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ORIGINAL ARTICLE

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Evaluation of the weathering intensity of wood-based panels under outdoor exposure

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Abstract In this study, the deterioration of wood-based panels at eight sites in Japan was investigated using outdoor exposure tests. In particular, the modulus of rupture (MOR) retention and internal bond strength (IB) retention after 5-year exposures were compared among panels and sites. The deterioration of panels located in southern Japan was higher than that of panels in northern Japan. To quantify the regional differences, the deterioration rates were calculated; the values showed clear regional differences. The deterioration rate for areas that receive much rain in the summer was higher than the rates for other sites. To eliminate regional differences, we carried out an analysis in terms of the "weathering intensity," a factor which combines weather conditions (precipitation and temperature). Panels for which deterioration progressed extensively during exposure periods showed a strong correlation between strength retention and the weathering intensity. The significance of these parameters is discussed.

Key words Wood-based panel · Outdoor exposure · Weathering intensity · Deterioration rate · Weather condition

Introduction

Plywood is a typical wood-based material used in residential construction in Japan. It is superior to other wood-based panels in terms of strength and dimensional stability. On the other hand, 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, basic information on long-term durability of wood-based panels is necessary. An estimation of how long a panel can maintain the required performance under actual environmental conditions has been the goal of many studies evaluating the durability of wood-based materials.

To evaluate the durability of such panels, outdoor exposure tests at eight sites in Japan using commercial wood-based panels have been conducted by the Research Working Group on Wood-based Panels of the Japan Research Society since 2004. In our previous reports, the results [thickness swelling,[1] internal bond strength (IB),[2] and bending properties[3]] of 5 years of exposure in Shizuoka City were discussed, along with accelerated aging treatment results. Because outdoor exposure tests are considered an accelerated aging test, based on the natural environmental conditions, the deterioration mechanism was thought to be similar to the deterioration that occurs when wood-based panels are actually used in housing construction. Many researchers have conducted outdoor exposure tests using wood-based panels.[4–8] In Japan, several studies on outdoor exposure tests using veneer-based samples have been reported.[9–11] Ten-year test results on wood-based panels were reported by Sekino and Suzuki.[12] Several other studies on the durability of mat-formed panels have also been published.[13–16]

Outdoor exposure tests have many disadvantages. One of the greatest is that results are limited by the test location.[17] Even when outdoor exposure tests use the same panels at all locations, there are differences in the deterioration of panels among the locations. Thus, the results of outdoor exposure tests conducted at specific sites are not applicable to sites with different weather conditions.

In this study, regional differences in the deterioration of panels are discussed. The deterioration rate of each panel was defined to compare test results. The deterioration rates were calculated using relationships between strength retention and the outdoor exposure period. Furthermore, we attempted to eliminate regional differences in the deterioration of panels by defining the "weathering intensity," based on weather parameters. The weathering intensity was defined as a weather-based force exerted on the panels during outdoor exposure tests. In this report, average daily temperatures and daily precipitation were selected as the weather parameters, and the weathering intensity was calculated to eliminate regional differences. The relationships

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Table 1. Specifications of the tested commercial panels and the modulus of rupture (MOR) and internal bond strength (IB) for control samples

Board type	Adhesive	Thickness (mm)	Density (g/cm^3)	Construction	MOR[a] (MPa)	IB[a] (MPa)
PB(PF)	PF	12.2	0.76	Three layer	21.6 ± 3.5	0.66 ± 0.08
PB(MDI)	MDI	12.1	0.80		29.7 ± 2.4	1.97 ± 0.17
MDF(MUF)	MUF	12.2	0.76	Homogeneous	44.9 ± 3.0	0.57 ± 0.07
MDF(MDI)	MDI	9.1	0.72		33.8 ± 1.4	1.03 ± 0.11
OSB(aspen)	PF	12.4	0.64	Three layer cross-oriented	37.7 ± 8.9	0.38 ± 0.12
OSB(pine)		11.8	0.68		36.0 ± 6.9	0.63 ± 0.20
PW(12)		12.0	0.64	Five ply	49.3 ± 13.4	1.11 ± 0.38
PW(9)		8.8	0.61	Three ply	71.8 ± 13.1	1.42 ± 0.37

[a] Data are given as means ± standard deviation

PB, particleboard; PF, phenol-formaldehyde; MDI, methyl diphenyl diisocyanate; MDF, medium-density fiberboard; MUF, melamine-urea-formaldehyde; OSB, oriented strandboard; PW, plywood

between the weathering intensity and the deterioration of the panels during 5-year outdoor exposure tests are discussed.

