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ORIGINAL ARTICLE

# Studies on pre-treatment by compression for wood drying I: effects of compression ratio, compression direction and compression speed on the reduction of moisture content in wood

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**Abstract** To remarkably reduce the moisture content (MC) in a short time, pre-treatment by compression for wood drying was systematically studied in terms of effects of compression ratio, compression direction and compression speed on the reduction of MC in Poplar and Chinese fir. The results showed (1) MC reduction was about 108 and 176 % after compression at a ratio of 60 % from water-saturated condition, and it was about 1.8 and 3.0 % every 1 % compression ratio for Poplar and Chinese fir, respectively. (2) Compressions in tangential, radial and 45° direction were very effective in MC reduction, suggesting that pre-treatment by compression is very effective on round wood and timbers of flat grain, vertical grain and in-between vertical and flat grain. Of all the compression directions, the tangential compression showed a maximum MC reduction. (3) For Poplar, when the compression speed was 0.5, 1 and 3 mm/min, MC reduction had no big change; while it became small when the compression speed was 5 and 10 mm/min. For Chinese fir, reduction of MC decreased with the increase in compression speed. After all, the pre-treatment by compression is very effective to reduce the MC for wood drying.

**Keywords** Pre-treatment · Compression · Wood drying · Moisture content

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## Introduction

Drying is the most common and most energy-consuming operation in wood industry. From the falling down of the tree to drying procedure, it always takes a long time. The greenwood usually has high moisture content (MC), and it takes months for air drying to reduce the MC to a reasonable extent before putting in a drying kiln; otherwise, the energy consumption during the kiln drying is too high. Long-time air drying means not only a lot of precious space has to be occupied for a long time, but also a long cycle of wood industry procedure, which will greatly reduce the speed of recouping the fund, and therefore reduce the economy efficiency. Furthermore, during air drying, the blue stain or fungi attack will probably be developed for some species. This problem is more serious in summer in some places and in all year in the tropical area. Hence, a technical solution has to be found to reduce the MC of wood in a short time to a reasonable extent before putting the wood into the drying kiln. In another words, a new way of pre-treatment for wood drying is needed for wood industries.

Wood in high MC and high temperature has a much lower strength and much more flexibility. A lot of related studies have been done around this character. Norimoto [1, 2] bent the wood in a very small radius without any compression failure after the wood was microwave irradiated. Studies on 18 species by Iida [3] found they could be compressed in the direction perpendicular to grain in a ratio of 70 % after the microwave irradiation, the compression set could be fixed after drying, and also could be totally recovered after moisture and heat treatments. Observation by scanning electron microscope (SEM) on the compression wood by Iida [4] and Watanabe [5] found even the cell cavity was totally compressed, any failure and separation of the cell walls could not be detected; while the fracture of pit membrane was found on the aspirated pits at the boundary between the torus and margo, suggesting that compression treatment would facilitate the wood drying and impregnation [6–8]. Although a lot of studies [9–11] have been done on the pre-compressed wood in terms of improvement and mechanism of liquid penetration, and the early studies [12] showed the compression treatment could improve drying behavior, the studies on the reduction of moisture content by compression are not enough and systematical.

Poplar and Chinese fir showed they had much lower strength and much more flexibility in water-saturated condition compared with that in air-dried condition [13]. This makes it possible to reduce the water by compression at a not too high force without losing too much strength of wood [14]. However, the effects of compression ratio, compression direction and compression speed on the reduction of MC and on mechanical properties are not very clear. The compression ratio not only has an obvious effect on the efficiency of the treatment, but also on the efficiency of MC reduction. The compression direction determines the way the wood is compressed. The compression speed directly influences the efficiency of the treatment. The effects of compression ratio, compression direction and compression speed on MC reduction need to be systematically studied before practicing this technique in the industry.

Poplar and Chinese fir are two of the most popular plantation species planted in a large scale in China. The effects of pre-treatment by compression on the reduction of MC on Poplar and Chinese fir have not been systematically studied yet. Therefore, the purpose of this study is to systematically study the pre-treatment by compression for wood drying, focusing on the effects of compression ratio, compression direction and compression speed on the reduction of MC in Poplar and Chinese fir. In the later report, the effects of compression on the mechanical properties and other factors will be discussed.

