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ORIGINAL ARTICLE

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The aging effects of water immersion treatments in wet-bending for standardized testing of wood panels

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Abstract The durability of wood-based panels is one of the most important properties when they are used in residential construction. The main objectives of this study were to investigate the quantitative relationship between the Wet-bending A test and the Wet-bending B test, examine the aging effects of the treatments specified in the wet-bending methods, and discuss the relationship between wet-bending and outdoor aging tests conducted in Shizuoka, Japan. Wet-bending tests, internal bond tests after humidity treatment, and outdoor aging tests in Shizuoka were conducted using eight types of commercial wood-based panels. A linear relationship was found between the load-carrying capacity (LCC) from the Wet-bending A test and the LCC from the Wet-bending B test. The LCC from Wet-bending B could be obtained from LCC from Wet-bending A by multiplying it by 0.9, which may be applicable as a quantitative ratio of aging effects between the two. LCC for methylenediphenyl diisocyanate-bonded panels recovered to almost 100% of the initial strength. A certain relationship was found between the LCC after Wet-bending A and the LCC after a 1-year outdoor exposure in Shizuoka. Internal bond strength showed a good correlation between the JIS-A treatment and the 1-year outdoor exposure treatment.

Key words Wood-based panel · Durability performance · Outdoor exposure · Accelerated aging treatment · Bending property

Introduction

The durability of wood-based panels is one of their most important properties when they are used in residential construction. This is true not only for structural panels like plywood and oriented strandboard (OSB), but also for moisture-resistant domestically produced particleboard (PB) and medium-density fiberboard (MDF), which are frequently used as structural elements. The durability or moisture resistance of such panels is usually determined by standardized aging test methods that include various cycles of cold or hot water immersion, boiling, steaming, freezing, and drying.

In the past few decades, numerous studies on panel durability have been performed. Hann et al.[1] discussed mat-formed panels and Northcott and Colbeck[2] evaluated plywood durability. Lehmann[3,4] examined several accelerated aging tests while Dinwoodie[5] discussed the deterioration mechanism. McNatt and Link,[6] McNatt and McDonald,[7] and Karlsson et al.[8] tried to improve the ASTM six-cycle test.[9] Alexander et al.[10] reported on the durability of OSB. In Japan, Kajita et al.[11] conducted five standardized accelerated aging tests on panels of different resin types. Saito and Taniguchi[12] evaluated the durability of isocyanate-bonded PB through repetitive vacuum soaking and drying. In addition, Sekino[13] discussed the effect of water absorption on the bending properties of construction particleboard. However, very limited research has been reported[14] on the wet-bending tests included in standards from the Japanese Industrial Standards (JIS)[15,16] and the International Organization for Standardization (ISO).[17]

Outdoor exposure is considered to be an accelerated aging test and has been evaluated in various countries. Gressel[18] discussed its relationship with other accelerated aging tests, and Deppe[19] and Deppe and Schmidt[20] addressed the issue in Germany. River[21] and Okkonen and River[22] also focused on outdoor exposure and different aging tests in the United States. Alexopoulos[23] studied the durability of waferboard using large-size panels in Canada. Outdoor testing was also conducted in the United Kingdom[24] and a good correlation with the V313 aging test[25] was revealed. The common objectives of outdoor tests in this research have been to predict the deterioration or weakening of panels in actual use, and to establish the relationship with the standardized accelerated aging test methods. In Japan, several studies have been conducted with veneer-based

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material.[26–29] Sekino and Suzuki[30] reported the 10-year test results for wood-based panels including plywood, OSB, PB, MDF, hardboard, and cement-bonded PB. In addition, several other studies on the durability of MDF, OSB, and PB have been reported.[31–33] However, very few have examined the relationship to aging test methods, particularly with wet-bending tests.

In standardization activities,[34] three test methods are specified by the ISO for wood-based panels to determine moisture resistance and durability performance.[35] In 2003, ISO 16987[36] and ISO 16998[37] were established, derived respectively from the European V100 and V313 tests. In 2005, ISO 20585[17] was established, based on the JIS wet-bending test. In discussions of international standardization for the wood-based panels, evaluation of the aging effects of these test methods has become an important issue. Relationships among the intensities of aging treatment in the three different methods remains to be quantified, as the specific values of wood-based panel strength should be fixed in the ISO documents. Moreover, the relationship between two treatments in ISO 20585,[17] that is, hot water immersion and boiling water immersion, needs to be quantified.

