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ORIGINAL ARTICLE

Evaluation of particleboard deterioration under outdoor exposure using several different types of weathering intensity

Noboru Sekino · Haruna Sato · Koji Adachi

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Abstract The deterioration of particleboards for construction use was investigated by outdoor exposure tests at eight sites in Japan over 7 years. Two types of particleboard with different water resistances were tested and the deterioration of mechanical properties such as modulus of rupture, internal bond strength and lateral nail resistance was investigated. In order to eliminate regional differences in the board deterioration and also to standardize a deterioration factor for the board exposed to varying climate conditions, we introduced the weathering intensity (WI) defined by monthly precipitation multiplied by monthly average temperature. The significance of this factor was investigated by correlation analysis. Three conventional climate indexes relevant to the durability of wood were also investigated to analyze their significance to WI for particleboard deterioration. It was found that our definition of weathering intensity was the most accurate and the exposure period that reduces initial bending strength by half was calculated by the use of regression analysis for several different sites worldwide.

Keywords Particleboard · Deterioration · Outdoor exposure · Weathering intensity · Mechanical property

Introduction

Recently, mat-formed wood-based panels such as particleboard (PB) and medium-density fiberboard (MDF) have been widely used in residential construction. Therefore, the design of the service life for these panels has become important. Thus far, many studies have predicted the durability of wood-based panels using laboratory accelerated aging tests [1, 2] and outdoor exposure tests [3–7]. In addition, several studies [6–9] reported that the deterioration behavior in outdoor exposure tests correlates with that of the laboratory accelerated aging test. The results of outdoor exposure tests are sometimes used as basic indicators when determining standardized test methods [5, 10]. Further, they play a role that exhibits the service life of the panels used outdoors on that site.

However, there are many disadvantages associated with using outdoor exposure tests as a standard test. The main disadvantage is that the test results strongly depend on the climatic conditions of exposure site [11, 12]. Another disadvantage is a concern that the mechanisms of degradation may differ between outdoor exposure and actual environmental conditions under such as wall sheathing, roof sheathing, and floor sheathing.

To help overcome these disadvantages, the Research Working Group on Wood-based Panels of the Japan Wood Research Society has conducted the durability prediction project since 2004. As shown in Fig. 1 [13], the project consists of two series of research plan: one is correlation between laboratory aging and outdoor exposure at many test sites, $f(x)$; the other is that between laboratory aging and actual service in housing, $g(x)$. Although the collection of actual service data has not completed yet, that of outdoor exposure has done.

The outdoor exposure tests in this project were conducted at eight sites in Japan for up to seven years using

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N. Sekino (✉) · H. Sato
Faculty of Agriculture, Iwate University, Morioka 020-8550, Japan
e-mail: sekino@iwate-u.ac.jp

K. Adachi
Institute of Wood Technology, Akita Prefectural University, Noshiro 016-0876, Japan

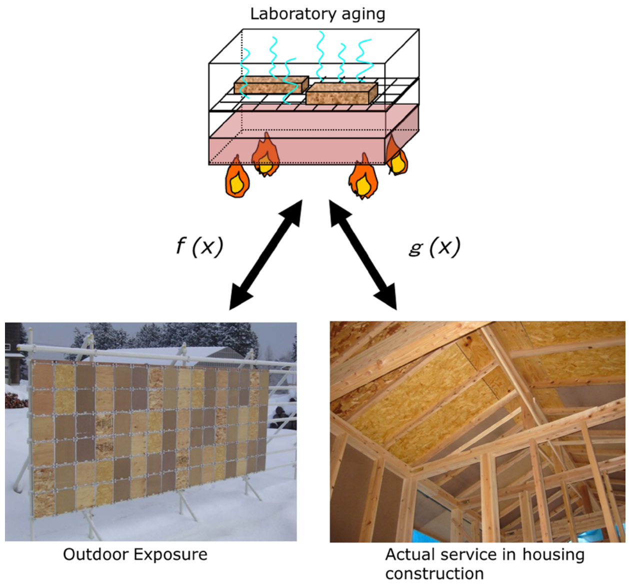

Fig. 1 Research scheme for evaluating long-term durability of wood-based panels [13]

several commercial wood-based panels. Thus far, deterioration rates of mechanical properties at each site were calculated and their regional differences were discussed [14, 15]. Furthermore, the research working group introduced the concept of weathering intensity (WI), as a method of eliminating regional differences, to standardize a deterioration factor of the board exposed to varying climate conditions [14–16].

In this study, we chose to use two types of particleboard with different water resistances as samples among several wood-based panels tested in the project. The objectives of the present study are first, to clarify the differences in deterioration rate among exposure sites with regard to bending strength, internal bond strength, and lateral nail resistance; then to introduce the WI defined as monthly precipitation multiplied by monthly average temperature to eliminate regional differences. Furthermore, three conventional climate indexes relevant to the durability of wood were investigated for their significance to WI. Finally, we predict the outdoor service life of the particleboards for several sites worldwide.

Experimental

Sample panels

Two types of commercial particleboards made from recycled wood with a conventional three-layer construction in which different adhesive was used were chosen as the samples in this study: a phenol–formaldehyde resin-bonded board, PB(PF), and a methyl diphenyl diisocyanate resin-bonded board, PB(MDI). The specifications of the boards and their initial mechanical properties are listed in Table 1. The initial mechanical properties of PB(MDI), modulus of rupture (MOR), internal bond strength (IB), and lateral nail resistance (LNR) were higher than that of PB(PF) depending on density. Kojima et al. [17] investigated the water resistance of these particleboards in terms of the thickness swelling by conducting five types of accelerated aging treatment: Japanese Industrial Standard Wet-bending *B* test (JIS-B), APA D-1 (American Plywood Association treatment), V313 (European Standard 321 treatment), ASTM 6-cycle (ASTM D1037 treatment), and Vacuum Pressure Soaking and Drying treatment (VPSD). In the present paper, IB after application of each aging treatment was analyzed to further examine the difference in water resistance for the two boards as shown in Fig. 2. Details of the treatment conditions of the five tests are provided in Ref. [17] and [18]. Figure 2a shows the relationship between the thickness change (TC) and IB after application of the aging treatments for PB(PF); these results indicate that the IB retention of PB(PF) dropped to less than 50 % when there was an increase of more than 5 % in the thickness of the board. On the other hand, the same relationship for PB(MDI), as shown in Fig. 2b, indicates that PB(MDI) possessed a higher IB retention than PB(PF) if it was subjected to the same treatments. Figure 2c shows the TC–IB retention relationship for both panels, which suggests that the degradation mechanism does not change for either panel even if the water resistance of the boards differs: an increase of TC causes bond breakage and a resultant reduction of strength properties.