Materials and methods

Sample panels

The four groups of commercial wood-based panels used in this research – particleboard (PB), medium-density fiberboard (MDF), oriented strandboard (OSB), and plywood (PW) – are widely used for construction in Japan (Table 1). Each panel group included two panel types of differing specifications to give eight panels in all. 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 were made from imported products with different wood species. The PW 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 produces very little methyl diphenyl diisocyanate (MDI)-bonded PB or MDF, MDI-bonded PB and MDF were selected because manufacturers in Japan show a strong preference for PB and MDF with high durability performance. The parallel direction on each panel surface was defined by the machine direction for PB and MDF, surface strand alignment for OSB, and surface veneer grain direction for PW. The mechanical properties, i.e., internal bond strength (IB) and modulus of rupture (MOR), of the commercially manufactured panels were measured before aging treatment and are summarized in Table 1.

Outdoor exposure tests at eight sites in Japan

Fig. 1. Map of outdoor exposure test sites in Japan

For each panel type, 12 test sample boards, each 300 mm × 300 mm, were subjected to the outdoor exposure test at eight sites in Japan (Fig. 1): Asahikawa (43°N, 142°E), Morioka (39°N, 141°E), Noshiro (40°N, 140°E), Tsukuba (36°N, 140°E), Shizuoka (34°N, 138°E), Okayama (South; 34°N, 133°E), Okayama (North; 35°N, 133°E), and Miyakonojo (31°N, 131°E). Annual average temperatures, annual precipitation, and climate classifications are listed in Table 2. Monthly average temperatures and monthly precipitation for 5 years are shown in Fig. 2. All four edges of the sample boards were coated with a protective agent to prevent excessive edge swelling due to water contact during exposure. The boards were set vertically on a test frame that faced south. The outdoor tests began in March 2004 and will run until 2013. In this article, the results of 5 years of exposure are discussed. Two test sample boards of each type of panel were removed after 1, 2, 3, 4, and 5 years of exposure, and their IB and bending properties were measured after reconditioning at 20°C and 65% relative humidity (RH) for 2 weeks. Eight bending samples with a dimension of 250 mm × 50 mm and thirteen IB test samples (50 mm × 50 mm) were prepared from the reconditioned samples. The bending and IB tests were performed in accordance with JIS A-5908[18] and were conducted using a universal testing machine (Model TCM-1000, Shinkoh).

Table 2. Weather conditions and climate classifications for the eight sites

Location	Annual average temperature[a] (°C)	Annual precipitation[a] (mm)	Classification
Asahikawa	6.4	1091	Low temp. / low prec.
Morioka	9.8	1265	
Noshiro	11.1	1746	Low temp. / middle prec.
Tsukuba	13.2	1308	Middle temp. / low prec.
Okayama (N)	13.7	1398	
Shizuoka	16.1	2327	Middle temp. / high prec.
Okayama (S)	20.3	1160	High temp. / low prec.
Miyakonojo	21.9	2435	High temp. / high prec.

