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ORIGINAL ARTICLE

Effects of water soaking and outdoor exposure on modulus of rupture and internal bond strength of particleboard

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Abstract Phenol–formaldehyde resin-bonded particleboard (PF board) and isocyanate resin-bonded particleboard (MDI board) were soaked in water at 40, 70 and 100 °C, and the relationships between soaking conditions and board properties were analyzed. The relationships between the deterioration of board properties resulting from water soaking and those arising from outdoor exposure were also analyzed. At 100 °C, the modulus of rupture (MOR) and internal bond strength (IB) of the PF board decreased significantly within the first hour, and subsequently constant values were shown with increasing soaking time. This low constant value was defined as the lower limit. At 70 °C, both the MOR and IB decreased with increasing soaking time, and reached the lower limit. At 40 °C, however, neither decreased significantly with increasing soaking time and neither reached the lower limit. The MOR of the MDI board showed the same trend as the PF board. However, the IB of the MDI board showed a different trend to the PF board, that is, the lower limit of IB required extensive soaking, even at 100 °C. The MOR and IB of both the PF and MDI boards reached the lower limit when thickness change peaked. On the other hand, the MOR and IB for outdoor exposure were lower than those for water soaking, even at the same thickness change. The MOR and IB of water soaking decreased owing to the collapse of the bonding points caused by board swelling. On the other hand, the board properties of outdoor exposure decreased owing to the collapse of the bonding points, and biodegradation also added to the decrease.

Keywords Particleboard · Water soaking · Outdoor exposure · Accelerated aging · Bonding point

Introduction

In order to evaluate the durability of wood-based boards, various accelerated aging tests are used [1–3]. Most involve water soaking at various temperatures. In JIS A 5908, for example, the A test is 2 h water soaking at 70 °C, and the B test is 2 h water soaking at 100 °C [4]. For the Engineered Wood Products Association, the test is 8 h water soaking at 66 °C followed by 14.5 h drying at 82 °C [5]. Although the most widely used accelerated aging test is water soaking at various temperatures and times, no optimum test has yet been decided upon.

Numerous studies have been made on the relationships between cyclic boil-dry treatment and board properties [6–8], but very few have detailed the effects of water-soaking condition on board properties. For example, when we compare 2 h water soaking at 70 °C (A test in JIS) and 2 h water soaking at 100 °C (B test in JIS), obviously the latter is more severe than the former, decreasing the latter properties more than the former [4]. Comparing 6 h water soaking at 70 °C with 2 h water soaking at 100 °C, it is very difficult to predict which condition decreases the board properties. In order to develop an optimum accelerated aging test, it is paramount to determine the effects of soaking temperature and time on board properties.

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Thereby, the purpose of this study is to clarify the roles played by soaking temperature and time.

The reason for decrease in board properties is the collapse of the bonding points of the binder [9, 10]. This collapse results from wood failure (Fig. 1b), decomposition of the binder (cohesive failure, Fig. 1c) and the reduction of bonding strength between the binders and the element surface (particle surface in this study; interface failure, Fig. 1d) [11]. When boards are manufactured, the particles are compressed into a high-density structure. As a result, swelling stress is generated within the particles owing to spring-back, and this swelling stress is released when the particles swell owing to water soaking. Phenol–formaldehyde resin and isocyanate resin are highly durable to water [12], and do not decompose when soaked in water, even at 100 °C; thus, both cohesive failure and wood failure hardly occur after swelling stress is released. Accordingly, the bonding points must inevitably collapse as a result of interface failure. When a board swells to maximum thickness, the board properties presumably cease to fail. After a certain increase in the soaking time, the values remained constant; and this low constant value is defined as the lower limit in this study, and we also confirm this matter.

As for failure resulting from outdoor exposure, boards were exposed outdoors at eight sites in Japan for 7 years (2004–2011), and their properties were evaluated [13–15]. The relationships between the reduction of board properties owing to water soaking and those owing to outdoor exposure were then compared and analyzed.