Outdoor exposure tests

For each board type, 12 test samples, each 300 × 300 mm, were subjected to outdoor exposure tests at eight sites in Japan [14]: Asahikawa (43°N, 142°E, 135 m above sea level), Morioka (39°N, 141°E, 190 m), Noshiro (40°N, 140°E, 17 m), Tsukuba (36°N, 140°E, 24 m), Shizuoka (34°N, 138°E, 48 m), Maniwa (35°N, 133°E, 272 m), Okayama (34°N, 133°E, 5 m), and Miyakonojo (31°N, 131°E, 155 m). All the samples were coated with a waterproof agent on their panel edges and then, they were set vertical to the ground on a south facing exposure stand. Two test samples were picked every year and the MOR and IB were investigated after full reconditioning at 20 °C and relative humidity of 60–65 %. Further details of this method are provided in Ref. [14].

No method of assessing the nail joint property of wood-based panels subject to outdoor exposure has yet been established. In this study, stainless steel nails (SUS304, 50 mm in length, 6.3 mm in head diameter, 2.75 mm in shank diameter) were driven at a point 12 mm from the

Table 1 Specifications of the tested two commercial particleboards and their initial mechanical properties

Board type (symbols)	PB(PF)	PB(MDI)
Adhesive	PF	MDI
Thickness (mm)	12.0	12.0
Density (g/cm^3)	0.75	0.80
MOR[a] (MPa)	20.7 ± 2.4	28.3 ± 2.1
IB[a] (MPa)	0.83 ± 0.09	2.19 ± 0.18
LNR[a] (kN)	1.74 ± 0.24	2.76 ± 0.23

PB particleboard, *PF* phenol–formaldehyde, *MDI* methyl diphenyl diisocyanate, *MOR* modulus of rupture, *IB*, internal bond strength, *LNR* lateral nail resistance (nail, N50; edge distance, 12 mm)

[a] Data are given as mean ± standard deviation ($n = 30$)

lateral edge of the board before outdoor exposure to investigate degradation of LNR. A further set of 12 test samples, each 300 × 300 mm, were also set on the exposure stand at four of the test sites: Morioka, Tsukuba, Okayama, and Miyakonojo. The four edges of the nail-driven samples were not coated with a waterproof agent to investigate the direct effect of panel edge degradation due to outdoor exposure on the LNR and IB near-panel edges. Two test samples were picked every year, and the LNR and IB were investigated after full reconditioning at 20 °C and relative humidity of 60–65 %. Further details of this method are provided in Ref. [19].

The outdoor exposure tests began between March and April 2004. Collection of the sample boards was conducted every year up to five years of exposure and the final collection of sample boards was after either six or seven years of exposure depending on the degree of board degradation: the exposure time for less deteriorated samples was extended to seven years. Climate conditions (annual average temperature and annual precipitation of the past 30 years) for the eight sites are as follows: Asahikawa (6.4 °C, 1091 mm), Morioka (9.8 °C, 1265 mm), Noshiro (11.1 °C, 1746 mm), Tsukuba (13.2 °C, 1308 mm), Shizuoka (16.1 °C, 2327 mm), Maniwa (13.7 °C, 1398 mm), Okayama (20.3 °C, 1160 mm), and Miyakonojo (21.9 °C, 2435 mm). Detailed conditions during the outdoor exposure test period are shown in Ref. [15].