The major objectives of this study were to investigate the quantitative relationship between the Wet-bending A test and the Wet-bending B test, examine the aging effects of the treatments specified in the wet-bending methods, and discuss the relationship between wet-bending and outdoor aging tests conducted in Shizuoka, Japan.

Experimental

Sample panels

The four groups of commercial wood-based panels used in this study are listed in Table 1. These were PB, MDF, OSB, and plywood, which are widely used for construction purposes in Japan. Each panel group included two panel types with different specifications. The PB panels were made from recycled wood with different binders. The MDF panels differed in thickness and binder type. The OSB panels were products imported from North America and Europe, each with a different thickness. The plywood panels also differed in thickness. Thus, eight types of panels were used in total. The parallel direction on each panel surface was defined by the machine direction for PB and MDF, the surface strand alignment for OSB, and the surface veneer grain direction for plywood.

Control and wet-bending tests

We performed bending tests on control samples, as well as the Wet-bending A test and the Wet-bending B test in accordance with JIS A 5908.[15] These involved testing the samples after soaking in hot water (A test) or in boiling water (B test) followed by soaking in water at room temperature. The size of each test piece was 250 mm in the parallel direction × 50 mm. Ten sample pieces of each type of board were used for the tests. Prior to testing, all samples were conditioned at 20°C and 65% relative humidity (RH) for 3 months. We conducted additional bending tests in the perpendicular direction for the OSBs and plywoods. We use the terms modulus of rupture (MOR) and modulus of elasticity (MOE) for the bending properties based on the thickness of specimen at the time when the bending test was actually conducted. In this article, we use the terms load-carrying capacity (LCC) and bending resistance (BRS) for the modulus of rupture and the modulus of elasticity, respectively, based on the original sample thickness.[6] The original sample thickness was defined as the thickness measured after cutting samples.

Aging treatments

To evaluate the aging effects of the treatment specified in wet-bending tests, we defined the “JIS-A treatment” and “JIS-B treatment” as follows. The JIS-A treatment involved immersion for 2 h in 70°C water, then immersion for 1 h in 20°C water, followed by rotary oven drying for 24 h at 60°C. The JIS-B treatment was the same as the JIS-A treatment except that the water for the initial immersion was at boiling instead of 70°C. After the JIS-A or JIS-B treatments, the test pieces were conditioned at 20°C and 65% RH for more than 2 weeks. We then conducted bending tests using eight sample pieces under each condition.

Internal bond test

We conducted the internal bond (IB) test according to JIS A-5908[15] for control samples of the mat-formed panel prod-

Table 1. Specifications of the tested commercial panels

Panel type	Notation	Adhesive	Thickness (mm)	Density (g/cm^3)	Construction
Particleboard	PB(PF)	PF	12.2	0.76	Three layer
	PB(MDI)	MDI	12.1	0.80	Three layer
MDF	MDF(MUF)	MUF	12.2	0.76	
	MDF(MDI)	MDI	9.1	0.72	
OSB	OSB(NA)	PF	12.4	0.64	Three layer cross oriented
	OSB(EU)	PF	11.8	0.68	Three layer cross oriented
Plywood	PW(12)	PF	12.0	0.64	Five ply
	PW(9)	PF	8.8	0.61	Three ply

PB, Particleboard; PF, phenol–formaldehyde; MDI, methylenediphenyl diisocyanate; MDF, medium-density fiberboard; MUF, melamine–urea–formaldehyde; OSB, oriented strandboard; NA, imported from North America; EU, imported from Europe; PW, plywood ucts in Table 1. We also performed the IB test for plywoods as a comparison, even though this was not appropriate for this type of veneer-based product. We tested 20 samples of each panel type. After the Wet-bending A test and the Wet-bending B test, the broken test pieces were dried at 60°C for 24 h and reconditioned at 20°C and 65% RH for more than 2 weeks. IB specimens with dimensions of 50 × 50 mm were cut from undamaged parts of the bending specimens. Eight test pieces were used for each panel type for a total of 64 samples.

