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Evaluating the durability of wood-based panels using internal bond strength results from accelerated aging treatments

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Abstract In this study, the durability of wood-based panels was evaluated by comparing the internal bond (IB) strength retention after five different laboratory-based accelerated aging tests with the IB retention after 5 years of outdoor exposure in Shizuoka City. In each accelerated aging test, the IB retention of MDI-bonded panels showed high retention compared to other panels. Outdoor exposure in Shizuoka City resulted in an IB retention value for particleboard (PF) and oriented strandboard (aspen) of less than 10% after the 5-year exposure period. Medium-density fiberboards maintained their initial IB strength over the same period. Calculation of the mean IB retention for all board types allowed comparison of the severity of aging between the accelerated test methods and outdoor exposure. The ASTM six-cycle test method was the most severe among the standard treatment cycles applied.

Key words Wood-based panel · Internal bond strength · Durability performance · Accelerated aging treatments · Outdoor exposure

Introduction

Mat-formed wood-based panels, such as particleboard (PB) and medium-density fiberboard (MDF), have become widely used in residential construction in recent years. For such use, long-term durability of the wood-based panels is important. Estimating how long panels maintain the required performance under actual environmental conditions has been a goal of studies evaluating the durability of wood-based materials. To achieve this, the deterioration mechanism(s) must be clarified in relation to various conditions. Many researchers have conducted outdoor exposure

tests using veneer-based materials in Japan.^{1–4} Sekino and Suzuki reported 10-year test results for wood-based panels, including plywood (PW), oriented strandboard (OSB), PB, MDF, hardboard, and cement-bonded PB.⁵ Several other studies on the durability of MDF, OSB, and PB have also been published.^{6–8} However, many problems exist when applying test results obtained in North America and Europe^{9–13} to Japan, which has different weather conditions. For this reason, accumulating and evaluating test data in Japan is needed. To evaluate the durability performance of wood-based panels, mechanical tests using actual building materials should be conducted,¹⁴ but this is very difficult to realize.

Methods for evaluating the durability of wood-based panels include long-term and short-term tests. Long-term evaluation, such as outdoor exposure tests, is a method to evaluate long time frames by incorporating the factor of elapsed time. However, outdoor exposure tests have many disadvantages, such as being time consuming and difficult to carry out; moreover, these tests suffer from differences caused by the test location.¹⁴ In contrast, short-term evaluations assess changes in mechanical properties after accelerated aging treatments, such as water immersion, boiling, steaming, freezing, or drying. Accelerated aging tests are superior to short-term outdoor exposure tests, and they are essential in determining the durability of wood-based panels. Such accelerated aging tests may seem artificial, but in recent decades, many attempts have been made to correlate degradation caused by outdoor aging with that by laboratory-based accelerated aging,^{15,16} including the use of ASTM D1037,¹⁷ APA D-1 and D-4,¹⁸ and V313¹⁹ tests, because the results of outdoor aging tests are sometimes used as basic indicators when determining standardized test methods.^{12,20} In a previous article, we focused on thickness swelling (TS) during some accelerated aging tests and outdoor exposure using eight types of commercial wood-based panels and determined the TS characteristics of each aging test. Furthermore, we clarified how laboratory-based accelerated aging test results corresponded to a given outdoor exposure test result.²¹ However, to understand the durability of wood-based panels, the internal bond

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strength is one of the most important factors. Moreover, clarifying how laboratory-based accelerated aging test results correspond to a given outdoor exposure test result is important.

The objectives of this study were to evaluate the effects of aging treatments on internal bond strength of some structural panel types, assess 5-year degradation caused by an outdoor exposure test conducted in Shizuoka, and establish a correlation in aging effects between accelerated aging treatments and outdoor exposure tests using the internal bond (IB) strength.

