles that of ductile metals [9]. Before compression, the water was bonded with matrix of wood, and the irregular zone of microfibrils of cellulose, which enlarged the gap between wood molecules and reduced the amount of "Velcro" hooks of hemicellulose side chains and cellulose fibrils that entangled with the rest of the matrix. During the compression, when a certain stress was reached, in one hand, the bond between wood molecules could be replaced by water which provides the hydroxyl or hydrogen and were replaced again by near molecules of wood, these replacement could be done over and over; in the other hand, hemicelluloses attached to the cellulose fibrils entangled with the rest of the lignin-rich matrix were disentangled and entangled in a new position, these entanglement and disentanglement could also be done repeatedly, and therefore, new steady interlocks of wood molecules were harmoniously developed. After the compression when the wood was recovered in size, a lock-in at the new position and the unspecific bonds re-form immediately in the new position of the fibrils (like Vecro connection that has been opened and closed) [10]. This in some extent explains why the mechanical properties remained well after the compression in wet condition.

Test of individual cell at moist condition by Keckes, etc. [10] proved that individual cell retains its stiffness after permanent deformation beyond the yield point, while the stress relaxation does not significantly damage the matrix. This is the other explanation that even at the highest compression ratio (60 % in this case), the mechanical properties were well retained after the pre-treatment by compression. In addition, the pre-treatment by compression possibly decreased the microfibril angle (MFA) of the wood cell, which improved the retainability of the mechanical properties. Increased MOE and MOR compared with the controlled specimen (0 % compression) were also probably attributed to the densification resulted from not 100 % recovery in size after the compression.

Figure 3 also showed, although the mechanical properties were over all well retained, they decreased slightly sometimes. This is probably due to the uneven distributed compression ratio and MC. In one hand, during the compression, the compression force was transported from outside to the center of wood, while the strength of latewood, early wood and parenchyma was not the same, the strength of the vessel and the fiber are not the same, consequently, the compression ratio in some place is probably much bigger than the other, resulting in partial damage. In the other hand, during the compression, the reduced and possibly uneven distributed MC would lead wood partially not-enough hygroplastisized, resulting in partial damage as well. Here, it is worth mentioning that, during the compression, the bond between wood constituents (hemicelluloses attached to the cellulose fibrils bonds with the rest of the lignin-rich matrix) and the bond between wood and water were replaced by each other repeatedly, in this dynamic courses, the effect of MC on the mechanical properties (unlike in the steady condition, MC over equilibrium moisture content (EMC) has no effect on the mechanical properties), need to be studied systematically.

Conclusions

1. The RR decreased 0.18 and 0.20 % every 1 % compression ratio when the compression ratio was lower than or equal to 50 and 40 % for Poplar and Chinese fir, respectively, over this compression ratio, the RR decreased rapidly; The RR had the maximum value in T compression for Poplar, while had the minimum value in 45° compression for Chinese fir; The RR of specimens compressed at 3, 5 and 10 mm/min were bigger than those at 0.5 and 1 mm/min for Poplar; For Chinese fir, the RR difference among all the compression speed was quite small compared with that for Poplar.

   The RR at all conditions was not less than 73.3 and 79.7 % for Poplar and Chinese fir, respectively. In another word, the wood retained more than 84.0 and 92.0 % of original size. This concluded that the pre-treatment by compression for wood drying is viable in terms of RR at all compression ratio, compression direction and compression speed we tested.
2. The mechanical properties difference was not significant between the specimen compressed in different compression ratio, while was significant between the specimens compressed in different compression direction and different compression speed except the MOR of Poplar between different compression direction. For Chinese fir, MOR and MOE in 45° compression specimen showed the maximum value.

   The mechanical properties at all conditions showed a slight loss or increase compared with the controlled specimens, they retained at least 83.1 and 88.1 % of MOR, 84.9 and 83.7 % of MOE for Poplar and Chinese fir, respectively. This concluded that the pre-treatment by compression for wood drying is viable in terms of mechanical properties at all compression ratio, compression direction and compression speed we tested.
3. For the wood industry practice, well-retained RR and mechanical properties mean that pre-treatment by compression for round wood in radial direction, for flat grain timber in radial direction, for vertical grain timber in tangential direction, for in-between vertical and flat grain timber in 45° direction are viable in terms of RR and mechanical properties.

   As a compromise between RR, mechanical properties and wood processing efficiency, 3 or 5 mm/min compression speed for Poplar and 5 or 10 mm/min compression speed for Chinese fir were recommended for wood industry practice.
4. After all, pre-treatment by compression for wood drying is viable in terms of RR and mechanical properties.

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