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Studies on pre-treatment by compression for wood impregnation II: the impregnation of wood compressed at different moisture content conditions

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Abstract

As a follow-up report, the impregnation of wood pre-treated by compression at different moisture content (MC) conditions was systematically studied in terms of impregnation during the release of compression and impregnation after release of compression. The results showed that for poplar with MC from 210 to 38.9% and Chinese fir from 175 to 43%, the impregnation during and short time after the compression release increased rapidly and increased slowly afterward. The impregnation during the compression release accounted for a rather large portion of the total impregnation, while took a short time, suggesting that the pre-treatment by compression was very significant in terms of impregnation time and amount for wood above fiber saturation point. The specimens with higher MC before compression tended to reach the maximum impregnation in shorter time than those with lower MC. The impregnation during the release of compression decreased with the decrease in MC before compression. The impregnation after the release of compression increased with the decrease in MC for poplar, while decreased first and then increased for Chinese fir. As a result, when the MC was higher than maximum moisture content allowed (MMCA), with the decrease in MC, the total impregnation decreased from 0.45 to 0.30 g/cm^3 for poplar and from 0.30 to 0.07 g/cm^3 for Chinese fir; when the MC was lower than MMCA, with the decrease in MC, the total impregnation increased from 0.30 to 0.38 g/cm^3 for poplar while from 0.07 to 0.16 g/cm^3 for Chinese fir. After all, by means of pre-treatment of compression, wood with a MC around MMCA tended to have the lowest impregnation.

Keywords: Pre-treatment, Compression, Moisture content, Wood impregnation

Introduction

Early studies [1] showed the impregnation of wood was very significantly improved in amount and speed by the pre-treatment of compression, and the effects of compression ratio, compression direction, compression speed and compression–unloading place on the liquid impregnation were systematically studied. All these studies were based on the water-saturated conditions to facilitate the studies by means of minimizing the effect from moisture content variation between individuals. The effects of moisture content on liquid uptake have been studied by Iida [2], but only on dry and wet conditions. A systematical study is needed to know the impregnation of wood pre-treated by compression at different moisture content (MC) conditions, because the impregnation treatment by compression method is most likely conducted at green condition due to the ease of compression at this condition, as well as the ease of impregnation compared with the dried condition, whereas the pits are usually aspirated [3]. However, the MC at green condition of different species and the MC at different period after falling down of the tree of the same species vary in a broad range. How the MC affects the impregnation after the pre-treatment by compression was still not clear. In

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addition, the benefits for drying resulted from more fluid flow paths by this pre-treatment [4], as well as the good maintenance of mechanical properties and volume after treatment [5, 6], necessitate this systematical study on impregnation of wood pre-treated at different moisture content conditions. Therefore, the objectives of this follow-up study were focused on the impregnations of wood pre-treated at different MC conditions. In order to fully understand the influence of MC on the impregnation, the total impregnation was investigated and discussed in two impregnation period—the impregnation during the release of compression and the impregnation after release of compression.

Materials and methods

Five trees of 10-year-old poplar (*Populus euramevicana* cv. 'I-214') plantation grown in the side of a pond with the diameter at the breast height of about 30 cm, the initial MC of about 200%, and the basic density of 0.32 g/cm^3, and about 5 m^3 of Chinese fir (*Cunninghamia lanceolata*) plantation from local market with the basic density of 0.31 g/cm^3, were collected from Taihu County of Anhui Province. The specimens were prepared with the size of 30 mm (R) × 50 mm (T) × 100 mm (L) and tested in radial compression.

All the specimens were vacuum pressure-treated so that all the specimens were fully water-saturated. They were subjected to a slow MC loss in a very humid chamber until the MC reached the set value; then, the specimens were packed tightly in airtight plastic film and stored in a refrigerator to make the MC evenly distributed. The MC was determined by the weight of the specimen and its dry weight. The dry weight was calculated by the volume of the specimen itself and the basic density of a physically longitudinal connected specimen. The MC was set in 8 and 7 levels from saturated MC to about 40% for poplar and Chinese fir, respectively. Ten repeats of specimen for each MC level, together with air-dried controlled specimens, were prepared and tested.