Experimental

Sample panels

The four groups of commercial wood-based panels used in this study, PB, MDF, OSB, and PW, are widely used for construction purposes in Japan (Table 1). Each panel group included two panel types of differing specifications giving eight panels in total. The PB panels were made from recycled wood with different binders. The MDF panels differed in thickness, binder type, and end-use application. The OSB panels used were imported products made from different wood species. The plywood panels also differed in thickness. Because the OSB used in this project was obtained from North America and Europe, these panels are not necessarily representative of the OSB typically used in Japan. Although North America has very little MDI-bonded PB or MDF, MDI-bonded PB and MDF were selected because fabricators in Japan show a strong preference for PB and MDF to achieve high durability. 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. In total, 22 original panels (100 cm × 200 cm) were prepared for each panel type. These were cut to sample panels (30 cm × 30 cm), and then we randomly selected 24 panels for accelerated aging tests and the outdoor exposure test. The mechanical properties of the panels before aging treatments were summarized in a previous article.²²

Accelerated aging test methods

To determine the IB strength of eight wood-based panel types, five different accelerated aging treatments were conducted: cyclic JIS-B treatment, cyclic APA D-1 treatment, the V313 procedure, the ASTM six-cycle procedure, and the vacuum pressure soaking and drying (VPSD) method. With the exception of the VPSD procedure, all treatments followed standard methods or modifications of these methods.

1. Cyclic JIS-B treatment consisted of immersion in boiling water for 2 h, followed by immersion in water at 20°C for 1 h, and then drying at 60°C for 21 h. The treatment was carried out one, three, or six times, and IB testing was conducted after reconditioning.
2. Cyclic APA D-1 treatment is specified by APA.¹⁸ It consists of immersion in water at 66°C for 8 h, drying at 82°C for 14.5 h, and settling at room temperature for 1.5 h. The treatment was carried out one, three, or six times, and IB testing was conducted after reconditioning.
3. V313 is the specified European Standard¹⁹ method for cyclic testing of moisture resistance. The procedure has also been adopted as the Japanese–Australian–New Zealand Standard (JANS) by the joint committee for Australia, New Zealand, and Japan. The test specimens are exposed to immersion in water at 20°C for 72 h, freezing at −12°C for 24 h, drying at 70°C for 72 h, and settling at room temperature for 4 h. The treatment was carried out one, three, or six times, and IB testing was conducted after reconditioning.
4. The ASTM six-cycle method is a common test method and is specified in ASTM D1037 for mat-formed panel products.¹⁷ It consists of six repetitions of combined treatments made up of immersion in water at 49°C for 1 h, steaming at 93°C for 3 h, freezing at −12°C for 20 h, drying at 99°C for 3 h, steaming at 93°C for 3 h, and drying at 99°C for 18 h. The treatment was carried out one, three, or six times, and IB testing was conducted after reconditioning.
5. VPSD consists of a vacuum pressure soaking and drying procedure. It consists of soaking under vacuum for 0.5 h, soaking under pressure (290 kPa) for 1 h, and drying at

Table 1. Specifications of the commercial panels tested and internal bond (IB) strength under control conditions

Abbreviation	Panel types	Adhesives	Thickness (mm)	Density (g/cm ³)	Construction	IB ^a (MPa)
PB (PF)	Particleboard	PF	12.2	0.76	Three layer	0.66 ± 0.08
PB (MDI)		MDI	12.1	0.80		1.97 ± 0.17
MDF (MUF)	MDF	MUF	12.2	0.76		0.57 ± 0.07
MDF (MDI)		MDI	9.1	0.72		1.03 ± 0.11
OSB (aspen)	OSB		12.4	0.64	Three layer cross-oriented	0.38 ± 0.12
OSB (pine)		PF	11.8	0.68		0.63 ± 0.20
PW (12)	Plywood		12.0	0.64	Five ply	1.11 ± 0.38
PW (9)			8.8	0.61	Three ply	1.42 ± 0.37

