

Effectiveness of principal component analysis for analyzing particleboard subjected to outdoor exposure

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Abstract In order to investigate the strength reduction of particleboards subjected to outdoor exposure at eight sites across Japan, the climate factors, i.e., temperature, sunshine duration, and precipitation were analyzed using a principal component analysis. The first principal component (PC1) had an eigenvalue of 2.31 and a proportion of 76.9 %, indicating that the PC1 combines the climate factors into one factor. All of the PC1 eigenvectors demonstrated high, positive values for each climate factor, demonstrating that the first principal component score (PC1 score) increases with increasing temperature, sunshine duration, and precipitation. The PC1 score was introduced as a new index for evaluating strength reduction, as the strength shows a strong correlation with the PC1 score: a higher PC1 score was linked to lower particleboard strength after the outdoor exposure test. The PC1 score can be calculated directly and unambiguously using the climate factors; further, the PC1 score was found to be a more powerful index than each individual climate factors or a combination of them.

Keywords Particleboard · Outdoor exposure · Principal component analysis · Principal component score · Climate index

Introduction

In general, particleboards are used only indoors rather than outdoors. In order to increase the demand for

particleboards, it is expected to find outdoor uses for them. Thus, basic data regarding their outdoor use are needed. Outdoor exposure tests on particleboards have been primarily conducted within North America [1–3]. However, in Japan particleboards have rarely been examined [4]. Therefore, an outdoor exposure test was conducted on particleboards at eight sites in Japan, namely, Asahikawa, Morioka, Noshiro, Tsukuba, Shizuoka, Okayama, Maniwa, and Miyakonojo (Table 1) [5]. The climate at these sites is representative of the Japanese climate.

With regard to the influence of climate factors on the strength reduction of particleboards, Kojima et al. reported that temperature (cumulative temperature: ΣT) and precipitation (ΣP) are important factors in reducing the strength of particleboards subjected to outdoor exposure [6]. Additionally, they demonstrated that the sunshine duration (ΣS) had a high correlation with reducing strength [6]. Owing to the correlation between these climate factors, a comprehensive evaluation of climate factors on board strength reduction becomes a complex affair. Thus, in this study the three factors (temperature, precipitation, and sunshine duration) were combined into a first principal component (PC1) through principal component analysis to analyze climate factors in a simple manner. The relationship between the PC1 score and strength after outdoor exposure test was then determined, and the PC1 score was effective for analyzing particleboard subjected to outdoor exposure.

Materials and methods

Outdoor exposure and strength tests

In this study, commercially available phenol–formaldehyde resin-bonded particleboards were used. For the strength

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Table 1 Sites, latitude, longitude, and climate factors from April 2004 to March 2009, and PC1 score at the eight sites

Site no.	Site	North latitude (°)	East longitude (°)	Climate factor									PC1 score
				<i>T</i>			<i>S</i>			<i>P</i>			
				Mean (°C)	SD (°C)	COV (%)	Mean (h)	SD (h)	COV (%)	Mean (mm)	SD (mm)	COV (%)	
1	Asahikawa	43	142	7.2	0.31	4.2	1598	76.2	4.77	946	91.2	9.65	-2.37
2	Noshiro	40	140	11.5	0.23	2.0	1444	126.0	8.72	1470	193.4	13.2	-1.47
3	Morioka	39	141	10.5	0.25	2.4	1691	62.3	3.68	1315	153.1	11.6	-1.15
4	Tsukuba	36	140	14.3	0.34	2.3	1963	175.4	8.94	1399	252.2	18.0	0.38
5	Maniwa (Tsuyama) ^a	35	133	14.2	0.21	1.5	1781	50.8	2.85	1274	252.7	19.8	-0.25
6	Okayama	34	133	16.7	0.19	1.2	2026	62.3	3.08	1057	299.1	28.3	0.68
7	Shizuoka	34	138	16.9	0.36	2.1	2104	123.2	5.86	2302	660.2	28.7	2.11
8	Miyakonojo	31	131	17.0	0.19	1.1	1989	118.0	5.93	2566	433.8	16.9	2.06

The PC1 score was calculated using the standardized *T*, *S*, and *P*

SD standard deviation, *COV* coefficient of variance, *T* annual mean temperature, *S* annual sunshine duration, *P* annual precipitation, *PC1* principal component

^a Tsuyama is located near Maniwa. Owing to a lack of climate factors for Maniwa, climate factors for Tsuyama were used instead

tests, modulus of rupture (MOR) and internal bond strength (IB) were measured. Further details can be found in previous reports [5, 7, 8]. Asahikawa, Noshiro, Morioka, Tsukuba, Maniwa, Okayama, Shizuoka, and Miyakonojo are numbered from 1 to 8, respectively, as listed in Table 1. Smaller numbers indicate sites that are further north, and larger numbers indicate sites heading south.