[a] Data are average values of the past 30 years

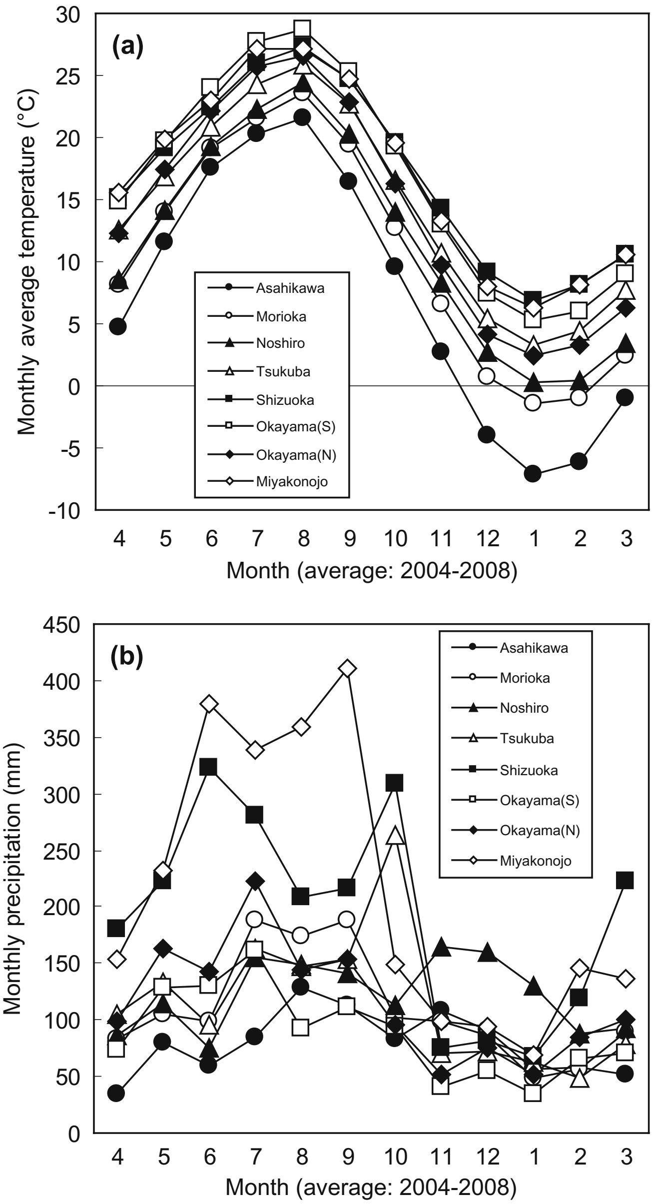

Fig. 2. Climate conditions for the eight sites: **a** monthly average temperature, **b** monthly precipitation. The *numbers* on the x-axis represent the months of the year

Results and discussion

Characteristics of MOR and IB retention in the outdoor exposure tests at eight sites

The MOR and IB for the control samples (untreated) are shown in Table 1. In this article, the strength retentions are defined as follows:

MOR retention (%) = (MOR after outdoor exposure / MOR for control samples) × 100

IB retention (%) = (IB after outdoor exposure / IB for control samples) × 100

Figures 3 and 4 show the changes in the strength retentions for 5-year outdoor exposure tests in eight regions. If the strength retention was greater than 100%, we deemed it to be 100% retention.

Figure 3 shows that the MOR retentions of the two particleboards decreased linearly at all exposure sites. The decrease of phenol-formaldehyde (PF)-bonded particleboard [PB(PF)] was higher than that of methylene diphenyl diisocyanate (MDI)-bonded particleboard [PB(MDI)], and MOR retention of PB(PF) was less than 50% after 2-year exposure at four sites. On the other hand, MOR retention of PB(MDI) was less than 50% after 5-year exposure at only two sites [Okayama (South) and Miyakonojo]. MDFs maintained comparatively high MOR retentions at all sites for 5 years. The MOR retentions of oriented strandboard made from aspen [OSB(aspen)] in Shizuoka and Miyakonojo were less than 50% after only 1-year exposure and were only 10% after 5-year exposure. For OSB(aspen), there were two patterns of decreasing MOR retention: (1) linearly decreasing sites in Northern Japan, i.e., Asahikawa, Morioka, Noshiro, and Tsukuba, and (2) exponentially decreasing sites in Southern Japan, i.e., Shizuoka, Okayama (South), Okayama (North), and Miyakonojo. The MOR retention of oriented strandboard made from pine [OSB(pine)] tended to decrease linearly for all regions. The variation among plywoods was large, so any characteristic tendencies were unclear.