PB, particle board; PF, phenol-formaldehyde; MDI, methylenediphenyl diisocyanate; MDF, medium-density fiberboard; MUF, melamine-urea-formaldehyde; OSB, oriented strandboard; PW, plywood

^aData are given as the mean ± SD (*n* = 10)

Table 2. Detailed steps used in each cycle of the five accelerated aging tests

Method	Exposure	Temperature (°C)	Pressure (kPa)	Time (h)
Cyclic JIS-B	Water soak	100		2
	Water soak	20		1
	Dry air heat	60		21
Cyclic APA D-1	Water soak	66		8
	Dry air heat	82		14.5
	Conditioning			1.5
V313	Water soak	20		72
	Freezing	-12		24
	Dry air heat	70		72
	Conditioning			4
ASTM 6 cycle	Water soak	49		1
	Steam	93		3
	Freezing	-12		20
	Dry air heat	99		3
	Steam	93		3
	Dry air heat	99		18
VPSD	Vacuum			0.5
	Pressure soak		290	1
	Dry air heat	60		22

Conditioning refers to settling at room temperature

60°C for 22 h. The treatment was carried out one, three, five, or ten times, and IB testing was conducted after reconditioning.

Reconditioning involved oven drying for 24 h at 60°C followed by 2 weeks of conditioning at 20°C and 65% relative humidity (RH). These five treatments are summarized in Table 2. Eight test pieces measuring 50 × 50 mm were taken from each panel for the IB test. After each treatment, IB testing was performed in accordance with JIS A-5908.²³ The loading rate was controlled at 2 mm/min.

Outdoor exposure test

For each panel type, 12 test sample boards, each 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 each sample were coated with a protective agent to prevent excessive edge swelling from water adsorption during test exposure. The boards were set vertically on a test frame facing south. The outdoor test was started in March 2004 and will run till 2013. In this report, the results of 5 years of exposure are discussed. Two test sample boards of each panel type were removed after 1, 2, 3, 4, and 5 years of exposure, and the IB was measured after reconditioning that consisted of drying at 60°C for 24 h and conditioning at 20°C and 65% RH for 2 weeks. Thirteen pieces measuring 50 × 50 mm were taken from each panel for the IB test.

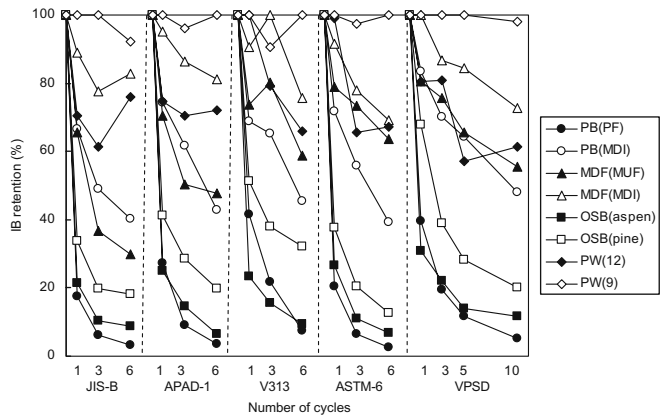


Fig. 1. Internal bond (IB) retention in five kinds of accelerated aging tests. *PB*, particle board; *PF*, phenol-formaldehyde; *MDI*, methylenediphenyl diisocyanate; *MDF*, medium-density fiberboard; *MUF*, melamine-urea-formaldehyde; *OSB*, oriented strandboard; *PW*, plywood, *VPSD*, vacuum pressure soaking and drying

Results and discussion

Characteristics of IB deterioration after each accelerated aging treatment

The values of IB for control samples (no treatment) are shown in Table 1. In this article, the IB retention was defined as follows:

$$\text{IB retention (\%)} = (\text{IB after treatment} / \text{IB of control samples}) \times 100 \quad (1)$$