The compression was completed by a fully computer-controlled Instron 5582 Universal Test Machine whose compression head was connected with a special adapter. The specimen was put between two stainless plates of the adapter and was compressed by the plate driven by the compression head of the machine at a speed of 3 and 5 mm/min and a compression ratio at 60 and 40% for poplar and Chinese fir, respectively. The compression was fixed by means of tightening the nuts on four bolts located at the corner of the adapter. Then, the specimen, together with the adapter with tightened nuts, was totally immersed in Patent blue solution (0.2% mass concentration). The release of compression was conducted by loosening the nuts in the solution and was weighed immediately after the release of compression. The specimens were continuously immersed in the solution and were weighed in some interval until the difference of weight in two consecutive measures was less than 0.2 g in 1 h. The impregnations during the release of compression, as well as for different time after the release of compression, were calculated by the weight of Patent blue solution gained per unit volume of wet wood (g/cm^3).

Results and discussion

The impregnation of wood compressed at different MC conditions at different time (Fig. 1) showed that the impregnation after the completion of compression release (0 min) accounted for a rather large portion in amount, even though it can be finished in a short time and continuously increased afterward. The specimens with higher MC before compression tended to reach the maximum impregnation in shorter time than those with lower MC. For example, for poplar, it reached 95% of maximum impregnation in several minutes for specimens with high MC, while that in more than several hours for those with low MC. The controlled specimen (air-dried without compression) showed the impregnation increased continuously over the whole-time range (5000 min). It concluded that the pre-treatment by compression was very significant in terms of impregnation time and amount and therefore a very efficient impregnation treatment for wood above fiber saturation point.

In order to further investigate the impregnation at different periods, the total impregnation (in this case, the impregnation in 2000 min) was divided into impregnation during the release of compression and that after the release of compression (Fig. 2).

The impregnation of wood during the release of compression

It was observed that the recovery of wood was finished as soon as the completion of the compression release even under the computer control which can finish the compression release in the air in a few seconds. In this test, the compression was released in the Patent blue solution in a few minutes. It was assumed that the recovery of wood was finished soon after the completion of the compression release, and the impregnation at this moment was regarded as impregnation during the release of compression. The impregnation during the release of compression decreased from 0.42 to 0.22 g/cm^3 and 0.18 to 0.03 g/cm^3 with the decrease in MC before compression from 210 to 86% and 175 to 116% and remained almost constant with the continuous decrease in MC from 86 to 39% and 116 to 43% for poplar and Chinese fir, respectively (Fig. 2).