Experimental

Particleboards used in this experiment

Phenol–formaldehyde resin-bonded particleboard (PF board) and isocyanate resin-bonded particleboard (MDI board) were used in the experiments. The density and thickness of the boards were 0.75 g/cm^3 and 12.2 mm for the PF board and 0.80 g/cm^3 and 12.1 mm for the MDI board, respectively. Further details are provided in the references [10, 13–15]. The boards were commercial products that did not include detailed information such as binder content. Both types of boards satisfied the waterproof category of Type 18 and Type P under JIS A 5908 [4]. Type 18 satisfies 18 MPa in modulus of rupture (MOR) and Type P indicates waterproof boards. The initial MOR and internal bond strength (IB) of the PF board were 20.3 (2.29) and 0.83 (0.09) MPa, respectively. The number in parentheses indicates the standard deviation. The initial MOR and IB of the MDI board were 28.8 (2.10) and 2.19 (0.18) MPa, respectively. The MOR and IB tests were conducted in compliance with JIS [4]. The number of specimens for measuring the initial values of MOR and IB each was 30.

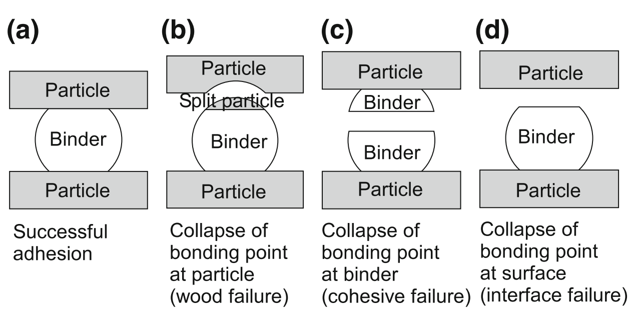

Fig. 1 Schematic showing the collapse of a bonding point

Water-soaking conditions

For the MOR tests, board specimens measuring 275 × 50 mm were soaked in water at 40, 70, and 100 °C. Soaking times at 40 °C were 2, 12, and 336 h; at 70 °C 1, 2, 6, 24, and 168 h; and at 100 °C 1, 2, 6, 24, and 72 h. The number of specimens for the MOR tests was five. The specimens were dried in an oven at 30 °C for 48 h, and subsequently, were conditioned at a constant temperature of 20 °C and relative humidity of 65 % for 7–10 days until the weight stabilized. The moisture content of the specimens was approximately 10 %. After conditioning, the thickness of the specimens was first measured in order to determine thickness changes (TC), and then, the MOR tests were conducted. After the MOR tests, specimens measuring 50 × 50 mm were taken from the two edges of the original 275 × 50 mm specimens for the IB tests, and subsequent IB tests were conducted. The number of MOR and IB tests was five and ten, respectively. The MOR was determined using the thickness of the specimen after conditioning. The MOR retention and IB retention are calculated by the following relation:

$$\text{MOR (or IB) retention } (\%) = \frac{\text{Value after accelerated aging test}}{\text{Value before accelerated aging test}} \times 100$$

The thickness change is calculated by the following relation:

$$\text{Thickness change } (\%) = \frac{t_1 - t_0}{t_0} \times 100$$

where t_0 and t_1 are the air-dried thickness before and after the accelerated aging test, respectively.

Outdoor exposure

Twelve specimens of PF board and MDI board measuring 300 × 300 mm were set up on an exposure stand that faced south at an angle of 90° to the ground. The cut edges of the specimens were coated with enamel paint as a waterproof agent prior to outdoor exposure. Two specimens were collected for testing at 1–5, 6 or 7 years to evaluate the board properties. The outdoor exposure was conducted at eight sites in Japan: Asahikawa, Morioka, Noshiro, Tsukuba, Shizuoka, Okayama, Maniwa, and Miyakonojo. Table 1 lists the latitude, longitude and climate conditions of these eight areas from February 2004 to March 2011. Details of the outdoor exposure can be found in the references [10, 13–15].