## 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 samples were prepared with the size of 3 cm (R/T) × 5 cm (T/R) × 10 cm (L) and tested in tangential compression, radial compression and 45° compression, as shown in Fig. 1. The tangential compression was carried on the vertical grain samples with the compression direction parallel to the annual ring; the radial compression was carried on the flat grain samples with the compression direction perpendicular to the annual ring; and the 45° compression was carried on in-between tangential and radial samples with the compression face having 45° with the annual ring. The 45° compression samples were prepared and tested because in the industry practice, most boards are neither vertical grain boards nor flat grain boards, but the boards in-between vertical and flat grain.

To minimize the effects of sample variation on the test results, all the samples were oven-dried first so that the growth stress was released in some extent, and then vacuum pressure treated so that all the samples were fully water saturated having a similar MC. Based on the oven-dried weight, the MC can be calculated in water-saturated condition and after-compression condition.

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 which thank to fully computer-controlled Instron 5582 Universal Test Machine. A special adapter was connected to the compression head to facilitate the compression.

## Results and discussion

### Effects of compression ratio on MC reduction

To limit the variation, the tests were radially compressed at the speed of 3 and 5 mm/min for Poplar and Chinese fir, respectively. The compression ratio for both tree species was 10, 20, 30, 40, 50 and 60 %.

Compression ratio is the proportion of the compressed size to the initial size before the compression along the compression direction, standing for the degree that the

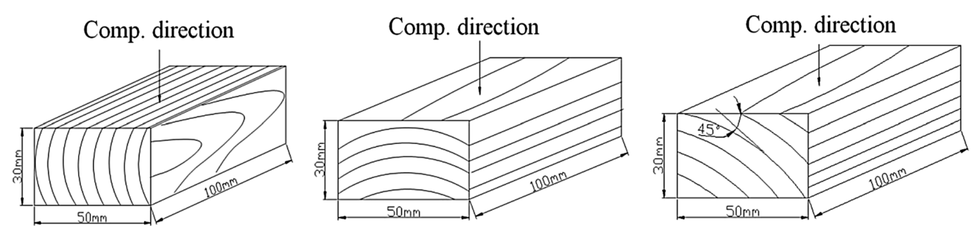


**Fig. 1** Three-directions compression: tangential (*left*), radial (*center*) and 45° (*right*)

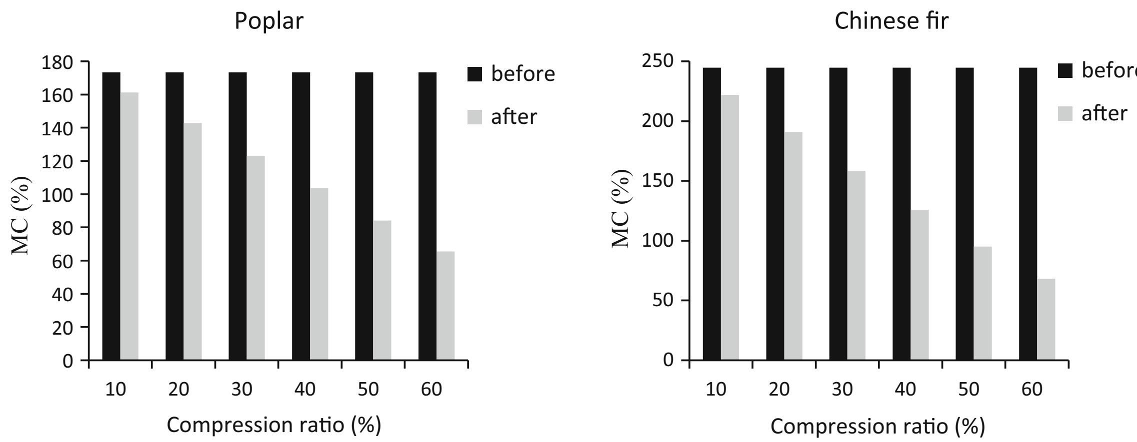


**Fig. 2** Moisture content (MC) before and after compression showing an increased difference with the increase of compression ratio

wood is compressed. The MC before and after compression at different compression ratio of Poplar and Chinese fir (Fig. 2.) showed the MC was reduced from 173 to 65 % and 244 to 68 %; the MC reduction was 108 and 176 % for Poplar and Chinese fir, respectively, suggesting the MC reduction by means of compression is extremely large, and therefore is very effective in removal of water. Figure 2 also showed that the MC difference between before and after compression increased gradually with the increase in compression ratio. Higher compression ratio reduces larger volume of lumen where most of the water is stored in the wood. During the compression, the pressure within wood was increasing, that around water was increasing at the same time. The pressure became the driving force penetrating the water out of wood. For Poplar, the free water was mainly stored in the lumen of vessels. The penetration of water occurred mainly in vessels along longitudinal direction, although a little penetration in fiber and ray existed. For Chinese fir, the free water was mainly stored in the lumen of the tracheids. The penetration of water occurred mainly in tracheids along longitudinal direction. The water release tends to reduce the pressure difference between water in the inner wood and in ambient wood, while the constant compression increased this difference. Therefore, with the increase in compression ratio, more water was penetrated out of the wood.