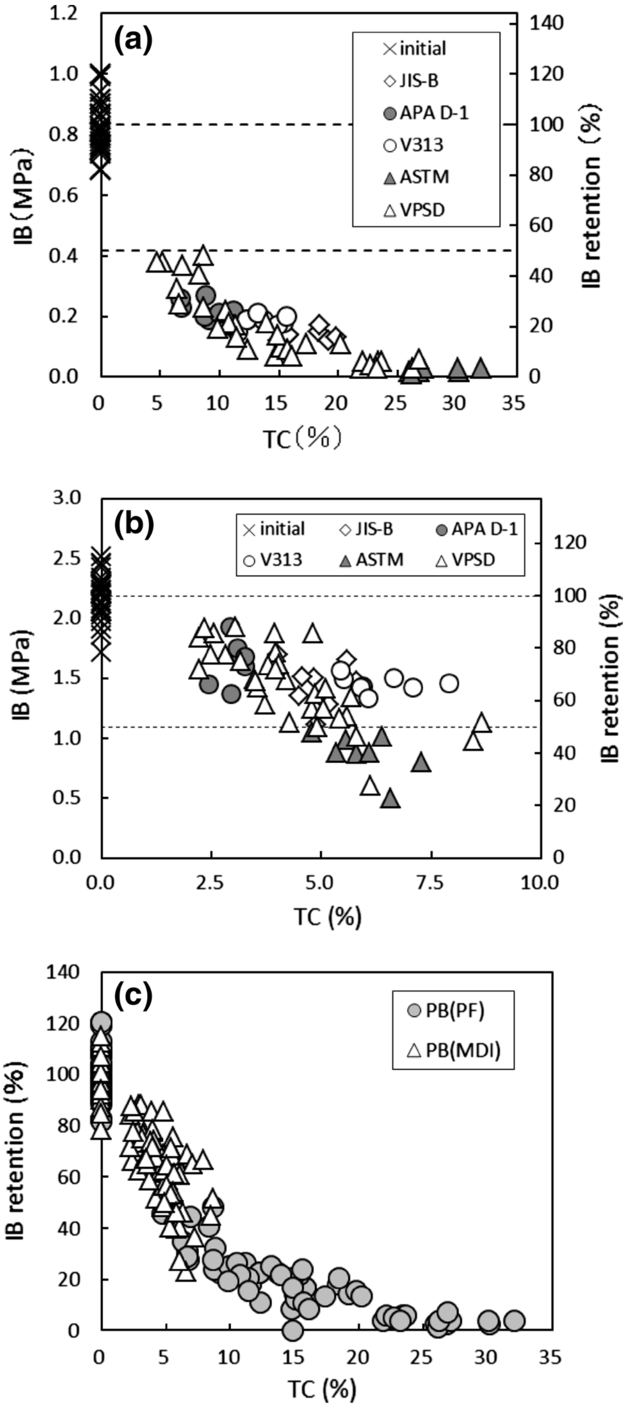

Fig. 2 Comparison of water resistance evaluated by various accelerated aging treatments between tested two types of particleboards: TC thickness change, **a** internal bond strength (IB) for PB(PF), **b** IB for PB(MDI), **c** IB retentions for both PB(PF) and PB(MDI); data are *plotted* irrespective of types of treatment

Results and discussion

Deterioration of the mechanical properties over a 7-year outdoor exposure

Figures 3 and 4 show the exposure time dependence of the mechanical properties of the sample boards: the lateral axis is a logarithmic axis indicating the exposure period, and the vertical axis is a linear axis indicating the measured value and the retention rate of certain mechanical properties. The linear relationship between the time scale and the degradation of panels enabled quantification of regional differences by comparing regression coefficients and is discussed further in Table 2.

Comparing Fig. 3a, b, it was found that the MOR of PB(PF) deteriorated more than that of PB(MDI); PB(MDI) retained more than half of its initial MOR after up to 7 years of exposure at many test sites. Figure 3c, d shows the deterioration of the IB of PB(PF) and PB(MDI), respectively. It was found that the IB of PB(PF) deteriorated more than that of PB(MDI) and that the variation amongst exposure sites was much greater in PB(PF) than in PB(MDI). The deterioration of the IB and LNR both of which were measured near the panel edge of PB(PF) is shown in Fig. 4a, b, respectively. Comparing Figs. 3c and 4a, the deterioration of the IB of PB(PF) near the edge of the panel occurred more rapidly than that near the center of the panel. This indicates the importance of protecting the panel edges by a waterproof agent to prevent rainwater penetration. In the case of deterioration behavior near the edge of the panel (Fig. 4a, b), the deterioration of the LNR was less than that of the IB under the same exposure time. For this reason, the LNR is considered to depend on the face layer with the highest density throughout the panel thickness and to be less affected by rainwater penetration, whereas the IB is dependent on the core layer with the lowest density throughout it where rainwater easily penetrates.

Table 2 lists the coefficients of regression for each mechanical property and the logarithm of exposure period. In order to quantify regional differences, the deterioration rate (A) was calculated as follows:

$$y = -A \times \log(t) + B \tag{1}$$

where, y is the strength (i.e., MOR, IB, and LNR), t is the time of outdoor exposure in accumulated months, and B is the intercept. By comparing the value of A among exposure sites for each mechanical property, the degree of regional difference was calculated from the ratio of the maximum value to the minimum value, the results are as follows: MOR of PB(PF), 1.35 (9.00/6.69); MOR of PB(MDI), 1.73 (8.81/5.09); IB of PB(PF), 1.91 (0.44/0.23); IB of PB(MDI), 2.59 (0.75/0.29); edge part IB of PB(PF), 1.25 (0.45/0.36); LNR of PB(PF), 1.22 (0.77/0.63). The degree of regional difference for PB(PF) was less than that of PB(MDI). In terms of mechanical properties, MOR was less subject to regional differences than IB for each PB. The overall trend of deterioration behavior due to outdoor exposure depended on climate conditions, although the results show that this dependence was greater for some mechanical properties, IB of PB(MDI) and PB(PF).