Figure 1 shows the changes in IB retention found for each of the five accelerated aging test methods. The IB retention for the cyclic JIS-B treatment, cyclic APA D-1 treatment, V313 method, and ASTM six-cycle method are for six repeated cycles. The IB retention for VPSD was determined after ten repeated cycles. In this article, if IB retention became greater than 100%, we defined it as 100% retention. As shown in Fig. 1, for all aging treatments, the IB retention, except for plywood, decreased exponentially with increasing number of cycles. This is because the structure of plywood was different from those of the other panels. For PB (PF) and OSB (aspen), the IB retentions became less than 10% for all treatments. In contrast, the IB retention of PB (MDI) was greater than 40%. Moreover, MDF (MDI) was about 80% for all aging treatments. To compare element size, the IB retention for MDF was generally higher than those of PB or OSB. This is the why the element size strongly affected the internal bond strength. Of the standard methods, the ASTM six-cycle procedure provided the most severe treatment. This observation agreed with our previous article focusing on the TS results from accelerated aging treatments.²¹

To compare the deterioration rates for each treatment, the IB retention of boards versus the number of aging cycles (*t*) is given by:

$$\text{IB retention} = A + (100 - A) \times \exp(-t/B) \quad (2)$$

Table 3. Coefficients A and B for the five accelerated aging treatments using six boards^a

	Cyclic JIS-B		Cyclic APA D-1		V313		ASTM 6 cycle		VPSD	
	A	B	A	B	A	B	A	B	A	B
PB(PF)	4.7	0.50	5.6	0.69	11.5	0.99	4.3	0.56	13.9	0.85
PB (MDI)	41.2	1.26	40.2	2.33	49.9	1.42	38.4	1.97	62.4	1.78
MDF(MUF)	28.0	1.49	46.7	1.21	68.7	0.63	66.1	1.23	67.8	1.29
MDF(MDI) ^b	80.3	0.99	76.3	3.71	–	–	60.9	3.76	45.4	8.89
OSB (aspen)	9.5	0.49	10.2	0.56	12.4	0.48	8.5	0.62	17.7	0.55
OSB (pine)	18.6	0.59	23.4	0.71	34.2	0.76	15.5	0.76	23.5	1.85

^aThe coefficients A and B were determined by nonlinear least-squares regression

^bRegression analysis could not be performed for MDF (MDI) subject to the V313 method

Table 4. IB retention resulting from the 5-year outdoor exposure test in Shizuoka City

	1 year (%)	2 years (%)	3 years (%)	4 years (%)	5 years (%)
PB (PF)	41 (18)	26 (13)	18 (7)	8 (4)	7 (2)
PB (MDI)	100 (9)	88 (12)	83 (9)	57 (7)	42 (6)
MDF (MUF)	100 (7)	96 (9)	100 (15)	100 (15)	95 (12)
MDF (MDI)	100 (9)	100 (7)	97 (7)	100 (14)	97 (7)
OSB (aspen)	34 (16)	51 (14)	43 (12)	7 (2)	6 (3)
OSB (pine)	79 (20)	60 (17)	36 (10)	31 (14)	15 (7)
PW (12)	100 (19)	61 (37)	49 (17)	84 (21)	75 (24)
PW (9)	100 (25)	91 (37)	83 (23)	92 (23)	97 (15)

Numbers in parentheses indicate standard deviations ($n = 13$)

where A and B are empirical constants.²⁴ Coefficient A is the saturation value and B indicates the decreasing rate. These coefficients were determined by nonlinear least-squares regression. Table 3 shows the values of A and B for the five accelerated aging treatments using six mat-formed panels, excluding plywood. Comparing A and B values among the panels under the same treatment, the A and B values for MDF (MDI) were the highest for the treatments used. The value of A was lowest for PB (PF).

Next, we examined the relationship between the TS and IB retention, as shown in Fig. 2. The IB retention tended to decrease exponentially with increasing TS. This tendency of IB retention was consistent with previous experimental reports.^{25–27} Saito et al.^{25–27} suggested that the IB strength tended to decrease exponentially with increasing TS, regardless of the kind of resin used in particleboards. In this article, the TS of boards (T) versus IB retention (R) is given by $R = \exp(4.590 - 0.084T)$. This result is shown as a curve in Fig. 2.

