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ORIGINAL ARTICLE

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Passive impregnation of liquid in impermeable lumber incised by laser

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Abstract Square lumber specimens of laser-incised Douglas fir (*Pseudotsuga menziesii* Franco) were treated with steam before dipping. Two types of steam (saturated steam and superheated steam), three steam-injection times (5, 10, and 20 min), four different time intervals (moving time) between steam treatment and dipping (immediate, 3, 10, and 30 min), and four different dipping times (0.5, 1, 3, and 12 h) were used in the study. The maximum absorption was 480 kg/m^3 when saturated steam was injected for 20 min and the specimen was immediately dipped into liquid for 12 h. Samples treated with this condition not only absorbed the maximum amount of liquid but also penetrated over 83.4% and 87.3% of the total area along and across the grain, respectively. The optimum conditions were then applied to laser-incised sugi (*Cryptomeria japonica* D. Don) and Japanese larch (*Larix leptolepis* Gordon) where the absorption of liquid was 415 and 187 kg/m^3, respectively. It was shown that initial moisture content below the fiber saturation point was good for passive impregnation. The absorption of liquid and its distribution in wood indicates that it can be a good preservative treatment method for impermeable woods.

Key words Laser incising · Passive impregnation · Steam injection · Wood preservation

Introduction

Wood is a renewable building material, but becomes subject to degradation by a variety of natural agents if used untreated in many applications. To ensure long-term service life, wood must be protected from its natural attacking agents. Wood can be protected from the attack of decay fungi, harmful insects, or marine borers by applying chemical preservatives. The degree of protection achieved depends on the preservative used and the penetration and retention of the chemicals that are impregnated.[1] Because penetration and retention varies depending on wood properties, treatability varies among wood species, particularly their heartwood, which generally resists preservative treatment more than sapwood.[2] A low degree of pitting[3,4] makes Douglas fir wood impermeable, not only for solid wood but also for plywood.[5] It has a high percentage of virtually untreatable heartwood.[6–8] Pit aspiration, as well as the inclusion of heartwood substances, leads to reduced permeability in the case of Japanese larch and thus this species is categorized as extremely difficult to treat.[9] Sugi, which is extensively planted in Japan, is a lowly permeable species. Sugi wood has a high pit aspiration ratio up to 80% until moisture content decreases to the fiber saturation point,[10,11] and then causes a significant decrease in permeability.[10,12] Pressure treatment is recommended for all these species to get a standard level of penetration and retention. To meet minimum penetration and retention requirements for preservative-treated wood of this refractory species, incising prior to preservative treatment is recommended.[13]

Douglas fir (*Pseudotsuga menziesii* Franco), sugi (*Cryptomeria japonica* D. Don), and Japanese larch (*Larix leptolepis* Gordon) lumber have been used commonly in Japan to make wooden houses. Given that about 40% of the newly constructed houses in Japan are made from wood,[14] 89 million cubic meters of wood is consumed annually in which 40% is in the form of sawn lumber[15] to build wooden houses. If, still, these species could be satisfactorily and consistently treated with preservatives with a simple treatment method, their use, marketability, and value would further be enhanced for applications in adverse conditions.

To obtain long-term effectiveness, adequate penetration and retention of chemical preservative are needed for each wood species. Different methods of chemical impregnation are now available for impermeable timber such as the

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Bethel process, the Lowery process, and the Rueping process. Adequate levels of chemical penetration and retention can be achieved by these methods, but they are complicated and not suitable for treating small amounts of wood[16] because of high initial investment. It is also difficult to drive out air from the cell lumen by these processes, even by the hot and cold process. To solve these problems, a new method was developed by Hattori et al.,[14] which was described as a passive impregnation method of wood preservation. The benefit of this method is that a pressure tank is not required and a good level of impregnation can be achieved by a simple dipping process, although a needle incising machine is needed.

Incised Douglas fir was treated by the passive impregnation method in this study to determine the effect of passive impregnation when using different types of steam, different steam injection schedules, different levels of moving time from steam injection to dipping, and different dipping periods. The selected best condition was then applied to sugi and Japanese larch to observe effects of this condition.