Despite the obvious reduction of MC after the compression treatment, the wood mechanical properties remained well compared with the controlled samples. This aspect, as mentioned before, will be reported in the later report.

Linear relationship between MC reduction and compression ratio (Fig. 3) was found for the range of compression ratio we tested ($\leq$60 %), which suggested that the MC reduction was about 1.8 and 3.0 % every 1 % compression ratio for Poplar and Chinese fir, respectively. The coefficient for Poplar was lower than that for Chinese fir because the MC before compression treatment was about 173 % for Poplar, much lower than that for Chinese fir (244 %). The diameter of vessel in Poplar is much bigger than the tracheid in Chinese fir, the simple perforates in the vessels are much easier to be penetrated than the pit pairs on the tracheids; therefore, penetration in vessels of Poplar is much easier than that in tracheids of Chinese fir. However, the proportion of vessel in Poplar is only about 35 %, while the proportion of tracheids is more than 90 % [15]. The fiber is accounting for the most proportion of Poplar which is small in diameter and hard to be penetrated compared with the tracheid in Chinese fir. All these factors were attributed to a higher initial MC content and a higher MC reduction coefficient in Chinese fir.

One more factor worth mentioning is the density of wood. In this study, the oven-dried density of Poplar is 0.41 g/cm$^3$, about 20 % higher than that of Chinese fir (0.35 g/cm$^3$). The moisture content is the ratio of water weight to oven-dried weight of wood. Same water content in high density wood means lower MC. The water content in weight at the same MC of Poplar contains more water than that in Chinese fir, which also maximizes the difference of MC reduction coefficient between Poplar and Chinese fir.

Stress–strain (compression ratio) curve (Fig. 4) of both Poplar and Chinese fir can be divided into 3 stages. The stress increased rapidly at the beginning of compression (the first stage), and then increased slowly until the strain reached about 44 % for Poplar and 48 % for Chinese fir (the second stage). After this, stress increased rapidly again with the increase in compression (the third stage). At the beginning of the compression, the stress was under the proportional limited range; the energy of compression was stored in wood and the stress increased rapidly. When the stress is over the proportional limited point, part of the compression energy was consumed to fold the cell wall. In this study, the compression was conducted in the radial