Principal component analysis

Principal component analysis is a well-known multivariate analysis used to summarize multidimensional correlated data. The analysis finds principal components (PC) from several explanatory variables. The PCs are created such that the first PC accounts for the maximum variation, the second PC accounts for as much of the remaining variation as possible, and so forth. Since the PCs are not correlated with each other, irrelevant and unstable information is discarded. Only the most relevant and stable part of the variation is used. Standardized climate factors were analyzed using principal component analysis (Excel Tokei 2008, Social Survey Research Information Co., Ltd.).

Results and discussion

Climate factor at each outdoor exposure site

The climate factors affecting the strength (MOR and IB) are assumed to be temperature, precipitation, and sunshine duration [6]. Table 1 lists these climate factors for the eight sites from April 2004 to March 2009. The coefficient of

variance (COV) for temperature and sunshine duration was low for all sites, and the precipitation COV was higher than that of temperature and sunshine duration. In particular, the precipitation COV at sites 4, 5, 6, 7, and 8 was high.

Relationship between climate factor and strength

To clarify the correlation between climate factors and strength, the correlation coefficients between the climate factors and particleboard strength were investigated. Table 2 lists the IB values of particleboard subjected to outdoor exposure at the eight sites after 1–5 years. Table 3 lists the correlation coefficients between climate factors listed in Table 1 and the IB for each exposure term at the eight sites. The correlation coefficient between annual mean temperature listed in Table 1 and IB after 1 year listed in Table 2 (first column) was -0.851, listed at the top of the first column (first row, first column). The correlation coefficient between annual mean temperature and IB after 2 years (second column) was -0.809 (first row, second column). The mean, standard deviation, and COV of the correlation coefficients are also shown for temperature, sunshine duration, and precipitation. The mean of the temperature correlation coefficient was -0.878, higher than those for sunshine duration and precipitation. More importantly, the correlation coefficients of each climate factor were high.

Likewise, Table 4 lists the MOR values of particleboard subjected to outdoor exposure at the eight sites after 1–5 years and Table 5 lists the correlation coefficients between the climate factors and the MOR. The correlation coefficient for temperature was the strongest at -0.708.

Table 2 Internal bond strength (IB) of particleboard subjected to outdoor exposure at the eight sites

Exposure term (year)	IB (MPa)				
	1	2	3	4	5
Site 1	0.812 (0.07)	0.626 (0.05)	0.666 (0.10)	0.596 (0.13)	0.360 (0.25)
Site 2	0.630 (0.10)	0.540 (0.16)	0.464 (0.12)	0.287 (0.12)	0.377 (0.15)
Site 3	0.639 (0.09)	0.458 (0.11)	0.521 (0.14)	0.480 (0.14)	0.193 (0.11)
Site 4	0.605 (0.09)	0.573 (0.22)	0.318 (0.13)	0.320 (0.19)	0.140 (0.11)
Site 5	0.551 (0.10)	0.434 (0.14)	0.323 (0.13)	0.186 (0.07)	0.119 (0.10)
Site 6	0.556 (0.07)	0.324 (0.17)	0.185 (0.11)	0.208 (0.12)	0.186 (0.08)
Site 7	0.337 (0.15)	0.212 (0.11)	0.152 (0.06)	0.069 (0.03)	0.054 (0.02)
Site 8	0.229 (0.04)	0.125 (0.07)	0.092 (0.04)	0.057 (0.02)	0.056 (0.02)

Site nos. are listed in Table 1
Numbers in parentheses indicate standard deviations

Table 3 Correlation coefficients between internal bond strength and climate factors including PC1 score and weathering intensity (WI) at the eight sites

Exposure term (year)	Correlation coefficient					Mean	SD	COV
	1	2	3	4	5			
<i>T</i>	-0.851	-0.809	-0.990	-0.934	-0.806	-0.878	0.081	-9.23
<i>S</i>	-0.687	-0.700	-0.839	-0.655	-0.863	-0.749	0.095	-12.7
<i>P</i>	-0.918	-0.801	-0.691	-0.740	-0.650	-0.760	0.105	-13.8
PC1 score	-0.927	-0.875	-0.965	-0.887	-0.886	-0.908	0.038	-4.15
WI	-0.951	-0.884	-0.921	-0.907	-0.845	-0.902	0.040	-4.42