Outdoor exposure test

For each panel type, 12 test sample boards, each measuring 300 × 300 mm, were subjected to the outdoor exposure test on the campus of Shizuoka University (Shizuoka City, Japan; 34°N, 138°E). All four edges of the sample boards were coated with a protective agent to prevent excessive edge swelling due to water during the exposure. The boards were set vertically on a test frame that faced south (Fig. 1). The outdoor test was started in March 2004. Two sample boards for each panel type were removed for the property tests after an exposure of 1 year. Before the tests, the detached sample boards were dried at 60°C for 24 h and reconditioned at 20°C and 65% RH for 2 weeks. Eight bending specimens with dimensions of 260 × 50 mm and 13 IB test specimens were prepared from the reconditioned samples. The bending test samples were cut along the parallel direction of the test panels.

Fig. 1. Outdoor exposure test conducted in Shizuoka, Japan

Results and discussion

Mechanical properties of the panels

Results of the bending and IB tests are summarized in Table 2 (Table 1 defines the notation used the panel types). The bending test results showed the lowest MOR in the parallel direction for PB with phenol–formaldehyde (PF) resin and the highest value for PW(9). The higher MOR for PW(9) was due to its three-ply structure and the effect of face-ply strength. Plywoods showed a larger variation in bending strength than those of the other panels. In addition, the IB was lowest for the OSB(NA) and highest for the PB(MDI). The MDI-bonded particleboard, PB(MDI), showed higher bending properties and a higher IB than those for the PF-bonded panel [PB(PF)]. Generally both types of OSB showed the same values of MOR and MOE in the parallel direction. However, the OSBs made in Europe [OSB(EU)] had less anisotropic bending properties in a plane than those made in North America [OSB(NA)].

Wet-bending A and B tests

The results of the wet-bending tests are summarized in Table 3. For OSB and plywood, the bending properties were additionally measured in the perpendicular direction. In addition to LCCs and BRSs, the thickness swelling (TS) while wet and the IB strength after drying are shown. It has been reported that LCC and BRS after aging are sometimes higher than the original bending property values,[3] which may be attributable to their higher resistance to a bending

Table 2. Bending and internal bond properties under control conditions

Panels	MOR		MOE		IB (MPa)
	PL (MPa)[a]	PP (MPa)[b]	PL (GPa)	PP (GPa)	
PB(PF)	21.6 ± 3.5		3.44 ± 0.46		0.66 ± 0.08
PB(MDI)	29.7 ± 2.4		3.97 ± 0.19		1.97 ± 0.17
MDF(MUF)	44.9 ± 3.0		4.07 ± 0.22		0.57 ± 0.07
MDF(MDI)	33.8 ± 1.4		3.10 ± 0.15		1.03 ± 0.11
OSB(NA)	37.7 ± 8.9	17.2 ± 3.4	4.90 ± 0.69	1.74 ± 0.31	0.38 ± 0.12
OSB(EU)	36.0 ± 6.9	27.3 ± 4.2	4.68 ± 0.62	3.04 ± 0.30	0.63 ± 0.20
PW(12)	49.3 ± 13.4	33.5 ± 4.6	6.55 ± 0.84	2.45 ± 0.32	1.11 ± 0.38
PW(9)	71.8 ± 13.1	14.1 ± 4.4	8.78 ± 1.16	0.53 ± 0.18	1.42 ± 0.37

Data given as mean ± standard deviation
MOE, Modulus of elasticity; MOR, modulus of rupture; IB, internal bond strength; PL, specimen cut parallel to machine, face strand orientation, or face grain direction; PP, Specimen cut perpendicular to the parallel direction
[a] Specimen cut parallel to machine, face strand orientation, or face gain direction
[b] Specimen cut perpendicular to the parallel direction

load due to the increased thickness. Despite this, LCC has been widely used to determine the durability or moisture resistance of wood-based panels under bending conditions because LCC and BRS by definition measure the potential load that can actually be applied under in-service conditions. In the wet-bending tests, LCC and BRS decreased remarkably. The ratio of LCC to the initial strength (MOR) for the eight types of panels ranged approximately from 40% to 65% for the Wet-bending A test and from 30% to 60% for the Wet-bending B test.