Experimental

Materials

The two impermeable species of Douglas fir (*Pseudotsuga menziesii* Franco) and Japanese larch (*Larix leptolepis* Gordon), and sugi (*Cryptomeria japonica* D. Don) were selected for the study. The basic specific gravities of Douglas fir, sugi, and Japanese larch were 0.45, 0.34, and 0.51 respectively. Because steam injection was predicted to have different effects on different levels of wood moisture, Douglas fir and sugi were used in air-dried states and Japanese larch was green. Long posts of square cross section (120 × 120 mm) were cut to lengths of 650 mm as specimens for passive impregnation. Both ends of specimens were sealed before steam injection with urethane resin to prevent end penetration of liquid.

Methods

Holes were made with a CO_2 laser on the longitudinal surface by controlling the irradiation time with a power of 1500 kW. The same incising pattern was used for each species as shown in Fig. 1. By controlling the numerical control (NC) table specimens were incised with different incising density as shown in Table 1. Moisture content was measured before and after dipping by an oven-dry method (JIS Z 2101-1994). The possible maximum moisture content was obtained by Eq. 1.[17]

$$mc_{max} = \left(\frac{1.50 - S_g}{1.50 \times S_g}\right) \times 100\% \quad (1)$$

where mc_{max} is the maximum possible moisture content and S_g is the basic specific gravity. Saturated steam (saturated steam of 110°C with hot-plate temperature of 120°C) and superheated steam (from saturated steam of 110°C with hot-plate temperature of 160°C) were used for steam injection with a steam-injection press (VH2-1449; Kitagawa Seiki). These temperatures used could be controlled only by controlling the steam pressure with continuous observation of pressure sensors. Three different steam-injection

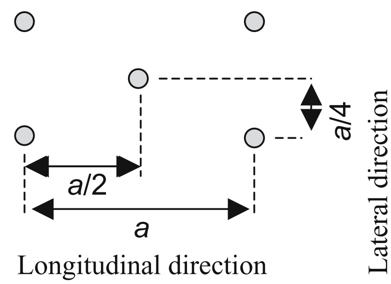

Fig. 1. Laser incising pattern on longitudinal surface and distances between holes for the different directions

Table 1. Detailed experimental conditions

Experiment no.	Species	Incising density (holes/m^2)	Type of steam	Steam treatment time (min)	Moving time (min)	Dipping time (h)
1	Douglas fir	10000	Saturated Superheated	20	Immediate	12
2	Douglas fir	10000	Best from Experiment 1	5 10 20	Immediate	12
3	Douglas fir	10000	Best from experiment 1	Best from experiment 2	Immediate 3 10 30	12
4	Douglas fir	10000	Best from experiment 1	Best from experiment 2	Best from experiment 3	0.5 1 3 12
5	Sugi	2500	Best from experiment 1	Best from experiment 2	Best from experiment 3	Best from experiment 4
6	Japanese larch	10000	Best from experiment 1	Best from experiment 2	Best from experiment 3	Best from experiment 4

times were used (5, 10, and 20 min) to determine the effects of steam injection time on impregnation of liquid.

The specimens were dipped into a water/fuchsine solution ($C_{19}H_{17}N_3 \cdot HCl$) after steam injection. Fuchsine solution (0.05% w/w) was used to identify the penetrated area of liquid because it has a similar level of permeability to water.[18] Four different intervals (moving time) between the press and dipping (immediately, 3, 10, and 30 min) and four different dipping times (0.5, 1, 3, and 12 h) were used. The penetrated area of fuchsine was measured both across and along the grain direction. For across the grain, it was measured at the center of the specimen. For along the grain, the penetrated area was measured at different depths [0 (irradiation surface), 30, 60, and 90 mm and on the opposite surface] from the laser-irradiated surface. To achieve this, a sample of 120 mm in length was cut near the center of the specimen and sliced according to the different depths along the grain. Samples were dried and smoothed by a planner before measuring the penetrated area. The penetrated area was calculated by image analysis by an image scanner (Epson; GT-9800F) and using Adobe Photoshop software.

Four variables were used for the experiment: steam type, steam injection time, moving time, and dipping time. Depending on these factors, there were four experiments done with Douglas fir and two additional experiments were used to implement the selected best condition of these four factors on sugi and Japanese larch. From each experiment, the best condition was selected for a factor and was implemented in the next experiment. Each experiment was repeated at least three times. The detailed experimental plan of the study is given in Table 1.