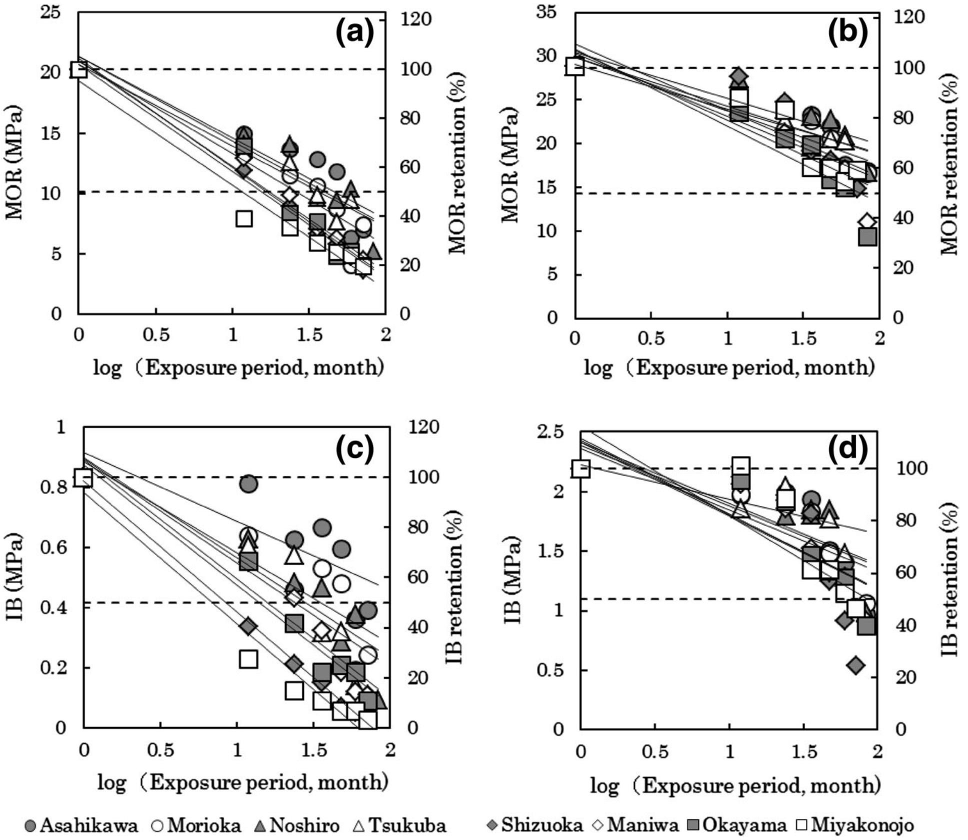

Fig. 3 Regional differences in the panel deterioration for 7 years outdoor exposure: **a** modulus of rupture (MOR) retentions for PB(PF), **b** MOR retentions for PB(MDI), **c** internal bond strength (IB) retentions for PB(PF), **d** IB retentions for PB(MDI). Straight lines indicate regression lines in each test site

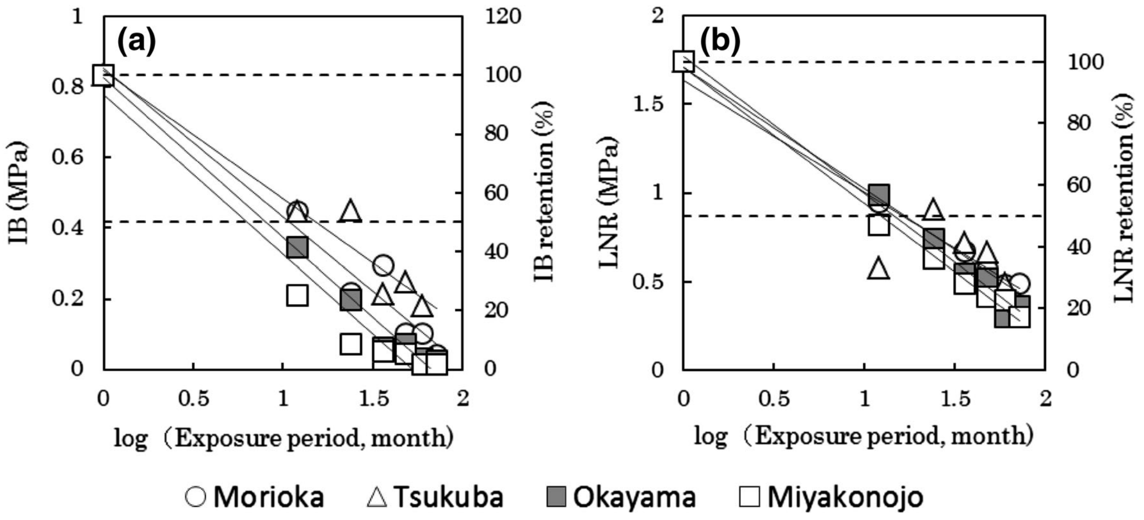

Fig. 4 Regional differences in the panel deterioration of PB(PF) for 6 years outdoor exposure: **a** IB retentions measured at positions including panel edges, **b** lateral nail resistance (LNR) retentions. Straight lines indicate regression lines in each test site

Correlation between weathering intensity (WI) and strength retention

If the WI corresponding to a deterioration factor in outdoor exposure was the same, the degree of deterioration of the mechanical properties of the PB would be similar at all sites. Based on this hypothesis, some attempts [15–17] have been made to find an appropriate method to calculate the WI by the use of factors such as precipitation, temperature, sunshine duration, and so on. Kojima et al. [15] found it the best method to use precipitation (P) multiplied by the temperature (T) during the period of outdoor exposure, i.e., $\sum(P \times T)$, as WI for the degradation of the MOR and IB of aspen-oriented strand board and PB(PF). Therefore, the same method was adopted in this study to calculate the WI for both types of PB: monthly precipitation (P_m) multiplied by monthly average temperature (T_m) at each test site was calculated during the period of outdoor exposure using data taken from the website of the Meteorological Agency in Japan [20].

Figure 5 shows the correlation between the logarithm of $\sum(P_m \times T_m)$ and the degradation behavior of IB for PB(PF) and PB(MDI): each point in Fig. 5a, b indicates data from an individual IB specimen. These points mingled and formed a correlation belt irrespective of their outdoor exposure site, which is different from the regionally separated degradation trend as shown in Fig. 3c, d.

Figure 5c shows the comparison between the IB retention of PB(PF) and that of PB(MDI): each point is an average of eleven sampling points on each specimen. The regression equations indicated in Fig. 5c can be used for discussing the difference in mechanical durability between PB(PF) and PB(MDI). The value of the WI that induced as much as 50 % of IB retention was calculated to be 5.35 and 4.70 for PB(MDI) and PB(PF), respectively, by the use of regression analysis. Since these values are logarithmic, the WI itself becomes 224 × 10^3 and 50 × 10^3. These results indicate that PB(MDI) was 4.5 times more durable than PB(PF): this implies that the mechanical durability of particleboards is dependent on manufacturing conditions such as the types of adhesive and the amount of additive used.

A similar analysis was conducted for the other mechanical properties. Table 3 lists the coefficients of regression calculated from the relationship between the retention of mechanical properties and the logarithm of $\sum(P_m \times T_m)$. The logarithm of WI that induced as much as 50 % of MOR retention was calculated to be 5.50 and 4.69 for PB(MDI) and PB(PF), respectively. These values were similar to that for IB. The WI itself becomes 316 × 10^3 and 49 × 10^3, respectively, which means that the durability of PB(MDI) with respect to MOR was about 6 times greater than that of PB(PF). Likewise, comparisons of durability among the mechanical properties of PB(PF) can be conducted as follows: the WI that reduced each mechanical property by half was 49 × 10^3 for MOR, 50 × 10^3 for IB, 20 × 10^3 for edge IB, and 23 × 10^3 for LNR. These results are quantification values of the durability of PB(PF). It was found that the IB and LNR measured at the panel edge were less durable than MOR and IB measured at the parts without panel edges since the panel edges were likely to be more affected by rainwater penetration than the panel surfaces.