WI is shown in Ref. [6]

T annual mean temperature, *S* annual sunshine duration, *P* annual precipitation, *PC1 score* score of first principal component, *SD* standard deviation, *COV* coefficient of variance

Table 4 Modulus of rupture (MOR) of particleboard subjected to outdoor exposure at the eight sites

Exposure term (year)	MOR (MPa)				
	1	2	3	4	5
Site 1	14.9 (1.63)	13.7 (1.10)	12.8 (1.87)	11.8 (1.75)	6.34 (1.50)
Site 2	14.9 (1.60)	14.1 (1.87)	9.63 (1.48)	9.41 (3.12)	10.3 (3.22)
Site 3	13.2 (0.91)	11.5 (2.13)	10.6 (1.05)	8.69 (0.83)	4.01 (0.45)
Site 4	14.1 (1.60)	12.5 (1.01)	9.85 (2.15)	7.70 (2.91)	9.44 (2.55)
Site 5	12.9 (1.38)	9.90 (2.48)	7.05 (0.63)	6.28 (1.94)	4.69 (0.94)
Site 6	14.0 (1.48)	8.33 (1.26)	7.65 (1.88)	4.77 (1.40)	5.22 (1.23)
Site 7	11.9 (2.31)	8.90 (1.54)	6.67 (0.73)	5.79 (0.87)	5.07 (1.09)
Site 8	7.90 (1.90)	7.17 (2.43)	5.86 (1.51)	5.14 (0.45)	4.88 (0.73)

Site nos. are listed in Table 1
Numbers in parentheses indicate standard deviations

Compared with the IB correlation coefficients (Table 3), the correlation coefficients for the MOR were lower.

From these results, it is apparent that the strength is related to the climate factors of temperature, sunshine duration, and precipitation. However, the climate factors have a complex correlation to one another, and consequently a simple regression analysis is insufficient to investigate the effects of each climate factor on strength reduction. Hence, it is important to combine the three climate factors (temperature, sunshine duration, and precipitation) into a PC1 using a principal component analysis.

Principal component analysis of climate factors

The climate factors listed in Table 1 were used for principal component analysis, and Table 6 lists the eigenvalues, proportion, cumulative proportion and eigenvectors for each PC. For PC1, the eigenvalue was 2.31 and the proportion was 76.9 %. All PC1 eigenvectors showed high, positive values for each climate factor, indicating that the PC1 score increases with increasing temperature, sunshine duration, and precipitation. This result implies that the high PC1 score is associated with a high degradation of particleboard

Table 5 Correlation coefficients between modulus of rupture and climate factors including PC1 score and weathering intensity (WI) at the eight sights

Exposure term (year)	Correlation coefficient					Mean	SD	COV
	1	2	3	4	5			
<i>T</i>	−0.603	−0.828	−0.926	−0.965	−0.216	−0.708	0.309	−43.7
<i>S</i>	−0.535	−0.796	−0.665	−0.807	−0.398	−0.640	0.175	−27.3
<i>P</i>	−0.859	−0.580	−0.691	−0.514	−0.175	−0.564	0.254	−45.0
PC1 score	−0.746	−0.845	−0.871	−0.883	−0.302	−0.729	0.245	−33.6
WI	−0.747	−0.760	−0.896	−0.816	−0.242	−0.692	0.258	−37.3

WI is shown in Ref. [6]

T annual mean temperature, *S* annual sunshine duration, *P* annual precipitation, *PC1 score* score of first principal component, *SD* standard deviation, *COV* coefficient of variance

Table 6 Eigenvalue, proportion, cumulative proportion, and eigenvector calculated using the principal component analysis of climate factors listed in Table 1

	PC1	PC2	PC3
Eigenvalue	2.31	0.544	0.149
Proportion (%)	76.9	18.1	5.00
Cumulative proportion (%)	76.9	95.0	100
Eigenvector			
<i>T</i>	0.621	−0.223	0.752
<i>S</i>	0.591	−0.497	−0.635
<i>P</i>	0.516	0.838	−0.177

T, *S*, and *P* were standardized

PC1 first principal component, *PC2* second principal component, *PC3* third principal component, *T* annual mean temperature, *S* annual sunshine duration, *P* annual precipitation

subjected to outdoor exposure. In contrast, the eigenvalues and proportions of PC2 and PC3 were much lower than those of PC1, showing that the PC1 accounts for the majority of the variability in the climate factors. Consequently, PC2 and PC3 were not pursued. The calculated PC1 scores are listed in Table 1, and high temperatures, sunshine duration, and precipitation increased their value.