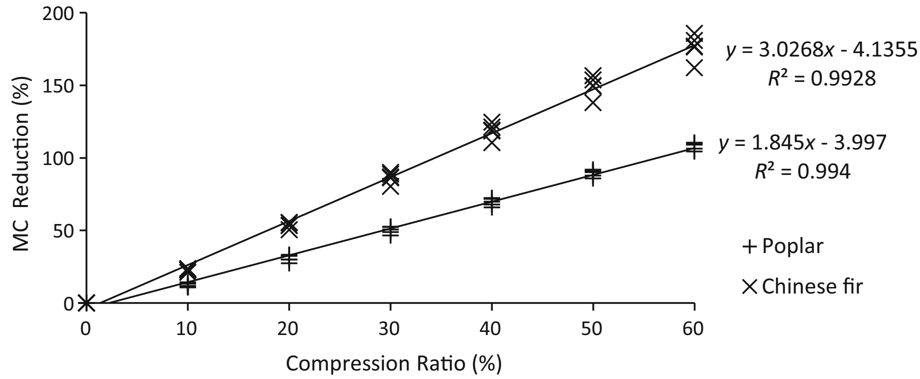


**Fig. 3** Relation between moisture content (MC) reduction and compression ratio

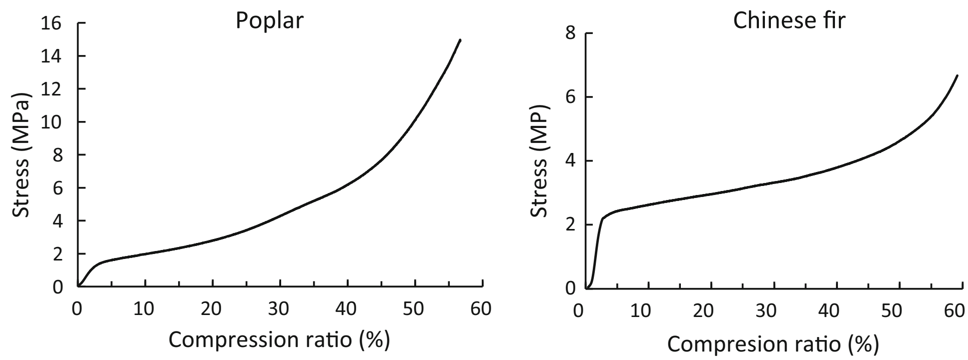


**Fig. 4** Stress-strain (compression ratio) curves of Poplar and Chinese fir during the compression pre-treatment

direction; the radial walls were first folded. After the radial walls were folded, the tangential walls were easily compressed to move from one to another, and the lumen of tracheids or vessels was becoming smaller and smaller. After this, the tangential wall contacted with another. At this moment, the stress increased rapidly again. The compression after this was acted on the tangential wall, which resulted in the rapid increase of stress.

Former studies [16] showed the cell wall ratio of plantation Poplar and Chinese fir was ranged from 49.73 to 53.98 % and from 40.94 to 43.89 %, respectively. In another word, suppose the lumen can be totally compressed, the compressible ratio of Poplar and Chinese fir was ranged from 46.02 to 50.27 % and from 56.11 to 59.06 %, respectively. This means after the radial walls were folded, the tangential walls of the same cell contacted to the other at a lower compression ratio in Poplar than that in Chinese fir. This explains in some extent, in the third stage, the stress of Poplar began to rapidly increase at a lower compression ratio (44 %) than that of Chinese fir (48 %).

## Effects of compression direction on the reduction of MC

All the samples for studying the effects of compression direction on the reduction of MC were compressed at the ratio of 60 and 40 % for Poplar and Chinese fir, respectively.

The results of MC before and after compression at different compression directions were showed in Fig. 5. The reduction of MC in tangential compression, radial compression and 45° compression, of both Poplar and Chinese fir is very obvious, suggesting that the pre-treatment by compression for the MC reduction is very effective in tangential radial compression, radial compression and in-between radial and tangential compression. For the wood industry practice, the effectiveness of the reduction of MC in radial compression means pre-treatment by radial compression for round wood is applicable; while the effectiveness of the reduction of MC by compression in radial direction, tangential direction and in-between radial and tangential compression means pre-treatment by compression is valid for flat grain timber, vertical grain timber and the in-between vertical and flat grain timber. After all, the pre-treatment of compression is very effective in the reduction of MC for round wood and all kind of timbers.

The reduction of MC is attributed to the volume shrinkage of wood. During the compression pre-treatment, regardless of the compression direction, the lumen of the cell is shrunk as mentioned before, the pressure within wood is higher than the ambience of wood, and the water, mainly composed of free water in the water-saturated state, will flow out of wood under this pressure. During the