For international standardization of wood-based panels, the specifications and requirements for panel strength are of great importance. MDF is a prime example.[38] Wet-bending strength values are needed for 3 moisture-resistant classes (G, general purpose; F, furniture grade; and LB, load-bearing), 3 high moisture-resistant classes (G, F, and LB), and 2 exterior-grade classes (G and LB). These 8 MDF groups each have 7 thickness classes. Thus, 56 figures are necessary for MDF specifications with consistency required across the whole range.

We conducted a regression analysis on the aging effect of the JIS-A and JIS-B treatments, and observed a linear relationship ($y = ax$) between the two. The mean LCC values for 12 conditions, including the perpendicular values for OSB and plywood, were used to obtain the relationship. Figure 2 shows that the LCC from the Wet-bending B test can be obtained by multiplying the LCC from the Wet-bending A test by 0.9. Although the Wet-bending A test was originally developed to differentiate melamine-type products from urea–formaldehyde bonded products, and the B test was used to validate the use of phenol–formaldehyde resin, the aging effect intensities for structural panels here were found to be in a quantitative relationship ratio.

Table 3. Results obtained by the Wet-bending A and B tests

Panel	Wet-bending A						Wet-bending B					
	LCC		BRS		TS (%)	IB (MPa)	LCC		BRS		TS (%)	IB (MPa)
	PL (MPa)	PP (MPa)	PL (GPa)	PP (GPa)			PL (MPa)	PP (MPa)	PL (GPa)	PP (GPa)		
PB (PF)	11.3 ± 1.9		1.84 ± 0.26		19.7 ± 2.2	0.25 ± 0.06	9.5 ± 1.3		1.56 ± 0.21		30.2 ± 2.2	0.13 ± 0.03
PB (MDI)	17.5 ± 1.3		1.99 ± 0.14		8.2 ± 0.8	1.51 ± 0.07	14.6 ± 1.2		1.90 ± 0.08		16.9 ± 0.8	1.35 ± 0.10
MDF (MUF)	18.2 ± 1.4		1.58 ± 0.07		15.1 ± 0.3	0.36 ± 0.06	14.8 ± 1.1		1.26 ± 0.07		21.1 ± 1.1	0.31 ± 0.07
MDF (MDI)	20.0 ± 1.0		1.57 ± 0.07		6.6 ± 0.2	0.98 ± 0.08	17.7 ± 0.8		1.32 ± 0.10		13.3 ± 0.6	0.87 ± 0.08
OSB (NA)	14.3 ± 2.2	9.2 ± 2.0	1.91 ± 0.28	0.80 ± 0.22	28.9 ± 4.2	0.13 ± 0.06	14.2 ± 1.0	7.9 ± 1.6	1.65 ± 0.17	0.73 ± 0.10	30.9 ± 2.6	0.10 ± 0.05
OSB (EU)	19.7 ± 3.0	14.9 ± 1.9	2.35 ± 0.43	1.50 ± 0.19	22.0 ± 1.5	0.34 ± 0.08	17.7 ± 2.6	13.6 ± 1.8	2.12 ± 0.27	1.41 ± 0.16	23.4 ± 2.7	0.28 ± 0.10
PW (12)	31.8 ± 4.4	22.0 ± 4.1	4.14 ± 0.59	1.67 ± 0.30	4.0 ± 1.3	1.07 ± 0.29	28.3 ± 3.9	19.0 ± 3.7	3.59 ± 0.71	1.44 ± 0.27	6.5 ± 1.2	1.10 ± 0.35
PW (9)	34.5 ± 9.5	10.3 ± 3.0	5.22 ± 1.36	0.43 ± 0.16	4.9 ± 1.0	1.55 ± 0.29	33.1 ± 8.1	8.3 ± 2.8	4.82 ± 1.28	0.43 ± 0.22	5.3 ± 1.6	1.70 ± 0.63