The 300 × 300 mm specimens were also conditioned; in order to conduct the MOR tests, specimens measuring 280 × 50 mm were taken from the 300 × 300 mm specimens. The moisture content of the specimens was approximately 10 % [13]. After conditioning, MOR tests were then conducted. For subsequent TC and IB tests, specimens measuring 50 × 50 mm were taken from the 280 × 50 mm specimens. The trimming of MOR, TC, and IB specimens has been reported in previous studies [10, 13]. As the thickness of the 50 × 50 mm specimens for TC test were not measured before outdoor exposure, the values were estimated from the mean thickness of the 300 × 300 mm specimens prior to outdoor exposure in order to determine TC. The number of specimens of MOR, TC and IB were eight, thirteen and thirteen, respectively.

Results and discussion

Thickness change

Figure 2a shows the relationships between soaking time and the TC of the PF board. The TC at 40 °C increased gradually with increasing soaking time, but was as low as 9 % at 336 h. The TC at 70 °C increased gradually with increasing soaking time, and was as low as 17 % at 168 h. The TC at 100 °C was as high as approximately 20 %, even with a short soaking time of 1 h, and was thereafter almost constant with increasing soaking time.

Figure 2b shows the relationships between soaking time and the TC of the MDI board. The TC at 40 °C increased at 12 h, but was as low as 6 % even at 336 h. The TCs at 70 and 100 °C increased with an increase in the soaking time, and the TC at 70 °C at 168 h was the same as that at 100 °C at 72 h. In addition, the TC of the MDI board was much lower than that of the PF board. Though the PF and MDI boards were waterproof, their TCs increased after

Table 1 Latitude, longitude and climatic conditions for outdoor exposure sites from February 2004 to March 2011

Sites	Groups	North latitude (°)	East longitude (°)	Annual average temperature (°C)	Annual precipitation (mm)
Asahikawa	Northern Japan	43	142	7.3	992
Morioka	Northern Japan	39	141	10.6	1,338
Noshiro	Northern Japan	40	140	11.6	1,500
Tsukuba	Northern Japan	36	140	14.4	1,371
Shizuoka	Southern Japan	34	138	17.0	2,342
Maniwa	Southern Japan	35	133	14.0	1,409
Okayama	Southern Japan	34	133	16.7	1,069
Miyakonojo	Southern Japan	31	131	16.9	2,515

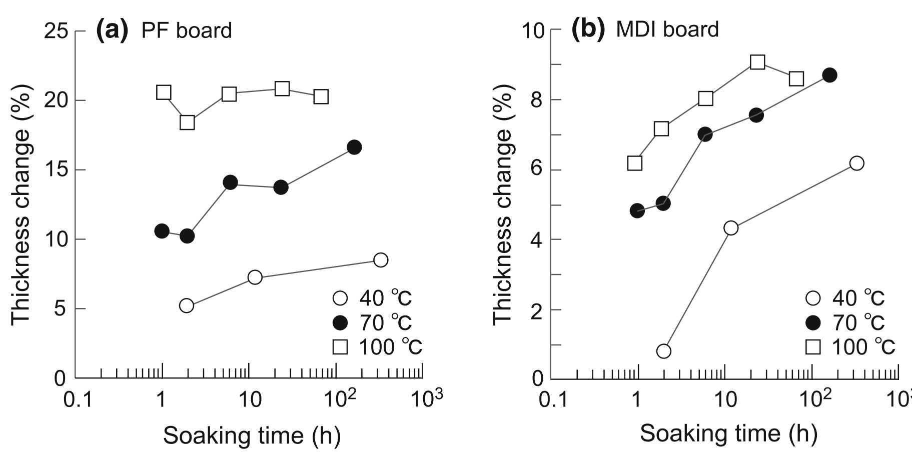

Fig. 2 Relationships between soaking time and thickness change. **a** Phenol–formaldehyde resin-bonded particleboard (PF board). **b** Isocyanate resin-bonded particleboard (MDI board)

soaking them in water for a prolonged period of 336 h, even at 40 °C.