The IB retentions are shown in Fig. 4. The decrease of PB(PF) was higher than that of PB(MDI). For PB(PF), the retentions at Shizuoka and Miyakonojo were less than 50% after 1-year exposure, and all sites located in Southern Japan had 50% retentions or less after 2-year exposure. Moreover, the retentions in Shizuoka, Okayama (North),

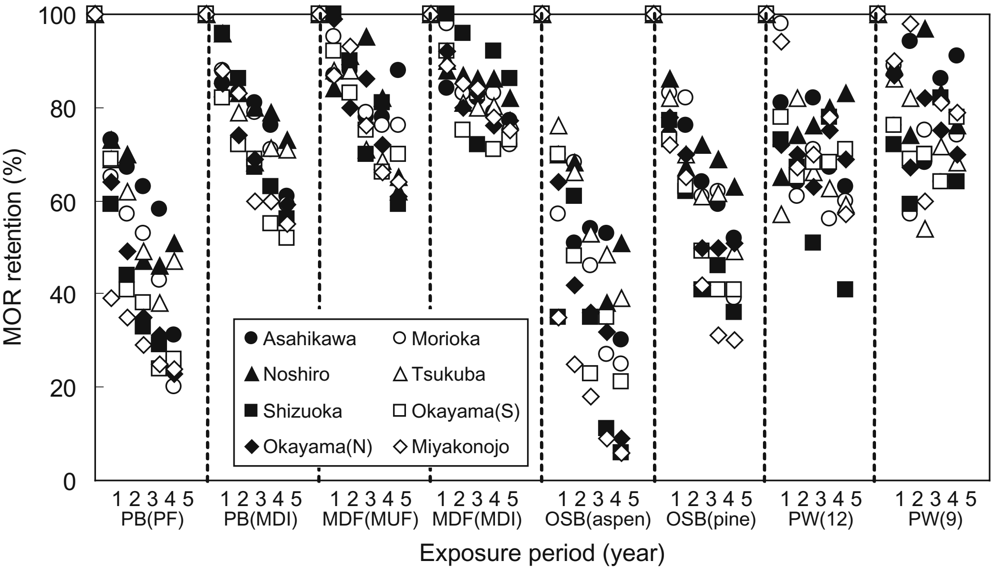

Fig. 3. Modulus of rupture (*MOR*) retentions for 5-year outdoor exposure tests at eight sites. *PB*, particleboard; *PF*, phenol-formaldehyde; *MDI*, methyl diphenyl diisocyanate; *MDF*, medium-density fiberboard; *MUF*, melamine-urea-formaldehyde; *OSB*, oriented strandboard; *PW*, plywood

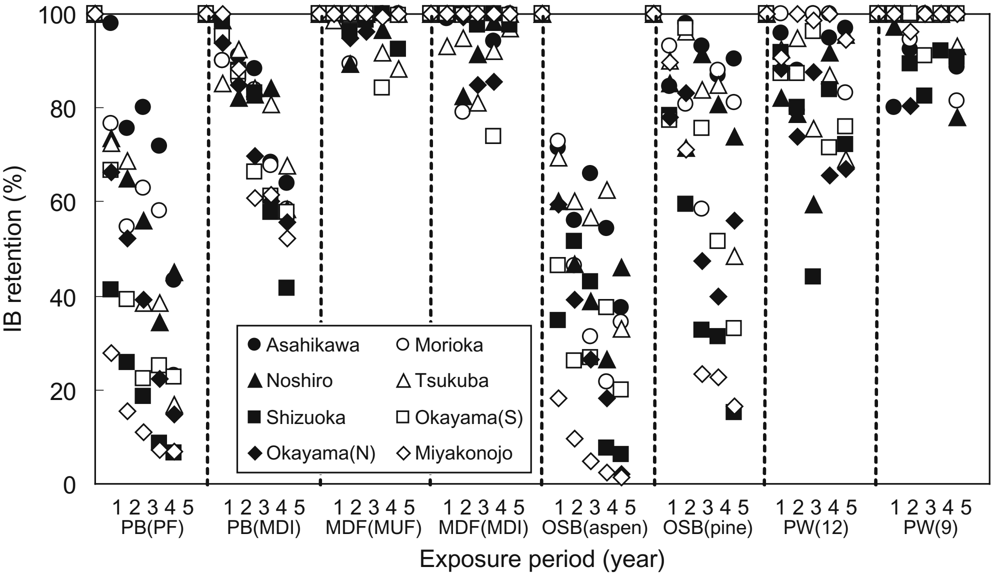

Fig. 4. Internal bond strength (*IB*) retentions for 5-year outdoor exposure tests at eight sites