Table 2 Regression equations and coefficient of correlation between the mechanical property and the logarithm of exposure periods ($y = -A \log(t) + B$, where t is the time of outdoor exposure in accumulated months)

Location	MOR		IB		Edge IB of PB(PF)	LNR of PB(PF)
	PB(PF)	PB(MDI)	PB(PF)	PB(MDI)		
Asahikawa						
A	6.72	5.62	0.23	0.50		
B	21.4	29.9	0.92	2.38		
r	0.908	0.888	0.794	0.762		
Morioka						
A	7.56	6.11	0.30	0.52	0.42	0.69
B	20.9	29.9	0.89	2.37	0.85	1.71
r	0.947	0.921	0.884	0.831	0.980	0.992
Noshiro						
A	6.97	5.30	0.33	0.51		
B	21.3	30.5	0.90	2.42		
r	0.935	0.856	0.913	0.745		
Tsukuba						
A	6.69	5.09	0.35	0.29	0.36	0.63
B	20.7	29.0	0.90	2.23	0.85	1.64
r	0.974	0.970	0.907	0.791	0.944	0.906
Shizuoka						
A	8.84	7.56	0.43	0.75		
B	20.7	31.4	0.82	2.55		
r	0.997	0.856	0.998	0.735		
Maniwa						
A	8.70	7.98	0.39	0.62		
B	21.0	30.6	0.89	2.41		
r	0.989	0.912	0.965	0.858		
Okayama						
A	9.00	8.81	0.40	0.62	0.45	0.77
B	21.2	30.8	0.88	2.43	0.83	1.77
r	0.978	0.910	0.973	0.837	0.995	0.994
Miyakonojo						
A	8.59	7.24	0.44	0.64	0.45	0.77
B	19.3	30.3	0.78	2.45	0.78	1.71
r	0.982	0.904	0.982	0.813	0.976	0.997

r coefficient of correlation, PB(PF), PB(MDI), MOR, LNR, IB, see Table 1

Analysis of three conventional climate indexes

Scheffer [21] proposed a climate index for estimating the potential for decay in wood structures above ground. Scheffer's climate index, *CI*, is defined by the following equation:

$$CI = \left(\sum (T_{\mathrm{m}} - 2)(D - 3)\right)/16.7 \tag{2}$$

where, T_{m} is the monthly average temperature (°C); *D*, the number of days in the month with 0.25 mm or more of precipitation.

The deterioration index, *DI*, originally proposed by Brooks and modified later by Kubo is defined by the following equation and it is considered to evaluate the degree of rust and rot [22]:

$$DI = \sum \left((H - 65)/10 \times 1.054^{T\mathrm{m}}\right) \tag{3}$$

where, T_{m} is the monthly average temperature (°C); *H*, the monthly average relative humidity (%).

The aridity index, *AI*, originally proposed as the soil climate by Lang and modified later by Martonne is defined by the following equation [22]:

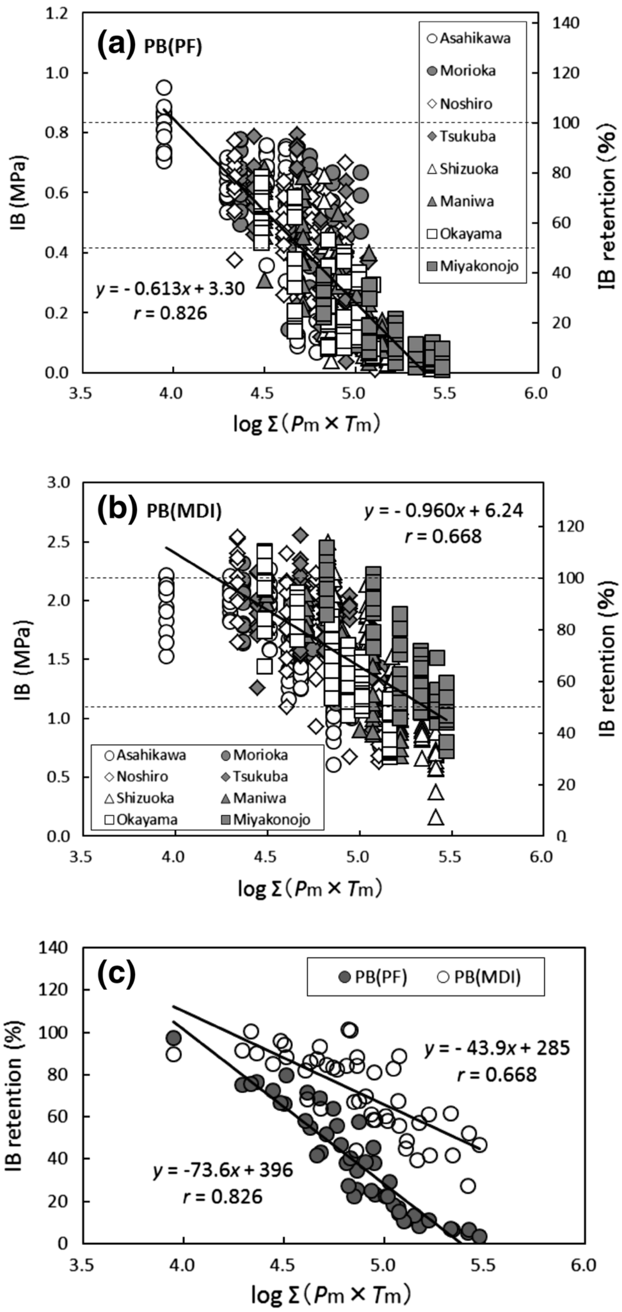

Fig. 5 Examples of relationships between deterioration in the panel mechanical property and the logarithm of weathering intensity (log $\sum(P_m \times T_m)$): **a** IB and its retention for PB(PF), **b** IB and its retention for PB(MDI), **c** comparison of IB retention between PB(PF) and PB (MDI)