Results and discussion

Change in moisture content

The moisture content differed for the different species before and after dipping (Table 2), because of individual differences between species and different drying methods. The lowest initial moisture content was for Douglas fir (17.4%), following sugi (23.0%) and Japanese larch (43.7%). Douglas fir and sugi had initial moisture contents below the fiber saturation point (FSP). After dipping, the highest moisture content was for sugi (159.2%), followed by Douglas fir (136.5%) and Japanese larch (86.3%). Following dipping, the sugi moisture content increased by 136%. Douglas fir had also absorbed a good amount (119%), whereas Japanese larch had absorbed only an additional 43%. These differences may be caused by the initial moisture contents as mentioned in the text. Below the FSP, injected steam displaces air from the cell lumens, which causes negative pressure when cooled in liquid. The small checks or cracks created during drying tend to aid the steam-injection process; however, above the FSP, injected steam has less effect because of the extent of liquid water in the cell lumens. Thus, sugi and Douglas fir absorbed liquid significantly more than larch. It was also remarkable that some of the Douglas fir specimens reached the possible maximum moisture content (Table 2). These results showed that a dipping time of 12 h is close to the optimum for Douglas fir. However, for sugi and Japanese larch, longer dipping times were needed under the same treatment conditions. Douglas fir absorbed 87% of the possible maximum moisture content, whereas sugi and Japanese larch absorbed only 70% and 67%, respectively.

Liquid absorption

Because of different impregnation conditions and different species, liquid absorption varied (Fig. 2). The maximum absorption (480 kg/m^3) was observed when treatment used saturated steam for 20 min and was followed immediately by dipping in liquid for 12 h. Specimens injected with saturated steam absorbed slightly higher amounts of liquid than those treated with superheated steam. The variation of density and cell structure of wood could have caused this small difference. It was observed that the steam-injection time had a positive relationship with liquid absorption, that is, the longer the steam-injection time, the higher the absorbed liquid amount (Fig. 2). This is mainly because the longer steam injection time allows a longer period for air to be driven out of the cell cavities, resulting in higher absorption of liquid during dipping. Specimens moved immediately into the liquid absorbed significantly more liquid than those that were dipped later. This is because specimens that were moved immediately into a dipping container provided little opportunity for cooling and refilling of cell cavities with air. The maximum absorption was observed for a dipping period of 12 h. Longer dipping time creates greater scope for deep penetration, resulting in greater liquid absorption. When sugi and Japanese larch were treated with the best impregnating conditions (saturated steam 20 min, immediate dipping for 12 h) among the conditions tested, it was observed that sugi absorbed significantly more liquid (415 kg/m^3) than Japanese larch (187 kg/m^3). This may be because of the lower initial moisture content of sugi. Similar

Table 2. Average moisture content of different species treated by the best condition

Species	Initial moisture content (a) (%)	Moisture content after dipping (b) (%)	Average change of moisture content after dipping ($c = b - a$) (%)	Possible maximum moisture content (%)
Douglas fir	17.4 ± 2	136.5 ± 22	119 ± 22	156
Sugi	23.0 ± 2	159.2 ± 27	136 ± 27	227
Japanese larch	43.7 ± 1	86.3 ± 2	43 ± 2	129