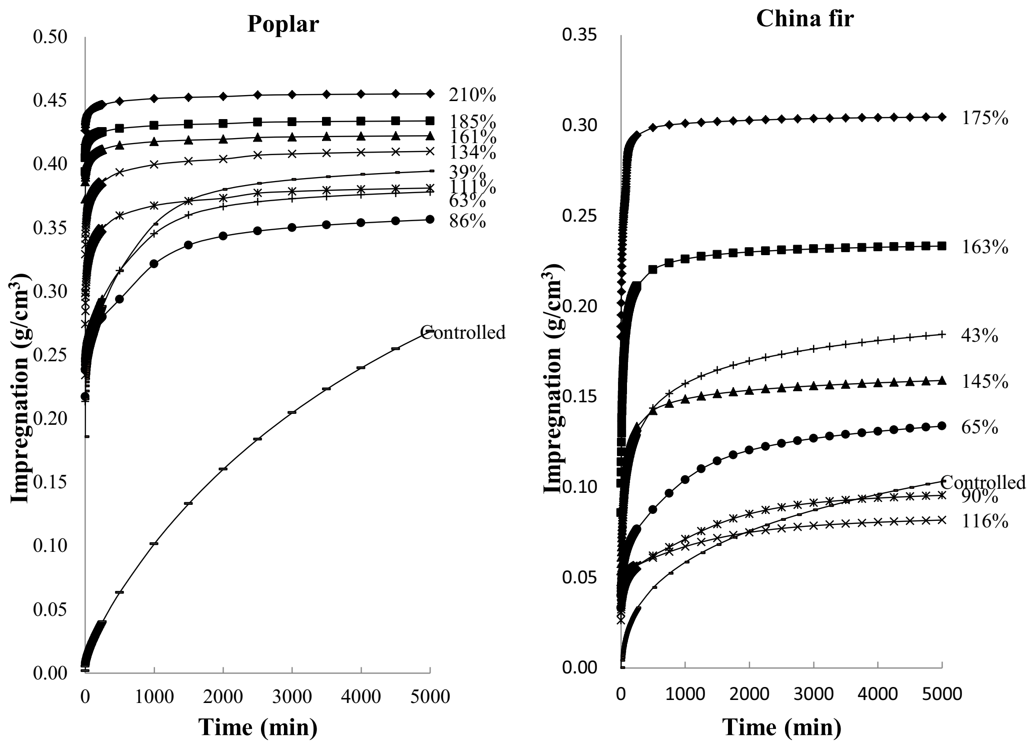

Fig. 1 Impregnation at different time. The time after the release of compression was regarded as 0 min. The impregnation reached almost maximum in a short time except the controlled

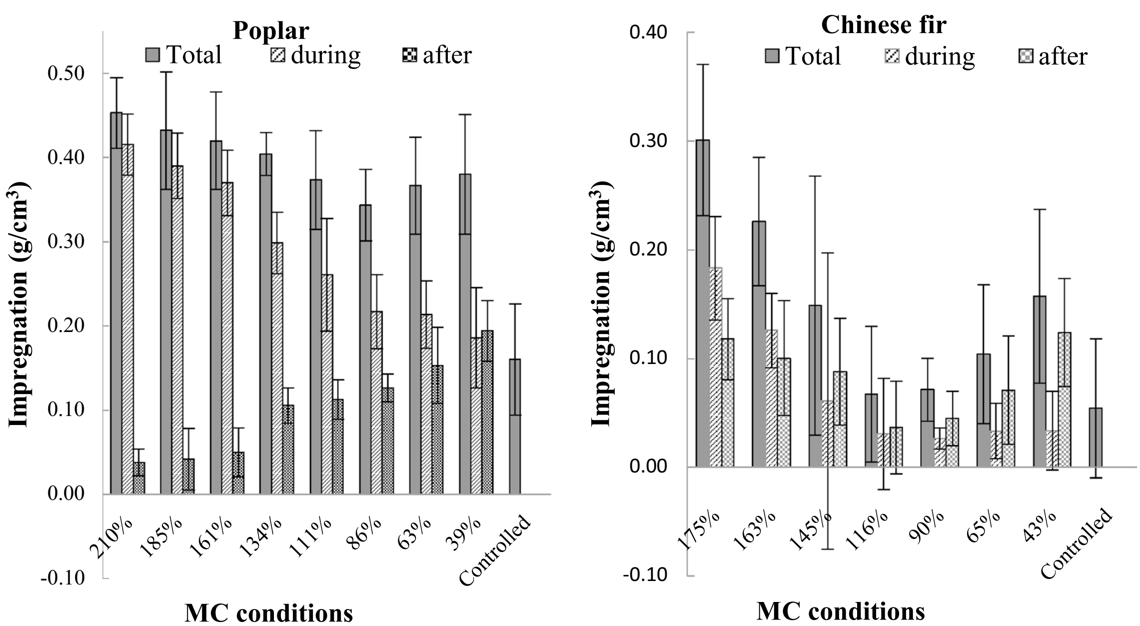

Fig. 2 Total impregnations, impregnation during the release of compression and impregnation after the release of compression of the specimen in different MC conditions (*error bar* standard deviation)

The reduction in MC was proportional to the compression ratio for a given wood species when it was compressed in water-saturated condition [7]. Therefore, the maximum MC allowed (MMCA), a critical MC value in the wood after the compression, is determined by a given compression ratio when it was compressed at water-saturated condition which, in this case, was 84.1 and 105.3% for poplar and Chinese fir, respectively. When the MC of wood before compression was above MMCA, the MC after compression remained almost constantly at about MMCA [6]. This means, in one hand, that the reduction in MC was decreased with the decrease in MC before compression, suggesting that the impregnation potential from increased available voids due to MC reduction followed by wood recovery was decreased with the decrease in MC before compression; in the other hand, the air entrapped after the compression was very limited because the bond between air and wood was nothing, while that between water and wood was strong. During the release of the compression, the wood was recovered to original size in Patent blue solution as it was before compression. The expanded volume of wood during recovery, in one hand, resulted in low pressure within wood compared the pressure outside of the wood, and therefore resulted in quick impregnation under the permeability driven by pressure gradient and, in the other hand, provided necessary rooms for impregnation. The more MC was reduced, the more rooms were available for impregnation. This explains why the impregnation during the release of compression decreased with the decrease in MC before compression for the specimen with a MC higher than MMCA.