Data given as mean ± standard deviation

LCC, Bending strength based on initial specimen thickness (load-carrying capacity); BRS, elastic modulus in bending based on initial specimen thickness (bending resistance); TS, thickness swelling under wet conditions in the bending test; IB, air-dried internal bond strength obtained after drying the bending specimen

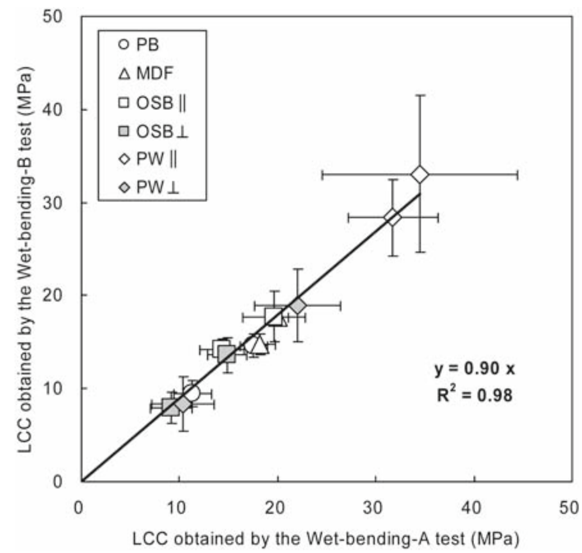

Fig. 2. Relationship between load-carrying capacity (*LCC*) values obtained by the Wet-bending A and Wet-bending B tests. *PB*, Particleboard; *MDF*, medium-density fiberboard; *OSB*, oriented strandboard; *PW*, plywood

Aging effect of JIS-A and JIS-B treatments

To clarify the aging effects of the treatments specified in JIS as the Wet-bending tests, the LCCs of wet bending were compared with the LCCs of the redried specimens after the same treatments for two PBs and two MDFs. Figure 3 shows the LCC retained as a percentage of the original strength, where "Wet" and "Dry" indicate the moisture condition of the samples. It is obvious that the LCC decreased under both the Wet-A and Wet-B conditions because the test pieces contained water. Furthermore, the LCC retention for Wet-A after immersion in 70°C water was slightly larger than that of Wet-B (boiling water immersion) for the four board types. We discovered that once they were dried, PB(PF) and MDF(MUF) recovered an LCC of about 80% of the initial value, and MDI-bonded panels [i.e., PB(MDI) and MDF(MDI)] almost recovered to their initial strengths when dried. Sekino and Okuma[39] reported that recovery of bending strength was found to some extent by redrying for PF resin-bonded and isocyanate resin-bonded particleboards.

For better understanding, we drew typical load–deflection curves under five different conditions for MDF(MDI) as shown in Fig. 4. For the wet condition after the 20°C water immersion, the ultimate deflection in Wet-B was slightly larger and the maximum load was lower than those for Wet-A, as expected. However, those failure points in the curves recovered up to approximately the same level of the control sample for load with some differences in deflection.

There are two possible explanations for MDI-bonded panels showing almost full recovery to their initial strengths when dried: the strength reduction of the material was offset by the increase in thickness, or both the strength and thickness returned to their original states during reconditioning. For the aging treatments, thickness change was one of the parameters of interest because the LCC was calculated based on the initial thickness. Having LCC and BRS based on the initial thickness may somewhat overestimate the real value compared with MOR and MOE, which are calculated based on the actual thickness at the time of the test. The interrelationships are $(LCC)/(MOR) = (1 + TS/100)^2$ and $(BRS)/(MOE) = (1 + TS/100)^3$. Figure 5 shows the TS changes during JIS-A and JIS-B treatments for different panel types. It was discovered that immersion in water at room temperature did not accelerate TS very much, and that the TS resulting from the JIS-B treatment was greater than from the JIS-A treatment for all types of panels tested. Note that MDI-bonded panels returned to their initial thickness after the reconditioning that followed the JIS-A treatment, which with LCC recovery explains why both strength and thickness recovered to almost 100% in those panels.