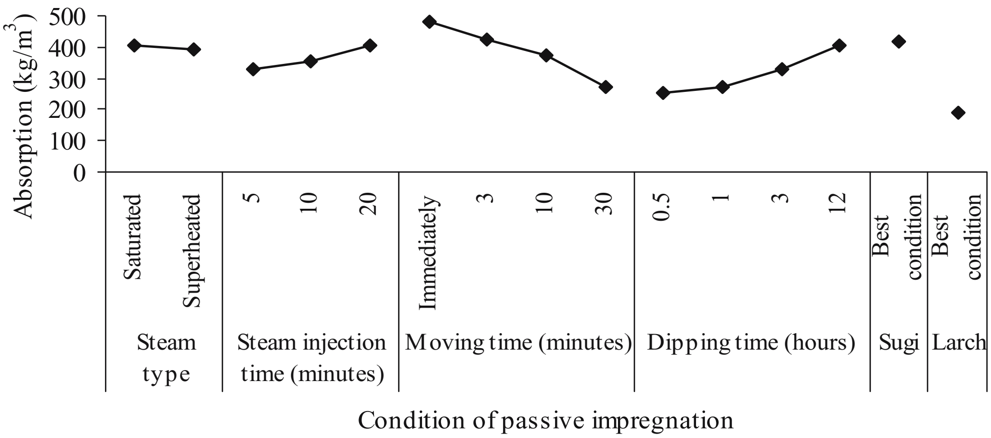

Fig. 2. Absorption of liquid by different conditions of passive impregnation

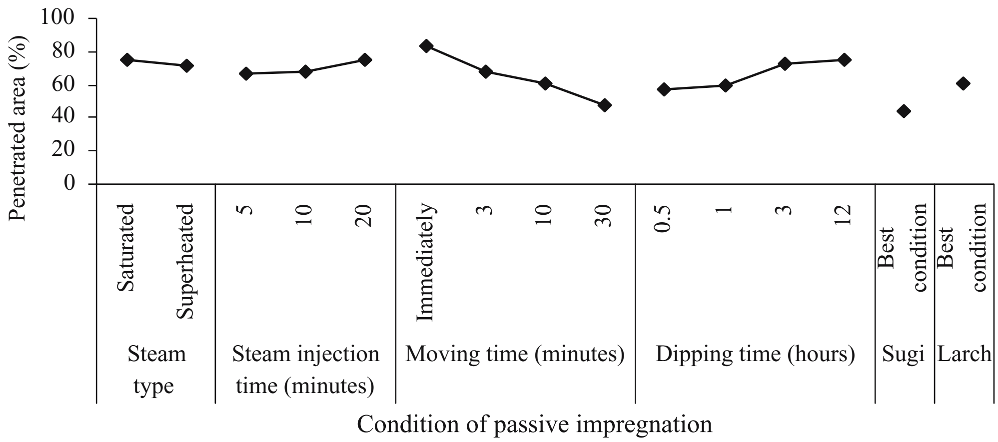

Fig. 3. Penetrated area as judged by the color of fuchsine across the grain

results were also reported by Hattori et al.[14] for sugi and Douglas fir.

Penetrated area indicated by fuchsine

Liquid penetration was clearly observed not only in the outer area but also in the inner area of specimens. The maximum liquid-penetrated area was 83.4% of the cross-sectional area for Douglas fir when saturated steam was injected for 20 min and dipping was performed immediately for 12 h (Fig. 3). For sugi and Japanese larch, the penetrated areas were 43.5% and 60.6% of the cross-sectional area, respectively. Hattori et al.[14] reported a similar trend for penetrated area. The high initial moisture contents of sugi and Japanese larch, along with the amounts and positioning of heartwood and sapwood in specimens, and the different sawing patterns of these species may have contributed to these low penetrated areas. The different cellular structural properties of sugi and Japanese larch may also have been contributing factors. Because of the higher incising density, the penetrated area was larger in Japanese larch than that in sugi, although it had higher initial moisture content. Similar trends to that of liquid absorption were found in all the cases. In general, it was found that saturated steam acted better than superheated steam, longer steam-injection times were better than shorter times, and immediate dipping for a long period proved better than delayed dipping for a short period (Fig. 3). It is concluded that passive impregnation can penetrate liquid deep into lumber in large amounts and with good distribution.

From Fig. 4, it appears that the penetrated area differs not only according to the impregnation conditions, but also to the location in a specimen. The maximum penetrated area was observed mostly at a 60-mm depth, that is, at the center of the sample, except for sugi. In case of sugi, the central portion (60–90 mm) showed the lowest penetrated area. This may be caused by the presence of heartwood at the central portion of the sugi specimens (Fig. 5), which restricts the penetration of liquid. For experiments 1, 2, and 4 in Table 1, the laser-irradiated surface absorbed more than the opposite surface, but the reverse phenomenon was also observed for experiments 3, 5, and 6. The highest penetrated area was observed at a 60-mm depth for a specimen that was treated with saturated steam for 20 min with immediate dipping for a period of 12 h.