Table 3 Regression equations and coefficient of correlation between the mechanical property retentions and the logarithm of weathering intensity ($\sum(P_m \times T_m)$)

	Mechanical property			
	MOR ($n = 374$)	IB ($n = 602$)	Edge IB ($n = 174$)	LNR ($n = 137$)
PB(PF)				
A'	−46.0	−73.6	−49.5	−29.8
B'	266	396	263	180
r	0.786	0.826	0.684	0.695
PB(MDI)				
A'	−31.3	−43.9		
B'	222	285		
r	0.675	0.668		

$y = A' \log(\sum P_m \times T_m) + B'$ where, y retention of mechanical property (%), P_m monthly precipitation (mm), T_m monthly average temperature (°C), r coefficient of correlation, PB(PF), PB(MDI), MOR, IB, LNR, see Table 1

$$AI = P_y / (T_a + 10) \tag{4}$$

where, P_y is the annual precipitation; T_a, accumulation of monthly average temperature above zero °C divided by 12 (°C).

Similar to the correlation analyses conducted in the previous section (Table 3), correlations between three types of conventional climate indexes and the retention of mechanical properties were investigated. The weather data for calculating *CI*, *DI*, and *AI* were taken from the website of the Meteorological Agency in Japan [20]. In addition, the scales of the x-axis were expanded to three types; not only the logarithm of WI but also its linear scale and square root. Therefore, this analysis used twelve ways (four types of WI multiplied by three types of x-axis) to investigate the best method for calculating the WI for particleboard deterioration. The method showing the highest correlation was considered to be best.

The results are listed in Table 4, the method showing the highest correlation among the twelve is highlighted in bold. Also, the best case for each WI was shown in Fig. 6 for MOR of PB(PF). It was found that for PB(PF) the logarithm of $\sum(P_m \times T_m)$ was best for three of the mechanical properties out of four. On the other hand, for PB(MDI), using $\sum CI$ and $\sum AI$ as the x-axis was found to be the most effective way to analyze the degradation of MOR and IB, respectively. Although the logarithm of $\sum(P_m \times T_m)$ was intermediate in the ranking list for PB(MDI), it may have the most potential practically since the weather data for monthly average precipitation and temperature is easy to collect worldwide, whereas recording the number of days with rainfall is more difficult, which is required for calculating *CI*.

Prediction of outdoor service life

We predict the outdoor service life of PB(PF) and PB(MDI) under various worldwide climate conditions on a hypothesis that the relationship shown in Fig. 6a is applicable in the

Table 4 Coefficients of regression equations and coefficients of correlation between the mechanical property retentions and the various weathering intensity (WI)

Board type	WI	*x* axis		Mechanical property			
				MOR ($n = 374$)	IB ($n = 602$)	Edge IB ($n = 174$)	LNR ($n = 137$)
PB(PF)	$P_m \times T_m$	$\log \sum(P_m \times T_m)$	A'', B''	−46.0, 266	−73.6, 396	−49.5, 263	−29.8, 180
			r	**0.786**	**0.826**	**0.684**	0.695
		$\sum(P_m \times T_m)$	A'', B''	-0.20×10^{-3}, 60.1	-0.30×10^{-3}, 67.0	-0.20×10^{-3}, 37.0	-0.10×10^{-3}, 45.0
			r	0.682	0.721	0.564	0.624
		$(\sum P_m \times T_m)^{1/2}$	A'', B''	−0.14, 81.9	−0.22, 102	−0.13, 59.1	−0.08, 58.4
			r	0.752	0.792	0.632	0.669
	DI	$\log \sum DI$	A'', B''	−24.9, 86.4	−35.9, 102	−13.9, 43.9	−12.6, 55.4
			r	0.434	0.411	0.238	0.362
		$\sum DI$	A'', B''	−0.18, 55.9	−0.27, 58.7	−0.10, 27.2	−0.09, 40.1
			r	0.445	0.437	0.233	0.346
		$(\sum DI)^{1/2}$	A'', B''	−3.01, 67.1	−4.43, 74.5	−1.68, 33.2	−1.49, 45.4
			r	0.447	0.430	0.238	0.352
	CI	$\log \sum CI$	A'', B''	−39.0, 129	−62.3, 177	−52.3, 101	−34.2, 113
			r	0.736	0.771	0.670	0.736
		$\sum CI$	A'', B''	−0.10, 64.2	−0.16, 72.3	−0.10, 43.7	−0.07, 50.6
			r	0.728	0.744	0.615	0.726
		$(\sum CI)^{1/2}$	A'', B''	−2.88, 82.7	−4.53, 102	−3.17, 67.3	−2.16, 66.0
			r	0.750	0.773	0.650	**0.742**
	AI	$\log \sum AI$	A'', B''	−51.3, 160	−74.9, 210	−49.4, 133	−32.0, 107
			r	0.717	0.682	0.629	0.681
		$\sum AI$	A'', B''	−0.10, 66.0	−0.15, 73.7	−0.09, 41.2	−0.06, 48.1
			r	0.678	0.657	0.572	0.645
		$(\sum AI)^{1/2}$	A'', B''	−3.18, 89.2	−4.72, 107	−3.00, 63.4	−1.98, 62.5
			r	0.706	0.677	0.607	0.671
PB(MDI)	$P_m \times T_m$	$\log \sum(P_m \times T_m)$	A'', B''	−31.3, 222	−43.9, 285		
			r	0.675	0.668		
		$\sum(P_m \times T_m)$	A'', B''	-0.10×10^{-3}, 82.9	-0.20×10^{-3}, 91.6		
			r	0.630	0.663		
		$(\sum P_m \times T_m)^{1/2}$	A'', B''	−0.10, 97.9	−0.14, 113		
			r	0.672	0.686		
	DI	$\log \sum DI$	A'', B''	−19.3, 104	−33.7, 132		
			r	0.429	0.530		
		$\sum DI$	A'', B''	−0.15, 81.0	−0.25, 91.1		
			r	0.475	0.577		
		$(\sum DI)^{1/2}$	A'', B''	−2.41, 89.6	−4.16, 106		
			r	0.460	0.563		
	CI	$\log \sum CI$	A'', B''	−28.4, 133	−38.6, 158		
			r	0.673	0.646		
		$\sum CI$	A'', B''	−0.08, 87.1	−0.11, 96.6		
			r	**0.734**	0.739		
		$(\sum CI)^{1/2}$	A'', B''	−2.19, 101	−3.06, 115		
			r	0.726	0.714		
	AI	$\log \sum AI$	A'', B''	−37.6, 160	−58.4, 206		
			r	0.670	0.736		
		$\sum AI$	A'', B''	−0.08, 88.0	−0.13, 102		
			r	0.665	**0.766**		
		$(\sum AI)^{1/2}$	A'', B''	−2.37, 105	−3.78, 128		
			r	0.677	0.762		