and Miyakonojo were less than 10% after 5-year exposure. MDFs maintained high IB retentions at all sites. For OSB(aspen), similar to the pattern for MOR retentions, decreasing IB retention exhibited two patterns: (1) linearly decreasing sites in Northern Japan, and (2) exponentially decreasing sites in Southern Japan. For OSB(pine), the decrease in retention was high. The retentions of the panels located in Southern Japan were less than 50% after 4-year exposure. For plywoods, because the variation in retention was large, no trend could be identified.

Based on these results, there were large differences in deterioration among the eight panels because of the different elements and resins used in each panel type. Moreover, regional differences were evident and were caused by weather conditions (precipitation, temperature). In particular, the deterioration of panels located in areas that receive much rain in the summer, i.e., Shizuoka and Miyakonojo, was larger than that at the other sites.

Calculation of the deterioration rate

The deterioration of the panels varied among exposure sites (Figs. 3, 4); this was caused by the different weather conditions (precipitation, temperature). To quantify regional differences, the deterioration rate (A) was calculated as follows:

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

where y is the strength retention, t is the number of months of outdoor exposure, and B is the intercept. Using this equation, the coefficient A was determined by linear regression analysis, and the results are shown in Fig. 5 (MOR retention) and Fig. 6 (IB retention). Also shown in the figures are the average deterioration rates for the eight sites. For all panels, the deterioration rates for Shizuoka, Okayama (South), Okayama (North), and Miyakonojo were high, and the rates for Asahikawa and Noshiro were

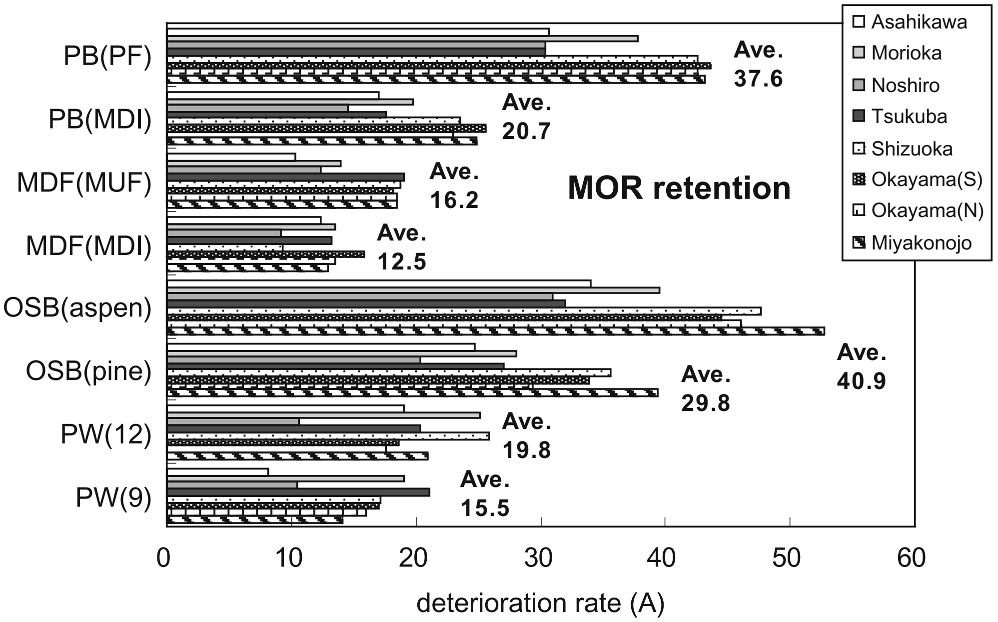

Fig. 5. The deterioration rate of MOR retention. The data shown in Fig. 3 were fitted to the equation $y = -A \times \log(t) + B$ and coefficient A was determined by linear regression analysis. *Ave*, average value for eight sites