Modulus of rupture

Figure 3a shows the relationships between soaking time and the MOR retention of the PF board. The MOR retention at 40 °C decreased gradually with an increase in soaking time, but was as high as 70 % at 336 h. As at 40 °C, the MOR retention at 70 °C decreased to 56 % with increasing soaking time, and was lower than that at 40 °C. The MOR retention at both 40 and 70 °C decreased with increasing soaking time, while that at 100 °C decreased to 59 %, even at 1 h, and subsequently was almost constant at approximately 60 %. It is obvious that a lower limit of approximately 60 % exists.

Figure 3b shows the relationships between soaking time and the MOR retention of the MDI board. At 2 h, the MOR retention at 40 °C was almost the same as that at 70 °C, which was 90 %. Both decreased with increasing soaking time. The MOR retention at 40 °C was 75 % at 336 h, while that at 70 °C was 65 % at 168 h. On the other hand, the MOR retention at 100 °C was almost constant at approximately 65 % (lower limit) irrespective of soaking time.

The MOR retention of the MDI board is higher than that of the PF board, which results in a corresponding higher durability of the former. Additionally, the MOR retention of both the MDI and PF boards at 40 °C did not decrease greatly with increasing soaking time, while that at 100 °C decreased greatly for a short soaking time and subsequently was almost constant, irrespective of soaking time. On the other hand, the MOR retention at 70 °C decreased with increasing soaking time, and finally reached almost the same retention at 100 °C.

Internal bond

Figure 4a shows the relationships between soaking time and the IB retention of the PF board. As in MOR, the IB retention at both 40 and 70 °C decreased with increasing soaking time. The IB retention at 70 °C decreased more than that at 40 °C, to 14 % at 168 h. On the other hand, IB at 100 °C was almost constant at 10–20 % (lower limit),

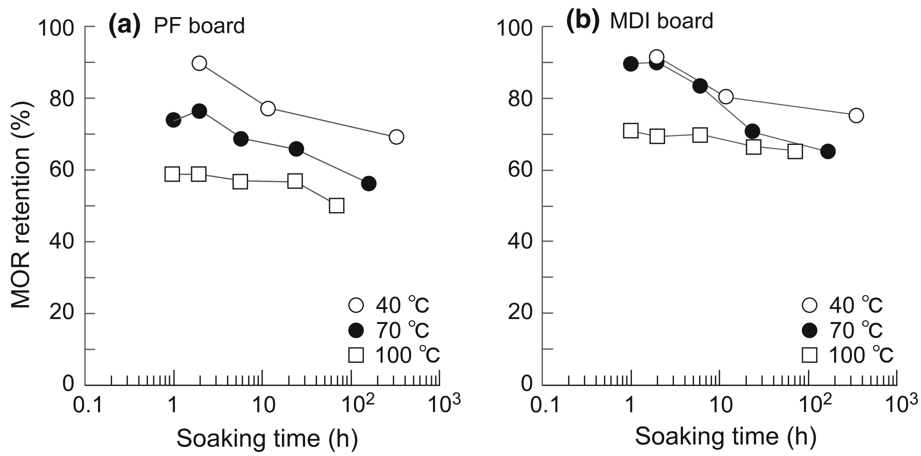

Fig. 3 Relationships between soaking time and MOR retention. *MOR* modulus of rupture. **a** Phenol–formaldehyde resin-bonded particleboard (PF board). **b** Isocyanate resin-bonded particleboard (MDI board)