IB retention in the outdoor exposure test in Shizuoka City

The outdoor exposure test is a natural weathering method and provides the basis for applying laboratory-based accelerated aging test methods as practical standards. Table 4 shows the IB retention values following 5 years of outdoor exposure in Shizuoka City. The annual average temperature during these 5 years was 16.9°C, compared to the 30-year average of 16.3°C. Annual precipitation (2304 mm) was the same as normal (2322 mm).²⁸

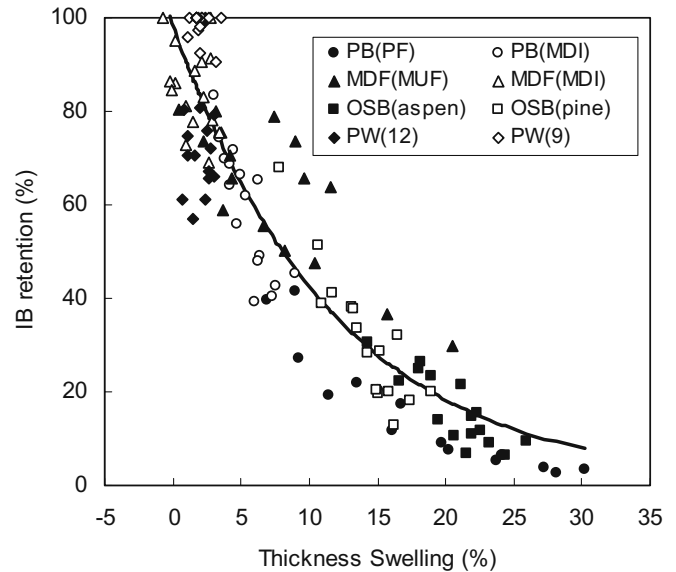
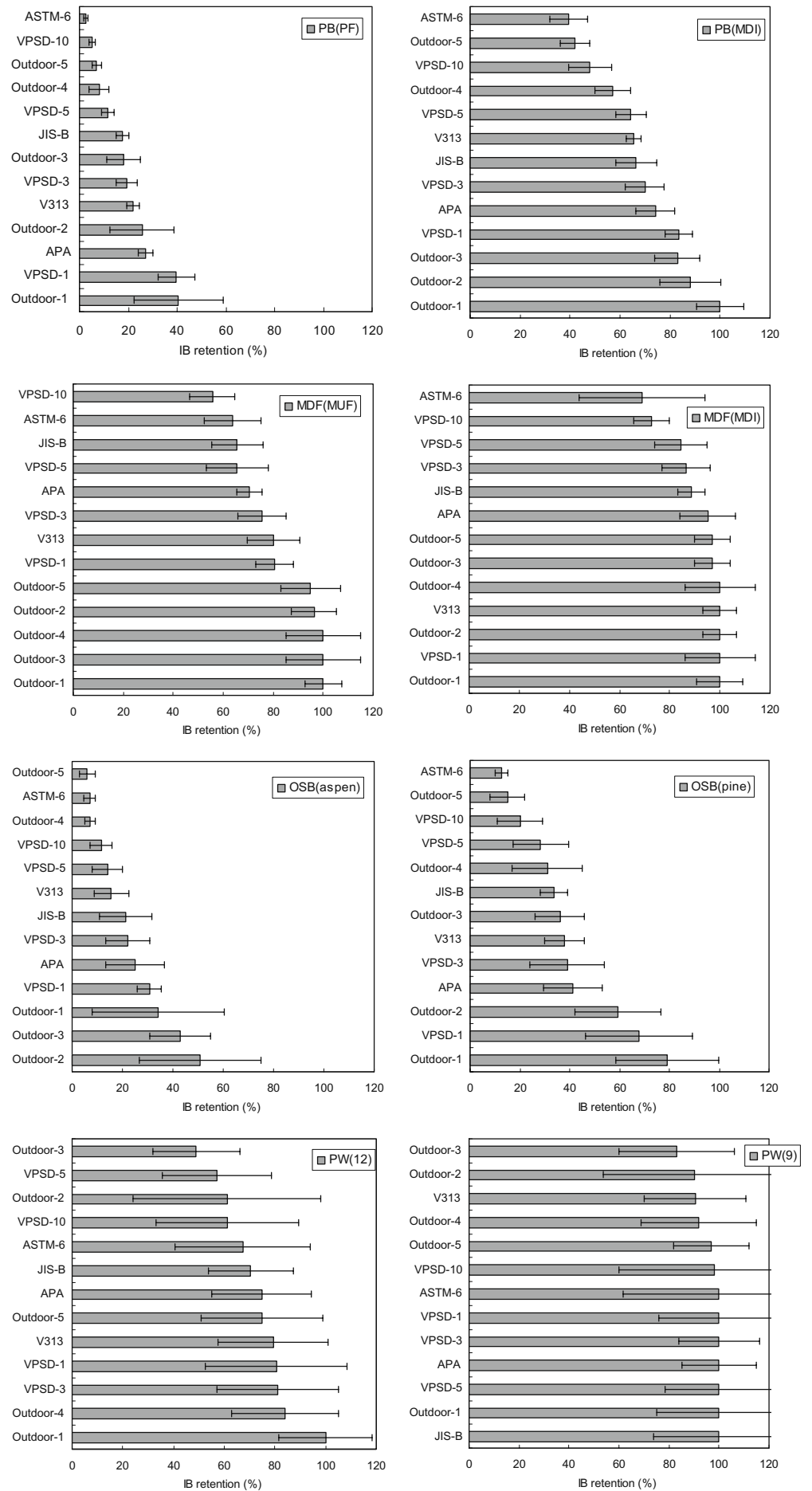