$y = A'' \log(\sum \mathrm{WI}) + B''$ or $y = A''\sum \mathrm{WI} + B''$ or $y = A''(\sum \mathrm{WI})^{1/2} + B''$ where, *y* retention of mechanical property (%), *r* coefficient of correlation, PB(PF), PB(MDI), MOR, IB, LNR, see Table 1

Numbers in bold show the highest *r* among the twelve calculation ways

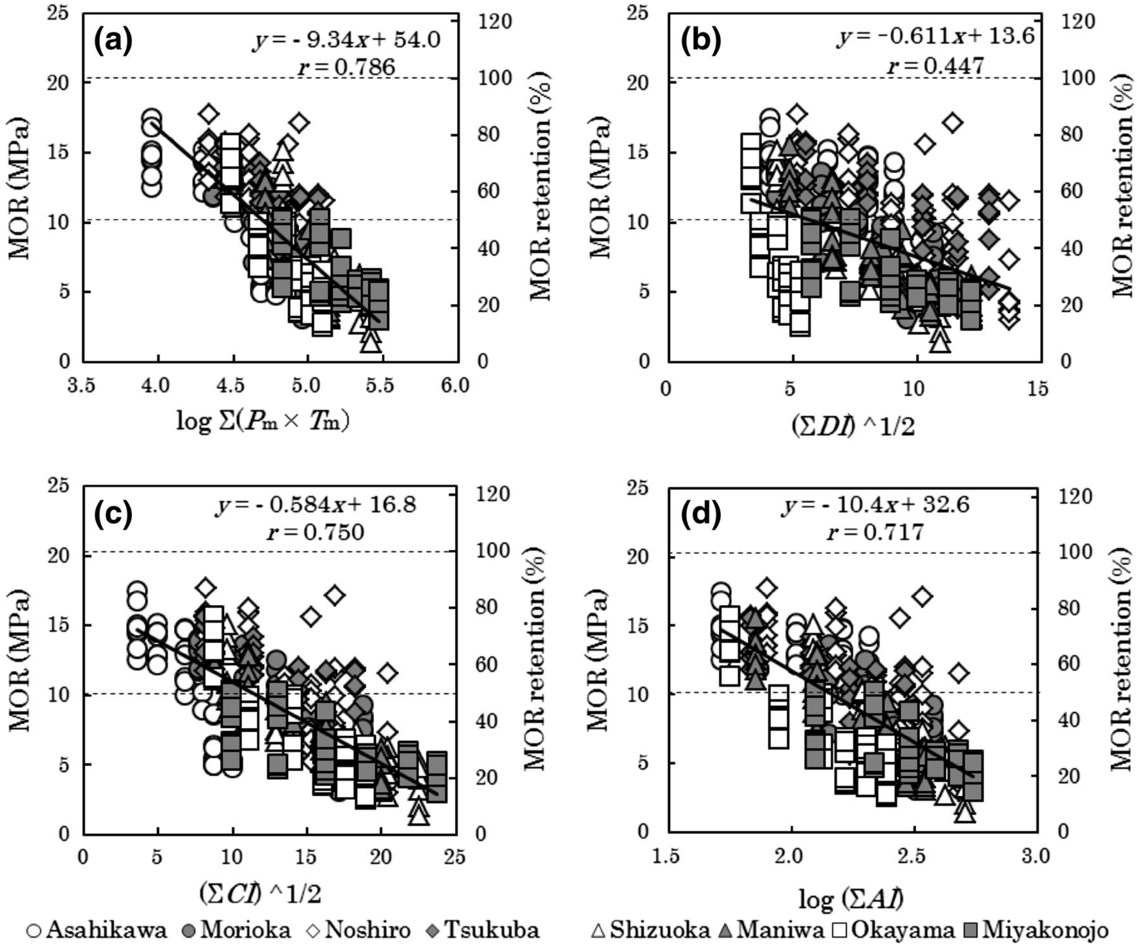

Fig. 6 Comparison of deterioration predicting accuracy among four types of WI for MOR of PB(PF): **a** $P_m \times T_m$, **b** *DI*, **c** *CI*, **d** *AI*

world outside Japan. In this study the service life in outdoor exposure is defined as the half-value period of initial MOR (Y_{MOR50}). The prediction for PB(PF) was conducted using the regression analysis with an x-axis of log $\sum(P_m \times T_m)$ listed in Table 4. Although PB(MDI) showed the best correlation when ΣCI was used as x-axis, it is not easy to calculate *CI* for each site as discussed above. Therefore, the prediction for PB(MDI) was conducted using the regression analysis with an x-axis of log$\sum(P_m \times T_m)$ similar to PB(PF).

From the regression analysis, the log$\Sigma(P_m \times T_m)$, which corresponds to 50 % of MOR retention, is calculated to be 4.70 and 5.50 for PB(PF) and PB(MDI), respectively. Then, the WI_{MOR50} that stands for the value of $\Sigma(P_m \times T_m)$ becomes 5.01×10^4 and 31.6×10^4 for PB(PF) and PB(MDI), respectively. Fifteen sites around the world were selected as shown in Fig. 7; some of these sites are well known as standard sites for testing the weathering resistance of building materials and paint. The procedure for obtaining the Y_{MOR50} at each site is as follows. First, an annual $\Sigma(P_m \times T_m)$, accumulated from January to December was obtained by the use of the mean P_m and the mean T_m through the past thirty years from 1981 to 2010. Then, Y_{MOR50}, was calculated by dividing WI_{MOR50} by the annual $\Sigma(P_m \times T_m)$ of each site, and the results are listed in Table 5. For reference, the values of Y_{MOR50} at the eight test sites in Japan were calculated in the same way, and the results are listed in Table 6.