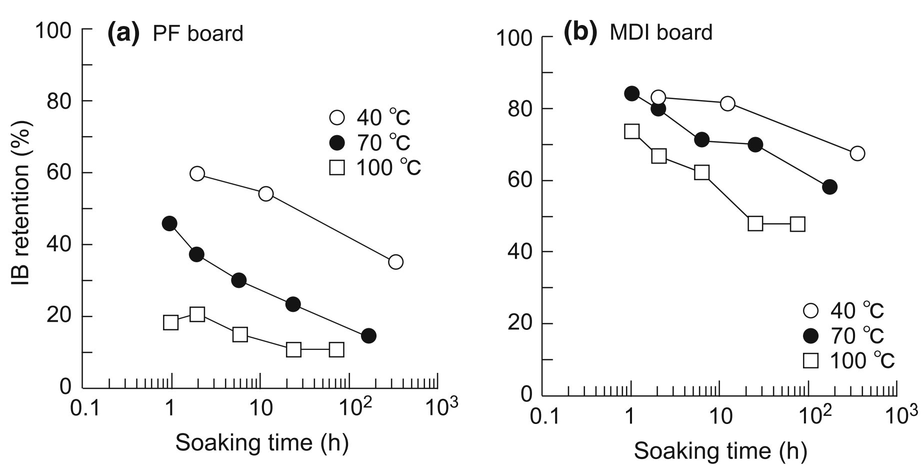

Fig. 4 Relationships between soaking time and IB retention. *IB* internal bond strength. **a** Phenol–formaldehyde resin-bonded particleboard (PF board). **b** Isocyanate resin-bonded particleboard (MDI board)

irrespective of soaking time. The IB retention at 70 °C at 168 h corresponded with that at 100 °C in 24 h.

Figure 4b shows the relationships between soaking time and IB retention of the MDI board. Although IB retention at 100 °C for the PF board decreased to 19 % at 1 h, IB retention for the MDI board reached 73 % at 1 h, but decreased with an increase in the soaking time and dropped to 47 % (the lower limit) at 72 h.

In both the PF and MDI boards, IB retention was lower than MOR retention. In particular, the IB retention of the PF board at 100 °C was very low. As IB is related to the bonding strength of the binder only [16], the bonding strength decreased because of water soaking, leading directly to a large decrease in IB. Although like IB, MOR is related to the bonding strength, it is also related to the particle shape [17–19], face-layer density [20], and many more factors. While the bonding strength decreased, these other factors were retained. Therefore, MOR did not decrease significantly and its value remained relatively unchanged as compared with the value of IB.

Reduction mechanism of board properties owing to water soaking

As discussed above, the MOR and the IB retention decreased when the TC increased. The MOR and IB are inversely related to the TC. Boards are manufactured through the high-density compression of particles, which generates significant local swelling stress within a board; this is the cause of spring-back when particles absorb water. Furthermore, particles swell when they absorb water. Spring-back and swollen particles are the causes of thickness swelling, which is controlled by the bonding strength of the binder at the bonding points among the particles (Fig. 5) [9, 10]. Water soaking causes a board to swell, thus collapsing the bonding points. Moreover, higher-temperature water soaking causes the board to swell to a greater extent [21], thus collapsing more bonding points. This is the reduction mechanism of board properties owing to water soaking. Thereby, when swelling stress is released completely and the boards have swollen to a limited extent owing to water soaking, the remained bonding points do not collapse at all. The TCs of both the PF and MDI boards swollen to a limited extent are likely to be 20 and 9 %, respectively. With increased soaking time, the board does not swell beyond these TCs, and thus board properties do not markedly decrease. Therefore, lower limits for both MOR and IB exist. Therefore, water soaking as an accelerated aging test must be a short-time soaking to achieve the lower limits.