Fig. 2. Relationship between thickness swelling and internal bond retention. The line is the regression curve

The tabulated results show that the IB retention of PB (PF) and OSB (aspen) was less than 10% after the 5-year exposure period, with a value of 15% for OSB (pine). In contrast, MDFs maintained their initial internal bond strength over the same period. These results are consistent with those obtained from laboratory-based accelerated aging in that MDI-bonded panels showed higher IB retention values than PF-bonded panels did under both sets of test conditions. Definitive conclusions cannot yet be drawn

Fig. 3. The spectrum of aging intensity as a result of the various treatments. The *numbers* in the y-axis labels indicate the number of years (outdoor) or number of repeated cycles (others). Values are the means of 8 (accelerated aging treatments) or 13 (outdoor exposure) test samples. *Error bars* represent standard deviations



because the outdoor exposure test will continue for another 5 years.

Severity of the aging treatments

A period of at least 5 years of outdoor exposure is necessary to obtain reliable results.²⁹ Thus, in this study, we attempted to compare the results of the five laboratory-based accelerated aging procedures and those of 1-, 2-, 3-, 4-, and 5-year outdoor exposure tests in Shizuoka City. In Fig. 3, the amount of IB retention resulting from each aging treatment has been used to construct an aging spectrum. The results obtained from a single standard treatment cycle were used for JIS-B and APA D-1, along with IB retention values from three and six standard treatment cycles of V313 and the ASTM six-cycle test, respectively. VPSD results were for one, three, five, and ten cycles. The spectrum indicates that the ASTM six-cycle method for PB (PF), PB (MDI), MDF (MDI), and OSB (pine), ten VPSD cycles for MDF (MUF), and 5-year outdoor exposure for OSB (aspen) were the most severe treatment conditions. The aging effects resulting from JIS-B, V313, and five VPSD cycles were comparable and of medium severity. One or three VPSD cycles and APA showed only nominal aging effects. The least severe changes arose from 1- or 2-year outdoor exposures, except for PW (9).