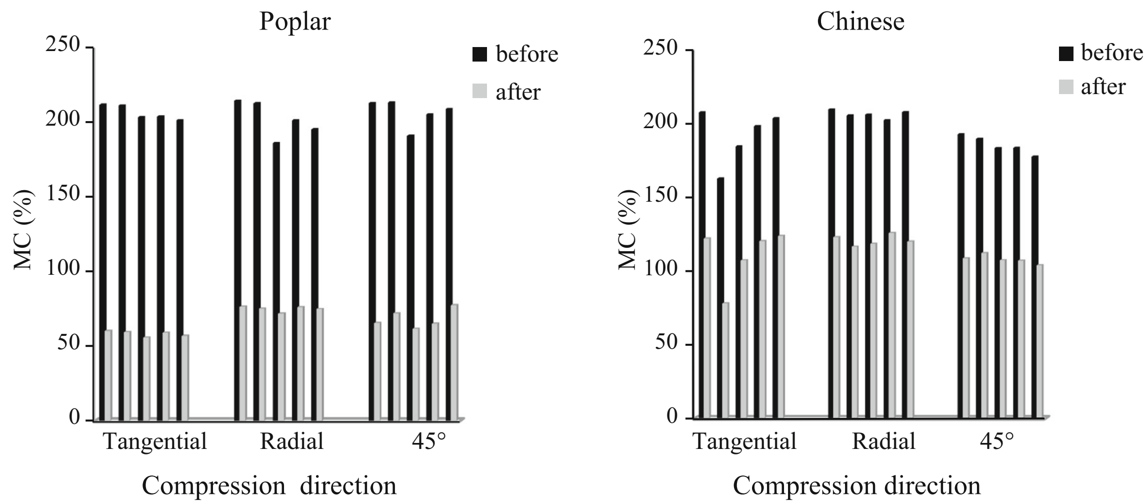


**Fig. 5** Moisture content (MC) before and after compression showing a big difference in 3 directions compression

compression, the pressure increases steadily, which not only provides the drive force of water movement, but also provides the force to break the pit or pit tori [4, 5], allowing more effective flow paths. This explains why the compression works well in the reduction of MC in radial, tangential and 45° directions.

Poplar showed a reduction of MC at about 130 %, which was higher than that of Chinese fir at about 90 % (Table 1). This is attributed to the compression ratio for studying the effects of compression direction on the reduction of MC: for Poplar, 60 % and for Chinese fir, 40 %. For both Poplar and Chinese fir, the tangential compression, showed a maximum reduction of MC (Table 1). Tangential compression allows more water flow along the radial direction along the ray, while for the radial and 45° compression, the flow along radial direction along the ray was deterred by the compression adapter that is close contacted with the compression surface of wood. This is one reason that the MC reduction of MC in tangential compression is bigger than that in radial and 45° compression. Moreover, the latewood is believed to have more water content than early wood because of lower pit aspiration ratio in latewood which resulted in higher permeability in latewood than early wood [17]. For the tangential compression, the compression ratio in early wood and late wood is exactly same due to the fact that early wood and late wood are in parallel connection along the compression direction; while for radial compression, there might be a slight lower of compression ratio in late wood than that in early wood due to the fact that late wood and early wood are in series connection along the compression direction, and the late wood has a higher compression strength than early wood because of the thicker cell wall. Based on the above consideration, water content difference and compression strength difference between latewood and early wood are probably one more reason for the fact that MC reduction in tangential compression is bigger than that in radial and 45° compression. Further study is needed to explain why 45° compression showed a minimum value in MC reduction.

**Table 1** The reduction of MC at different compression directions

| | Direction | *N* | Mean reduction of MC (%) | SD (%) | C.V. (%) |
|---|---|---|---|---|---|
| Poplar | 45° | 25 | 124.5 | 14.2 | 11 |
| | Radial | 25 | 128.4 | 12.4 | 10 |
| | Tangential | 25 | 140.3 | 7.8 | 6 |
| Chinese fir | 45° | 25 | 75.1 | 5.5 | 7 |
| | Radial | 25 | 92.5 | 21.6 | 23 |
| | Tangential | 25 | 105.1 | 29.3 | 28 |

*N* number of specimens tested, *SD* standard deviation, *C.V.* coefficient of variation

## Effects of compression speed on MC reduction

All the samples for studying the effects of compression speed on the reduction of MC were compressed in radial direction at the ratio of 60 and 40 % for Poplar and Chinese fir, respectively.

MC before and after compression at the different compression speed (Fig. 6) showed MC reduced obviously for all the compressions at the speed of 0.5, 1, 3, 5 and 10 mm/min, although the difference of MC reduction existed between them.

The results of the reduction of MC at different compression speed are listed in Table 2. For Poplar, when the compression speed was 0.5, 1 and 3 mm/min, the reduction