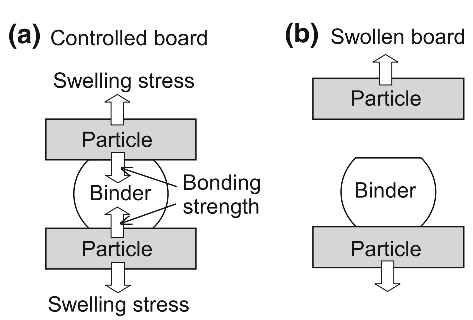

Fig. 5 Schematic of controlled board (**a**) and swollen board (**b**)

Reduction mechanism of board properties owing to outdoor exposure

The swollen thickness causes a reduction of board properties owing to water soaking as discussed above, while it also causes a reduction in properties owing to outdoor exposure. Figure 6a shows the relationships between TC and MOR retention of the PF board exposed outdoors for 1–7 years. The "Outdoor (North)" labels represent Asahikawa, Morioka, Noshiro and Tsukuba. The "Outdoor (South)" labels represent Shizuoka, Maniwa, Okayama, and Miyakonojo. This figure also includes the relationships between TC and MOR retention of the PF board soaked in water at various temperatures and times. The MOR retention of both water soaking and outdoor exposure decreased with increasing TC. Moreover, the MOR retention of water soaking was higher than that of outdoor exposure. Figure 6b shows the relationships between TC and IB retention of the PF board. The IB retention also decreased with increasing TC. Although the MOR retention of water soaking was higher than that of outdoor exposure (Fig. 6a), the IB retention of water soaking was almost the same as that of outdoor exposure. The MOR decreases owing to the degradation of face layers [10], while the IB decreases owing to the degradation of the core layer [10, 16]. Water soaking degrades both the face layers and the core layer together, while outdoor exposure degrades the face layers more severely than the core layer as the face layers are directly exposed to sunshine and rain. Thus, the MOR of outdoor exposure decreased more than that of water soaking.

Figure 7a shows the relationships between the TC and MOR retention of the MDI board. As in the PF board, the MOR retention of water soaking was also higher than that of outdoor exposure, but the difference of the MDI board was less than that of the PF board. Figure 7b shows the relationships between the TC and IB retention of the MDI board. The IB retention for both outdoor exposure and water soaking decreased with increasing TC. The IB retention of water soaking was slightly higher than that of outdoor exposure at TC of 7–10 %. Compared with the PF board, the TC of the MDI board exposed outdoors was much lower.

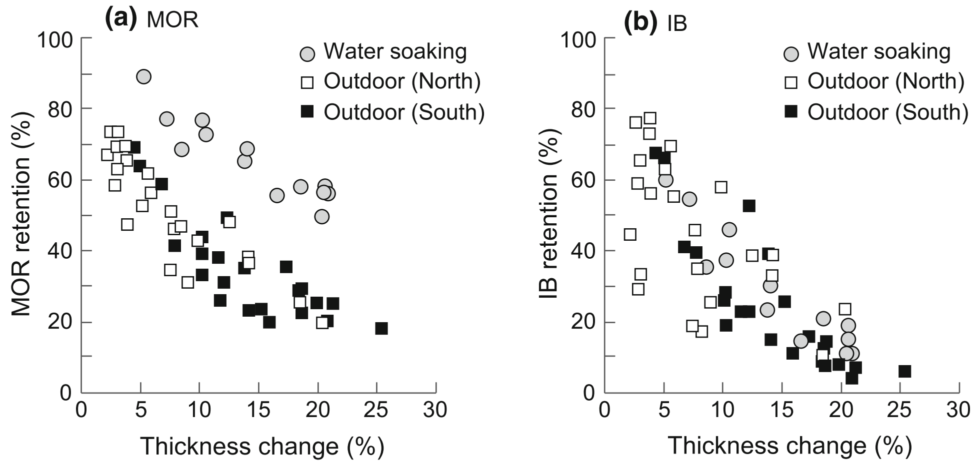

Fig. 6 Effects of thickness change on MOR retention (**a**) and IB retention (**b**) of PF board. *MOR* modulus of rupture, *IB* internal bond strength, *PF board* phenol–formaldehyde resin-bonded particleboard. Outdoor (North): Asahikawa, Morioka, Noshiro and Tsukuba; Outdoor (South): Shizuoka, Maniwa, Okayama and Miyakonojo