When the MC before compression is lower than MMCA, during the compression, as mentioned before, the air was more readily to move out of the wood than water; therefore, the MC reduction was decreased while the air deduction was increased with the decrease in MC. The impregnation potential from increased room due to the MC reduction decreased with the decrease in MC before compression, while that due to air deduction increased with the decrease in MC before compression. This turned out to be a similar impregnation amount during the release of compression.

The fact that the impregnation during the release of compression of wood with MC higher than MMCA was much higher than that with MC lower than MMCA was attributed to much different air influence. After the completion of the compression, in case that the MC before compression was higher than MMCA, the influence for impregnation during the release of compression from air was very limited due to very limited air which can be seen from the fact that the MC after compression remained almost same [6]; in case that the MC before compression was lower than MMCA, the influence from air was strong due to more air entrapped in wood after the compression. The air was in high pressure under the compression and would expand with the release of compression. The expansion of air would greatly deter the impregnation of wood.

The impregnation of wood after the release of compression

The impregnation after the release of compression increased from 0.04 to 0.19 g/cm^3 and 0.04 to 0.12 g/cm^3 with the decrease in MC before compression from 210 to 39% and 90 to 43% for poplar and Chinese fir, respectively. However, it decreased from 0.12 to 0.04 g/cm^3 with the decrease in MC before compression for Chinese fir from 175 to 116% (Fig. 2), a MC range over MMCA.

During the release of compression, the pressure gradient by wood recovery gradually decreased with the impregnation solution into the wood. Soon after the completion of compression release, it was assumed that there was no or very small compression pressure difference between inside and outside of wood. Then, the impregnation was mainly driven by the capillary pressure [3]. The Patent blue solution was mainly composed of water which wets the surface due to a strong force of attraction between the molecule of water and that of wood lumen surface. This adhesive attraction, together with the surface tension of water (cohesive force of water molecule), would lead to a continuous capillary impregnation. The more available voids occupied by entrapped air mean more capillary impregnation potential because the air was compressible and might move out of wood. The capillary impregnation did not finish until the increased entrapped air pressure equaled to capillary pressure. This explains why the impregnation after the release of compression increased with the decrease in MC before compression (Fig. 2) except the result of Chinese fir with a MC over MMCA.

The exception result for Chinese fir with a MC over MMCA was probably attributed to the anatomical structure difference between poplar and Chinese fir. Compared with the vessel and the perforate in poplar, the tracheid and pit in Chinese fir were more difficult to impregnate. The permeability of Chinese fir was much lower than that of poplar [8]. The recovery of wood was finished in a very short time, causing a pressure gradient. The Chinese fir wood might need a longer time to cease the pressure gradient than poplar did because of its much lower permeability. The Chinese fir was more likely to have the pressure gradient after the completion of compression release, causing the impregnation accumulation under the pressure gradient. At MC over MMCA conditions, the impregnation potential from MC reduction decreased with the decrease in MC before compression; therefore, at the given permeability, the time needed to cease the pressure gradient decreased with the decrease in MC before compression. That explains the impregnation after the completion of compression release decreased from 0.12 to 0.04 g/cm^3 with the decrease in MC before compression from 175 to 116%.

It was observed that, when the MC was over the MMCA, the MC after the completion of compression release was 6.6 to 46.2% more than that before compression in poplar (except water-saturated specimens which might need long time than the other), while that was 18.1 to 34.3% less than that before compression in Chinese fir. This proved in some extent that the pressure gradient ceased in a longer time in Chinese fir than poplar, and the pressure gradient might still exist in Chinese fir soon after the completion of compression release.