Relation between aging treatment and outdoor exposure

The outdoor exposure test is a natural weathering method considered to be an accelerated aging test. It may provide

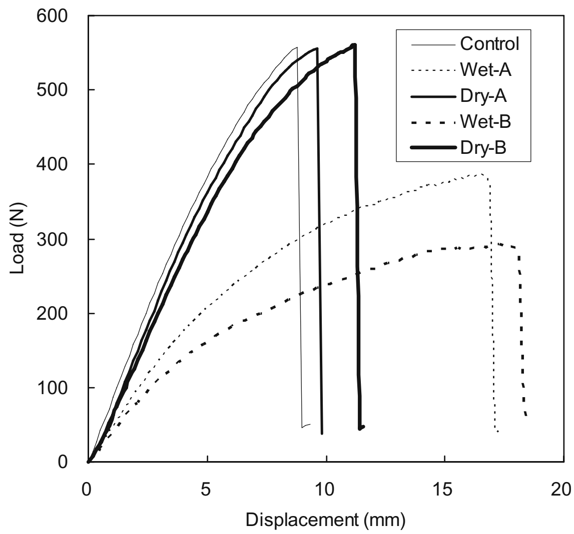

Fig. 4. Typical load–deflection curves of the MDF(MDI) panel in bending for the control sample under four different conditions

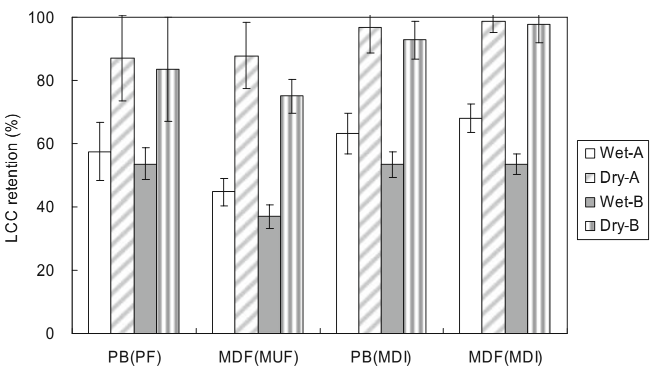

Fig. 3. LCC retentions of PB and MDF panels under wet and dry conditions. *Wet-A*, LCC obtained by Wet-bending A test; *Wet-B*, LCC obtained by Wet-bending-B test; *Dry-A*, LCC measured after JIS-A treatment; *Dry-B*, LCC measured after JIS-B treatment; *PF*, phenol–formaldehyde; *MUF*, melamine–urea–formaldehyde; *MDI*, methylenediphenyl diisocyanate

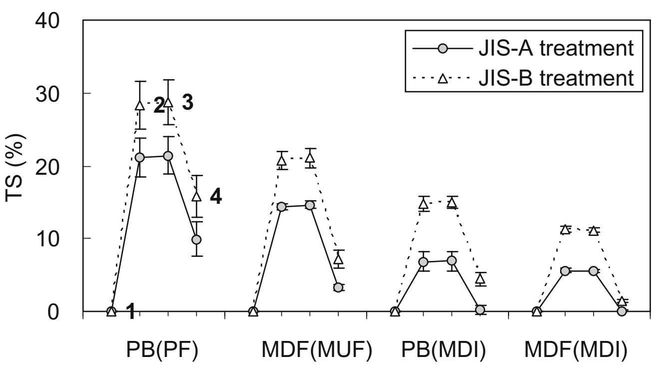

Fig. 5. Thickness swelling (*TS*) of four panels during JIS-A and JIS-B treatments. *1*, Control sample; *2*, after 2-h soaking at 70°C (JIS-A treatment) or after 2-h boil (JIS-B treatment); *3*, after 1-h water soaking; *4*, oven drying for 24 h at 60°C followed by 2-week conditioning at 20°C and 65% relative humidity