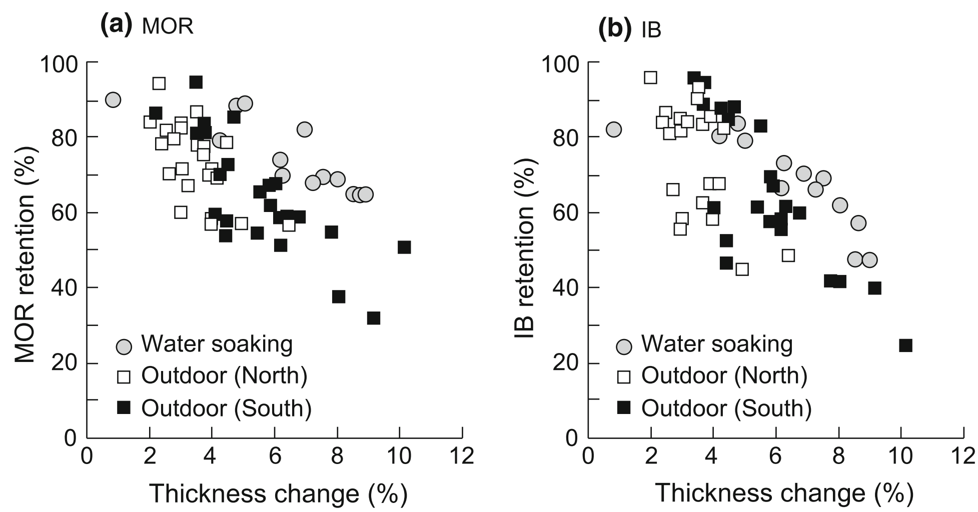

Fig. 7 Effects of thickness change on MOR retention (**a**) and IB retention (**b**) of MDI board. *MOR* modulus of rupture, *IB* internal bond strength, *MDI board* isocyanate resin-bonded particleboard. Outdoor (North): Asahikawa, Morioka, Noshiro and Tsukuba; Outdoor (South): Shizuoka, Maniwa, Okayama and Miyakonojo

As for both the PF and MDI boards exposed outdoors, the TC of the north group was lower than that of the south group. Conversely, temperature and precipitation in the south group are higher, which presumably swells board thickness considerably [21]. The swollen board forms many voids, presumably resulting in biodegradation [10]. Therefore, both MOR retention and IB retention in the south group were lower.

Except for the IB of the PF board, as for the MOR of the PF board, the MOR and IB of the MDI board, there are differences between water soaking and outdoor exposure. In particular, the MOR retention of water soaking was higher than that of outdoor exposure. The boards soaked in water have poor mechanical properties solely because of the collapse of the bonding points, and the mechanism for the reduction of the properties is very simple. In contrast, the boards exposed outdoors have poor properties because of the collapse of the bonding points and biodegradation [10]. These factors interact, resulting in a major reduction in the properties of the boards exposed outdoors than in the case of the boards soaked in water. These differences between outdoor exposure and water soaking cause different reductions in the properties of both boards.

Conclusions

At 100 °C, the MOR and IB retention of the PF board, and the MOR retention of the MDI board decreased to the lower limit for a soaking time of 1–2 h. At 70 °C; a long soaking time is required to reach the lower limit. At 40 °C, the lower limit could not be achieved, even for a long soaking time of 336 h. At 100 °C, the IB retention of the MDI board did not reach the lower limit for soaking time of 1–2 h, and 72 h was required to reach it. Thus a short-time soaking to reach the lower limit must be developed. In addition, because the reduction mechanism of the properties of the boards soaked in water is different from that of the boards exposed outdoors, it is difficult to predict the durability of outdoor exposure on the basis of the resultant durability of water soaking.

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