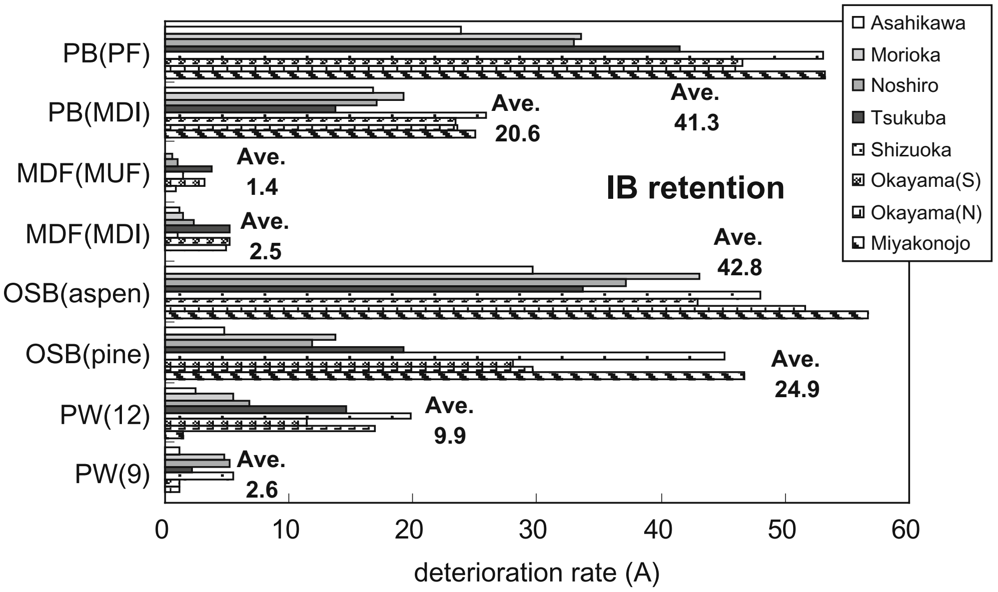

Fig. 6. The deterioration rate of IB retention. The data shown in Fig. 4 were fitted to the equation $y = -A \times \log(t) + B$ and coefficient A was determined by linear regression analysis. *Ave*, average value for eight sites

low (Fig. 5). Additionally, the average deterioration rates were in the order OSB > PB > PW > MDF, and the deterioration rates were different for the eight sites. In particular, the rates for panels located in Southern Japan were higher than those located in Northern Japan. The IB retentions (Fig. 6) showed the same tendency as the MOR retentions. Except for PB(PF) and OSB(aspen), the deterioration rates for IB retention were lower than those for MOR retention. This means that the surface of each panel began to deteriorate, but the deterioration did not penetrate the interior of the panels. On the other hand, for PB(PF) and OSB(aspen), the deterioration penetrated into the panels on 5-year exposure; thus, there was no difference between the deterioration of MOR retention and IB retention.

Analysis of the weathering intensity

It was clear that the deterioration of the panels due to outdoor exposure depended on the weather conditions at the exposure sites. Even if the deterioration rate is known for a specific area, it is not applicable to sites that have different weather conditions. This fact is considered a weak point of outdoor exposure tests. Thus, we introduced the "weathering intensity," which combined weather conditions in an attempt to eliminate regional differences. Generally, linear relationships existed between the strength retentions and the logarithm of exposure periods, and the slopes (deterioration rates) were affected by weather conditions (Figs. 5, 6). However, if the weathering intensity exerted on the panels was the same, the strength deterioration would be

Table 3. Parameter combinations showing the highest correlations for the eight panels