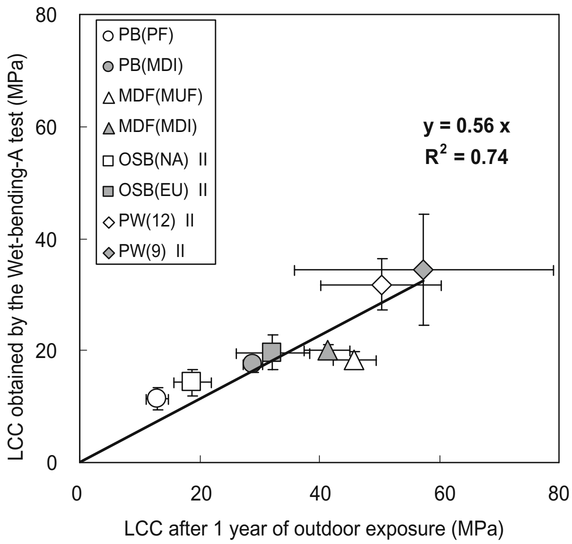

Fig. 6. Relationship between LCC after 1-year outdoor exposure and LCC obtained by the Wet-bending A test. *NA*, Imported from North America; *EU*, imported from Europe

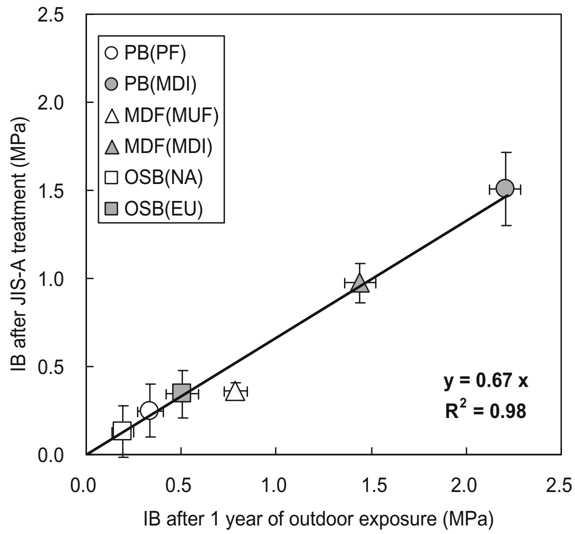

Fig. 7. Relationship between internal bond strength (*IB*) values after 1-year outdoor exposure and JIS-A treatment for mat-formed type panels

the basis for accelerated aging test methods to be used as practical standards. This means that the intensity of an accelerated aging treatment must be assessed by comparing it to outdoor test results. Although it has been said that at least a 5-year exposure is necessary to obtain reliable results,[19] we attempted a comparison between wet-bending and the 1-year outdoor test results in Shizuoka. Figure 6 shows the relationship between the LCC after outdoor exposure and the LCC from Wet-bending A for eight types of panels, including the perpendicular values for OSB and plywood. This shows a fairly good correlation, even though the bending strength was not a good indicator in the early stages of the outdoor exposure because surface degradation of the test panels strongly affected the results. The outdoor test will continue for 10 years, and the same comparison will be the subject of future research.

Durability performance has often been discussed using IB strength as an indicator of bond durability. Figure 7 shows the relationship between IB after the outdoor exposure and IB after JIS-A treatment for the mat-formed panel products. We found a good correlation between the two test results, and the slope of the regression line is expected to become steeper with increasing exposure period. If a 45° line results, the aging effects of two treatments would be comparable, which is one objective of durability studies.

Conclusions

Wet-bending tests and the outdoor exposure test were conducted using eight types of commercial wood-based panels. Results obtained are summarized as follows.

1. A linear relationship was found between the LCC from the Wet-bending A test and the LCC from the Wet-bending B test. The LCC from Wet-bending B could be obtained from the LCC from the Wet-bending A test by multiplying it by 0.9, which may be applicable as a quantitative ratio of aging effects between the two.
2. By redrying the specimens after water immersion, the LCC for PB(PF) and MDF(MDI) recovered to approximately 80% of the initial strength, and the LCC for MDI-bonded panels recovered to almost 100% of the initial strength.
3. A certain relationship was found between the LCC after Wet-bending A and the LCC after a 1-year outdoor exposure in Shizuoka. IB strength showed a good correlation between the JIS-A treatment and the 1-year outdoor exposure treatment.

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