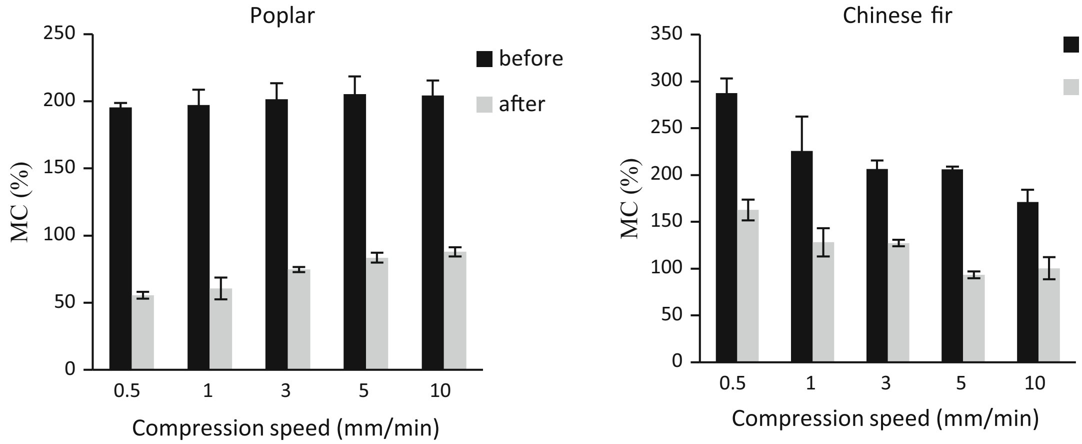


**Fig. 6** Moisture content (MC) before and after compression at the different compression speed

**Table 2** The reduction of MC at different compression speed

| | Speed (mm/min) | *N* | Mean reduction of MC (%) | SD (%) | C.V. (%) |
|---|---|---|---|---|---|
| Poplar | 0.5 | 5 | 131.8 | 10.5 | 8 |
| | 1 | 5 | 137.0 | 8.8 | 6 |
| | 3 | 5 | 137.5 | 11.4 | 8 |
| | 5 | 5 | 128.3 | 17.5 | 14 |
| | 10 | 5 | 120.6 | 11.0 | 9 |
| Chinese fir | 0.5 | 5 | 115.4 | 29.9 | 26 |
| | 1 | 5 | 102.4 | 28.7 | 28 |
| | 3 | 5 | 81.4 | 7.8 | 10 |
| | 5 | 5 | 81.2 | 5.3 | 6 |
| | 10 | 5 | 75.5 | 5.6 | 7 |

*N* number of specimens tested, *SD* standard deviation, *C.V.* coefficient of variation

**Table 3** Significance analysis on MC change of wood at different compression speed

| | Sum of squares | *df* | MS | *F* | Sig. |
|---|---|---|---|---|---|
| Poplar | | | | | |
| Among groups | 2,907.6 | 4 | 725.9 | 4.9 | 0.002[a] |
| Within group | 10,417.9 | 70 | 148.8 | | |
| Total | 13,325.5 | 74 | | | |
| Chinese fir | | | | | |
| Among groups | 17,290.2 | 4 | 4,322.6 | 11.8 | 0.000[b] |
| Within group | 25,721.9 | 70 | 367.5 | | |
| Total | 43,012.1 | 74 | | | |

*df* degree of freedom, *MS* means square, *F F* test statistic, *Sig.* significance

[a] Significant at 0.05 level

[b] Significant at 0.01 level

of MC between them had no big change, when the speed was 5 and 10 mm/min, the reduction of MC became small. For Chinese fir, the reduction of MC decreased with the increase in compression speed. Big diameter of vessels in Poplar allows more flow of water when the compression speed is high. However, for Chinese fir, compared with the vessel in Poplar, the tracheid is small, which deters the flow of wood when the compression speed is high.

Among the MC reduction at different compression speed, although the compression ratio for Poplar (60 %) was higher than that for Chinese fir (40 %), the difference between maximum and minimum was less than 20 % in Poplar, while that was more than 40 % in Chinese fir, suggesting that Chinese fir is more sensitive to compression speed than Poplar in terms of the reduction of MC. Significance analysis showed (Table 3) the compression speed had a significant effect on the reduction of MC. For Poplar, it is significant at 0.05 level and for Chinese fir at 0.01 level. This consists with the conclusion that the reduction of MC in Chinese fir is more sensitive to compression speed than that of Poplar.

## Conclusions

The MC reduction were about 108 and 176 % after compression at a ratio of 60 % from water-saturated condition with the initial MC of 173 and 244 % for Poplar and Chinese, respectively, suggesting that the MC reduction was very huge and the pre-treatment of compression for wood drying is very effective. MC reduction is dependent on the compression ratio. It was about 1.8 and 3.0 % every 1 % compression ratio for Poplar and Chinese fir, respectively, indicating that the MC reduction in Chinese fir is more effective than that in Poplar.

Compressions in tangential, radial and 45° direction were very effective in MC reduction, suggesting that the pre-treatment by compression for wood drying is very effective in round wood and all kinds of timbers, including flat grain timber, vertical grain timber and the in-between vertical and flat grain timber. Of all the compression directions, the tangential compression showed a maximum MC reduction.

For Poplar, when the compression speed was 0.5, 1 and 3 mm/min, MC reduction had no big change; while it became small when the compression speed was 5 and 10 mm/min. For Chinese fir, the reduction of MC decreased with the increase in compression speed. The reduction of MC in Chinese fir is more sensitive to compression speed than that in Poplar.

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