For all of the species tested, sapwood absorbed much more than heartwood (Fig. 5). The checks and cracks in the specimen (Fig. 5) were apparent after drying of specimens after dipping. The vertical dark parallel lines indicate the area penetrated by fuchsine along the hole left by the CO_2 laser. These holes exposed additional area for fluid penetra-

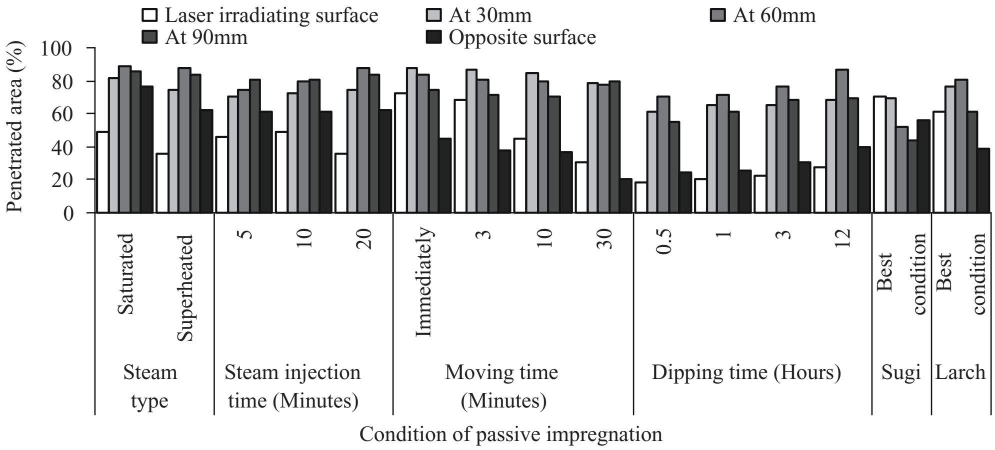

Fig. 4. Penetrated area as judged by the color of fuchsine along the grain for different species

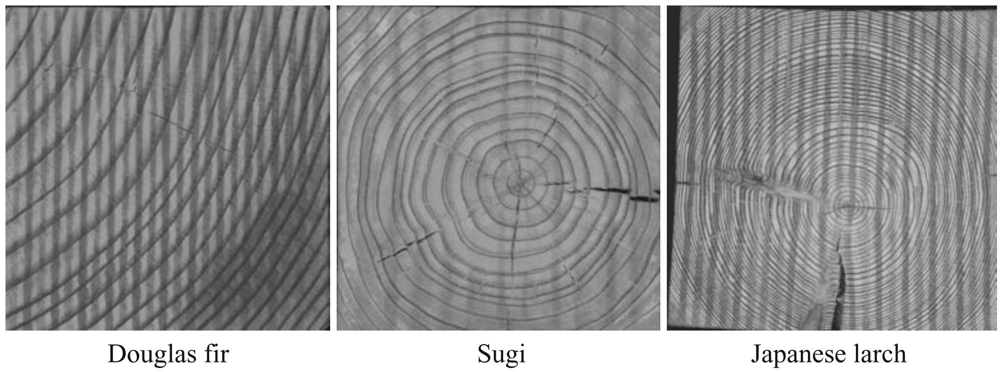

Fig. 5. Penetrated area indicated by the color of fuchsine for different species

tion and created the opportunity for longitudinal and lateral flow of fluid within the lumber. This phenomenon was more distinct in Douglas fir and Japanese larch than in sugi (Fig. 5). This difference may have been a result of the different structural properties of the different species and the low initial moisture content in the Douglas fir specimens.

Conclusions

Previous studies have shown that liquid impregnation in impermeable lumber poses a major challenge. Boring with a CO_2 laser improved the penetrability for impermeable species and appeared to offer a feasible approach for improving the impregnation of lumber. The conclusions of the study are:

1. Immediately dipped lumber absorbs more liquid than that dipped later because cooling in air allows air to reenter the cell lumen and prevents liquid absorption.
2. A long dipping time is better than a short dipping time because it provides more time for penetration to occur.
3. Saturated steam is somewhat better than superheated steam for passive impregnation.
4. Dry lumber is better than green lumber because it requires a shorter steam-injection time to remove the air from the cell lumen, which in turn results in higher absorption of liquid.

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