	MOR retention			IB retention		
	P_{max}(mm)	T_{min}(°C)	R	P_{max}(mm)	T_{min}(°C)	R
PB(PF)	20.0	17.5	0.858	No limit	17.5	0.930
PB(MDI)	20.0	15.0	0.761	20.0	15.0	0.743
MDF(MUF)	20.0	15.0	0.677	20.0	20.0	0.171
MDF(MDI)	20.0	15.0	0.424	20.0	20.0	0.064
OSB(aspen)	No limit	17.5	0.808	No limit	17.5	0.822
OSB(pine)	20.0	15.0	0.812	No limit	17.5	0.762
PW(12)	20.0	15.0	0.346	20.0	17.5	0.301
PW(9)	20.0	17.5	0.307	40.0	25.0	0.327

P_{max}, maximum precipitation; T_{min}, minimum temperature; R, coefficient of correlation

similar at all sites. Thus, by calculating the weathering intensity, an estimation of deterioration over the entire globe will be possible. In this report, daily precipitation and daily average temperatures were used to calculate the weathering intensity, as described below.

Daily precipitation (P) and daily average temperature (T) data at each exposure site for 5 years were taken from the website of the Meteorological Agency in Japan.[19] P multiplied by T was defined as the daily weathering intensity. The weathering intensity of each site (α) was calculated by summing the daily weathering intensity for 1-, 2-, 3-, 4-, and 5-year exposures. When the weathering intensity was calculated, we established two hypotheses:

(1) Even during periods of hard rain, not all rain was absorbed by the panels or contributed to deterioration. Thus, a maximum value of panel absorption of daily precipitation was set, and is referred to as P_{max}. That is, the daily precipitation of $P > P_{max}$ was defined as $P = P_{max}$, and the daily precipitation of $P < P_{max}$ was defined as $P = P$. P_{max} was set at six levels: 20, 40, 60, 80, and 100 mm, and no limit.

(2) Higher temperatures caused the panels to absorb water more quickly and also accelerated the drying rate. Thus, higher temperatures increased the deterioration due to panel water absorption. Precipitation below a certain temperature did not contribute to the weathering intensity. Thus, a minimum temperature was set, and is referred to as T_{min}, i.e., the daily precipitation at $T < T_{min}$ was defined as $P = 0$ mm, and the daily precipitation at $T > T_{min}$ was defined as $P = P$. T_{min} was set at five levels: 15.0, 17.5, 20.0, 22.5, and 25.0°C.

Based on the two hypotheses, the weathering intensity (α) was calculated as:

$$\alpha = \sum (P \times T)$$

where P and T are the restricted daily precipitation (mm) and the restricted daily average temperature (°C), respectively. Using this equation, the weathering intensity (α) was calculated for 30 levels that combined P_{max} (6 levels) and T_{min} (5 levels). Then, the logarithm of the weathering intensity ($\log\alpha$) and strength retentions of eight sites were subjected to linear regression analysis. The values of the parameters (P_{max} and T_{min}) with the highest coefficients of correlation are discussed.

Table 3 shows the parameter combinations with the highest coefficients of correlation for the eight panel types for MOR retention and IB retention. For PB(PF), the coefficients of correlation (R) were the highest among all panels for both MOR and IB retentions. Figures 7 and 8 show the relationship between strength retention and the logarithm of the weathering intensity ($\log\alpha$) for PB(PF). The values of T_{min} were the same for MOR and IB retentions (Table 3), but the value of P_{max} for IB retention was no limit, which was higher than that for MOR retention (20.0 mm). This means that IB is an indicator of the condition of the interior of the panels, and the deterioration of the interior of the panels requires a large amount of precipitation at one time. On the other hand, because the bending properties relate to the deterioration of the surface of the panels, less precipitation was required to progress surface deterioration. For both kinds of OSB, the deterioration was quite extensive at all sites after 5-year exposure. In particular, the deterioration of OSB(aspen) was the greatest (Figs. 3, 4) and the correlations for MOR and IB retentions were very high. For PB(PF) and OSB(aspen), the deteriorations were greater than those of the other panels, and the values of the coefficient of correlation between strength retentions and the logarithm of the weathering intensity were high. On the other hand, MDFs and PWs (for which deterioration had not progressed greatly after 5-year exposure) did not show decreased strength retention. Because the correlations between $\log\alpha$ and strength retentions were low for MDFs and PWs, it is difficult to discuss the significance of these parameters for the weathering intensity. For panels that deteriorated to some degree during the exposure periods, the correlations between the strength retentions and the logarithm of the weathering intensity were high, and the significance of the parameters can be discussed. However, for the panels that did not deteriorate greatly during the exposure periods, the correlations were lower, and the significance of the parameters cannot be discussed.