It was found that the outdoor service life differed by 10–13 times among the fifteen sites chosen in this study. Focusing on PB(PF), the MOR will reduce by half in around one year at humid sites such as Singapore and Miami, whereas, the same reduction will take ten years at dry sites such as Santiago. Also, the results indicate that PB(MDI) was about 6 times more durable than PB(PF), this again implies that the mechanical durability of particleboards depends on manufacturing conditions such as types of adhesive and amounts of additive used.

Conclusions

The durability of two types of particleboard, PB(PF) and PB(MDI) with different water resistances, were discussed

Fig. 7 Several sites worldwide and their climatic conditions (annual average temperature and annual precipitation) selected for prediction of outdoor service life

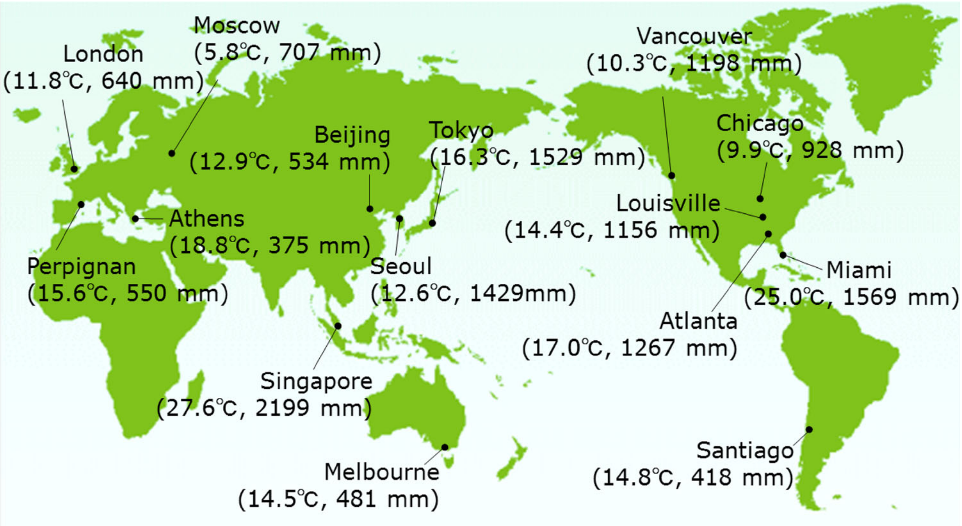

Table 5 Predicted outdoor exposure periods (Y_{MOR50}) that reduces the panel MOR by half

Sites	Annual $\sum(P_m \times T_m)$	Y_{MOR50} (year)	
		PB(PF)	PB(MDI)
Singapore	6.03×10^4	0.8	5.2
Miami	4.17×10^4	1.2	7.6
Seoul	2.93×10^4	1.7	10.8
Tokyo	2.88×10^4	1.7	11.0
Atlanta	2.16×10^4	2.3	14.6
Louisville	1.68×10^4	2.9	18.8
Beijing	1.22×10^4	4.1	25.9
Chicago	1.18×10^4	4.2	26.7
Vancouver	0.97×10^4	5.1	32.7
Perpignan	0.77×10^4	6.5	41.1
London	0.75×10^4	6.6	42.2
Melbourne	0.71×10^4	7.0	44.3
Moscow	0.64×10^4	7.7	49.0
Athens	0.57×10^4	8.7	55.3
Santiago	0.48×10^4	10.3	65.8

Table 6 Predicted outdoor exposure periods (Y_{MOR50}) that reduces the panel MOR by half for the eight test sites in Japan

Sites	Annual $\sum(P_m \times T_m)$	Y_{MOR50} (year)	
		PB(PF)	PB(MDI)
Asahikawa	1.04×10^4	4.8	30.5
Morioka	1.75×10^4	2.8	18.1
Noshiro	1.81×10^4	2.7	17.4
Tsukuba	2.11×10^4	2.4	15.0
Shizuoka	4.42×10^4	1.1	7.1
Maniwa	2.41×10^4	2.1	13.1
Okayama	2.14×10^4	2.3	14.8
Miyakonojo	5.00×10^4	1.0	6.3

by analyzing the results of outdoor exposure tests conducted at eight sites in Japan. First, differences in deterioration rates among test sites were quantified using the slope of regression analysis, and the results showed that the maximum regional difference lay between 1.2 and 1.9 times for PB(PF) and 1.2 and 2.6 times for PB(MDI), depending on the mechanical property.

The weathering intensity defined by monthly precipitation multiplied by monthly average temperature, $\Sigma(P_m \times T_m)$, was found to be significant in the standardization of a deterioration factor of the board exposed to varying climate conditions. Regression analysis between the logarithm of $\Sigma(P_m \times T_m)$ and the mechanical properties retained clarified that $\Sigma(P_m \times T_m)$ was a useful term to explain the differences in mechanical durability of particleboard with different water resistances.

Three conventional climate indexes, *CI*, *DI*, and *AI*, were investigated for their significance to WI through a regression analysis with three different scales of *x*-axis. It was found that for PB(PF) the logarithm of $\Sigma(P_m \times T_m)$ was best type of analysis for three out of the four mechanical properties, whereas, for PB(MDI) the logarithm of $\Sigma(P_m \times T_m)$ was intermediate in the ranking list of correlation coefficients. Furthermore, by the use of WI of $\Sigma(P_m \times T_m)$, the exposure period that reduces initial MOR by half was calculated for several sites worldwide. These results can be used to calculate the shortest service life for each site. Furthermore, the actual service life of particleboards could be predicted if the deterioration factors under practical environments are standardized in a similar way to those conducted in this study.

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