Relation between accelerated aging treatments and outdoor exposure tests

An important goal of this study was to determine the relationship between the accelerated aging methods and outdoor exposure tests. To this end, the mean IB retention was calculated for the eight types of panels to relate the severity of accelerated aging treatments to the IB retention arising from outdoor exposure. The mean IB retention (IBr) was given by:

$$\text{Mean IB retention} = [\text{IBr-PB (PF)} + \text{IBr-PB (MDI)} + \text{IBr-MDF (MUF)} + \dots + \text{IBr-PW (9)}] / 8 \quad (3)$$

Figure 4 shows how the mean IB retentions provide a bridge between accelerated aging treatment and outdoor exposure tests. In this figure, the type of aging treatment is given along the y-axis. The arrangement of treatments was determined in order of the size of the mean IB retention for six cycles (ten cycles for VPSD) or 5-year outdoor exposure. Based on this figure, the severity of each treatment can be appreciated. For example, the severity of 2-year outdoor exposure is about the same as a single VPSD cycle. Similarly, six APA D-1 cycles are of about the same severity as three JIS-B cycles or ten VPSD cycles. Additionally, 5-year outdoor exposure shows almost the same severity as five VPSD cycles. Of the standard methods, the ASTM six-cycle procedure provides the most severe treatment, with six JIS-B cycles being the most severe overall.

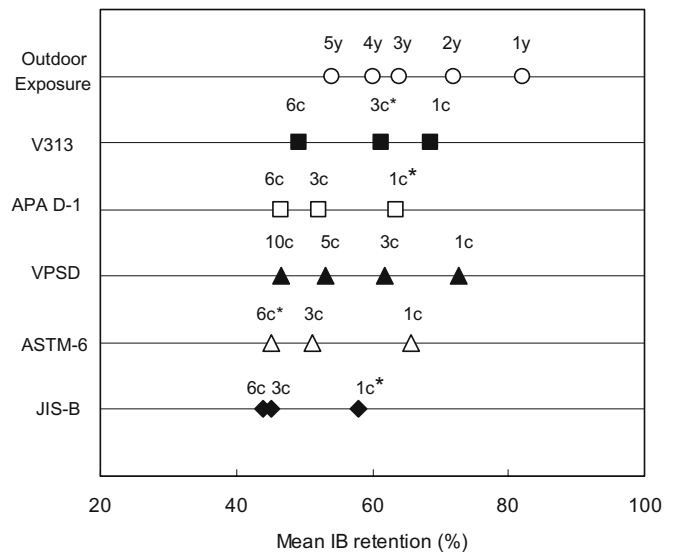


Fig. 4. Relation between accelerated aging treatments and outdoor exposure tests. *Asterisks* indicate treatment procedures using standard methods. *y*, years; *c*, cycles

Conclusions

The relationship between five laboratory-based accelerated aging tests and outdoor exposure in Shizuoka was assessed using IB strength retention criteria. The results were as follows:

1. For IB retention using five accelerated aging tests, the retentions for PB (PF) and OSB (aspen) panels were lower than those for the other panels for every treatment. MDI-bonded panels maintained higher retention, and except for PWs, the retention decreased exponentially. The ASTM six-cycle method was the most severe standard treatment.
2. After outdoor exposure tests in Shizuoka, the IB retention of PB (PF) and OSB (aspen) were less than 10% after the 5-year exposure period, with values of 15% for OSB (pine). MDFs, however, maintained their initial internal bond strength over the same period.
3. Calculation of mean IB retention values allowed the severity of accelerated aging test procedures to be compared to the results of outdoor exposure. The ASTM six-cycle test method showed the greatest severity among the standard treatment cycles, with six repetitions of the JIS-B cycle being the most severe treatment overall.

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