Relationship between PC1 score and particleboard strength

Tables 3 and 5 list the correlation coefficients between the PC1 score listed in Table 1 and particleboard strength, as well as those between the climate factors and strength. The PC1 score had a strong correlation with the IB, with a mean correlation coefficient of −0.908, and also a strong correlation with the MOR, with a mean correlation coefficient of −0.729. In both the IB and the MOR, the PC1 score provided better correlation and lower COVs than the individual climate factors. These results demonstrate that the PC1 score is a more powerful index than the individual climate factors.

Table 7 Weathering intensity (WI) of each exposure term at the eight sites

Exposure term (year)	WI				
	1	2	3	4	5
Site 1	3.87	4.22	4.45	4.56	4.63
Site 2	4.34	4.60	4.76	4.86	4.94
Site 3	4.36	4.62	4.74	4.87	4.95
Site 4	4.44	4.67	4.86	4.97	5.07
Site 5	4.48	4.67	4.84	4.96	5.03
Site 6	4.48	4.66	4.84	4.93	5.01
Site 7	4.83	5.01	5.15	5.26	5.34
Site 8	4.82	5.07	5.22	5.33	5.42

WI is shown in Ref. [6]. Site nos. are listed in Table 1

Kojima et al. [6, 9] proposed “weathering intensity (WI)” as an index for analyzing monthly climate data. The WI was calculated using temperature and precipitation ($WI = \log \Sigma(T \times P)$). We calculated the WI and present its values for each exposure term in Table 7. As discussed previously, the PC1 score was calculated using the climate factors listed in Table 1, whereas the WI was calculated using each monthly climate data per 1-year exposure term. Hence, there are five WI values for each exposure site, as the exposure term was a total of 5 years. Tables 3 and 5 list the correlation coefficients between the WI and the particleboard strength. As for the IB (Table 3), the correlation of the WI is the almost same as that of the PC1 score. As for the MOR (Table 5), the former is lower than the latter. The MOR is related to surface strength of particleboard [10]. Sunshine degrades the surface of particleboard, reducing the MOR. The PC1 score calculated using temperature, sunshine duration, and precipitation, while the WI calculated using temperature and precipitation. Therefore, the PC1 score is more effective than the WI owing to higher MOR correlation of the PC1 score.

The WI is a combination of climate factors involving mathematical transformation. The climate factors were combined in such a way as to maximize the correlation between each climate factor and strength. In other words, this index uses the assumption that the combination of climate factors has a linear relationship with strength. In contrast, the PC1 score is calculated statistically, without any assumptions on the relation between combination of climate factors and strength, and can be determined unambiguously. Hence, the PC1 score is a more powerful index than the WI for evaluating the degradation of particleboard subjected to outdoor exposure. In addition, the calculation of the WI was cumbersome, whereas the calculation of the PC1 score was straightforward.

Scheffer [11] also proposed a “climate index” for analyzing the relationship between climate factors and decay in the wood structure. For this study, this index is called the “Scheffer index”. The Scheffer index is calculated using a temperature and precipitation term, making it also very cumbersome (see Ref. [11]). In contrast, as discussed previously, it is easier to calculate the PC1 score. Additionally, Scheffer showed the Scheffer index map for North America, analyzing decay of wood structures. If instead the PC1 score is used, a PC1-score map would be easily demonstrated, and this will be shown in the next study.

Conclusions

The climate factors of temperature, sunshine duration, and precipitation were analyzed using a principal component analysis, and the PC1 score was introduced as a new index for evaluating the degradation of particleboard subjected to outdoor exposure. The strength of particleboards subjected to outdoor exposure showed a strong correlation with the PC1 score. In addition, the PC1 score can be determined directly and unambiguously using the climate factors, whereas the WI and the Scheffer index are cumbersome in that they require selecting climate factors using some assumptions. The PC1 score was found to be a more

powerful index than each individual climate factor for analyzing the strength of particleboard subjected to outdoor exposure.

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