The total impregnation of wood

The total impregnation of wood at different time was an accumulation of impregnation during the release of compression and that after the release of compression. As discussed before, the impregnation during the release of compression, for both species, decreased with the decrease in MC before compression when the MC was not less than the MMCA and remained almost constantly when the MC before compression was less than MMCA; the impregnation after the release of compression, for poplar, increased gradually with the decrease in MC before compression and, for Chinese fir, decreased with the decrease in MC before compression when the MC was not less than MMCA, and increased with the decrease in MC before compression when the MC was less than MMCA. As a result, the wood with a MC around MMCA had the lowest impregnation. That is why the curve of total impregnation of wood with MC lower than MMCA jumped their orders over the impregnation of wood with the MC around MMCA.

The MMCA for poplar and Chinese fir was related to the cell wall ratio, as well as the compression ratio applied. Compared with the Chinese fir, higher cell wall ratio of the poplar [1] means lower compressible voids, suggesting the MMCA of poplar is lower than that of Chinese fir. The compression ratio applied in this study for poplar was 60% and for Chinese fir was 40%. The compression ratio difference enlarged the variation of MMCA between two species, resulting in a MMCA of 84.1% for poplar and 105.3% for Chinese fir.

The MC around MMCA for poplar (84.1%) in this study was 86%; that was why the impregnation curve of 63 and 39% jumped their orders over that of 86%. The MC around MMCA (105.3%) for Chinese fir in this study was 116%; that was why the impregnation curve of 90, 65 and 39% jumped their orders over that of 116%. When the MC was less than MMCA, as mentioned before, the lower the MC before compression, the higher the impregnation after release of the compression due to more available voids occupied by air. That was why the total impregnation curve of those with lower MC before compression jumped higher. In this study, after some time of release of compression, the order of total impregnation curve of wood with MC before compression was 39, 63 and 86% for poplar and was 43, 65, 90 and 116% for Chinese fir (Fig. 1).

The fact that the specimens with higher MC before compression tended to reach the maximum impregnation in shorter time than those with lower MC (Fig. 1) was attributed to the impregnation of the former accounted more percentage of the maximum amount of impregnation than the latter (Fig. 2). For the specimen with high MC before compression, the fact that the impregnation of Chinese fir increased more sharply (big in amount and short in time) than poplar did (Fig. 1) was probably attributed to much lower permeability of former [8], in one hand, resulted in less impregnation during the release of compression and consequently more impregnation rooms available and, in the other hand, resulted in the existence of pressure gradient between inside and outside of wood since the low permeability needs a long time to cease this gradient, and consequently the impregnation driven by permeability in Chinese fir even after the completion of compression release, while that in poplar was driven by capillary pressure. The sharp increase in impregnation in Chinese fir was still the contribution from compression since the pressure gradient was from this compression followed by the recovery of wood although it happened after the completion of compression release.

Conclusions

For poplar with MC from 210 to 38.9% and Chinese fir from 175 to 43%, the impregnation during and short time after the compression release increased rapidly and increased slowly afterward. The impregnation during the compression release accounted for a large portion of the total impregnation, while took a short time, suggesting that the pre-treatment by compression was very significant in terms of impregnation time and amount for wood above fiber saturation point. The specimens with higher MC before compression tended to reach the maximum impregnation in shorter time than those with lower MC.

The impregnation during the release of compression decreased with the decrease in MC before compression. The impregnation after the release of compression increased with the decrease in MC for poplar, while decreased first and then increased for Chinese fir. As a result, when the MC was higher than MMCA, with the decrease in MC, the total impregnation decreased from 0.45 to 0.30 g/cm^3 for poplar and from 0.30 to 0.07 g/cm^3 for Chinese fir; when the MC was lower MMCA, with the decrease in MC, the total impregnation increased from 0.30 to 0.38 g/cm^3 for poplar while from 0.07 to 0.16 g/cm^3 for Chinese fir. After all, by means of pre-treatment of compression, wood with a MC around MMCA tended to have the lowest impregnation.

Abbreviations
MC: moisture content; MMCA: maximum moisture content allowed.

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Authors' contributions
YZ wrote the manuscript. XZ performed the experiment of the study and was responsible for data collection; YZ and II conceived and designed the experiments. YZ and JG analyzed the data. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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