Conclusions

In this report, panel deterioration during outdoor exposure tests at eight sites in Japan was discussed. First, we discussed the characteristics of MOR and IB retentions in outdoor exposure tests at eight sites. Regional differences were

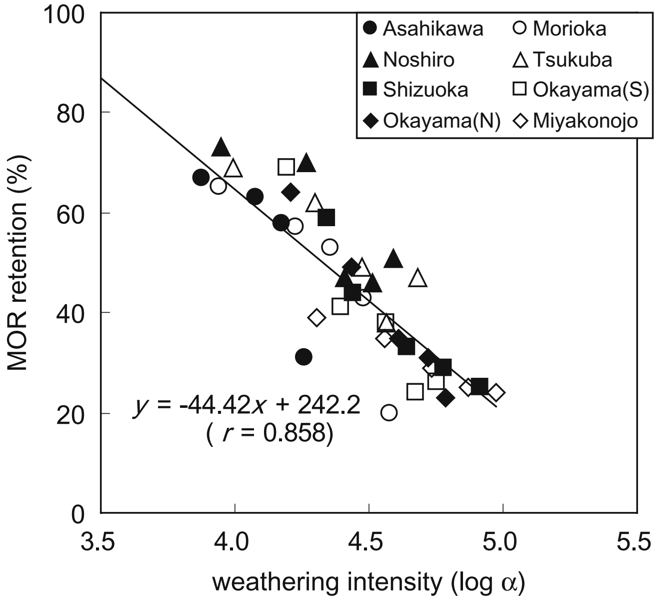

Fig. 7. Relationship between the MOR retentions and the weathering intensity (logα) for PB(PF). Conditions: P_{max}, 20 mm; T_{min}, 17.5°C

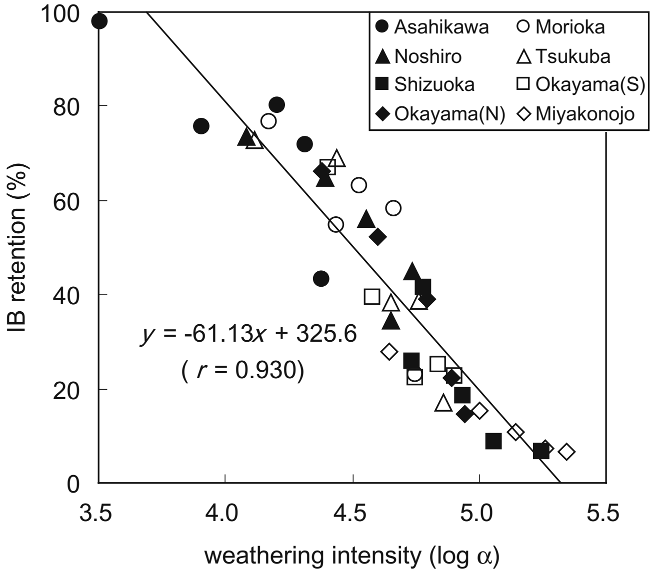

Fig. 8. Relationship between the IB retentions and the weathering intensity (logα) for PB(PF). Conditions: P_{max}, no limit; T_{min}, 17.5°C

clearly evident. In particular, the deterioration of panels located in areas that receive much rain in the summer was larger than that at the other sites. Next, we discussed the deterioration rate during outdoor exposure. The deterioration rates of the panels differed among the eight sites. In particular, the deterioration rates for panels located in southern Japan were higher than those located in northern Japan. Finally, we calculated the weathering intensity using temperature and precipitation levels to eliminate regional differences. The correlations between the strength retentions and the logarithm of the weathering intensity were high for panels that deteriorated to some degree during exposure.

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