Light Transmission of a Greenhouse (NARO Tsukuba Factory Farm) Built to Meet Building and Fire Standards

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Ⅰ Introduction

Crop yield depends on light interception by plants (Cockshull et al., 1992; Scholberg et al., 2000) and light use efficiency (LUE; dry matter production per intercepted light) (Higashide and Heuvelink, 2009). Light interception by plants is determined by plant conditions (leaf area index and light extinction coefficient), and by light level in a greenhouse. Light level in a greenhouse is lower than outside on account of the structural materials, which determine light transmission, one of the most important factors for greenhouse vegetable production. Researchers have experimented with greenhouse structures and covering materials (Baeza and López, 2012; Critten, 1993; von Elsner et al., 2000a, b), increasing light transmission to 80% in the Netherlands (Hemming et al., 2011).

Factory farms have been gaining ground in Japan through government support. Some have been built in urban zones, where they must meet building and fire standards (Hasegawa, 2013). To meet earthquake-resistance standards, they must incorporate sturdy frames. To meet fire standards, they may be covered in glass instead of plastic, thereby needing even sturdier frames. Such massive structural elements decrease light transmission (Kozai, 1974). The NARO Tsukuba factory farm, which incorporates a large controlled greenhouse for vegetable production, was built to meet these standards in 2011 (Nakano et al., 2012). We measured its light transmission in this study.

Ⅱ Materials and Methods

The experiment was conducted on the Tsukuba factory farm of the National Agriculture and Food Research Organization (NARO, Tsukuba, Japan; 140.1024782°E, 36.0285626°N). The greenhouse (40.5 m width, 63 m length, 2552 ㎡ area, 5.1 m eave height) is covered with ethylene tetrafluoroethylene film (F-clean GR diffused type, AGC Greentech, Tokyo, Japan) on the roof and with glass on the walls. To accommodate several hydroponic systems and crops (Nakano et al., 2012), it is divided with film into two large (18 m × 18 m = 324 ㎡) and eight small compartments (9 m × 18 m = 162 ㎡) (Fig. 1). The roof is supported by steel H-beams (250 mm × 125

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mm) set every 3 m in the north-south direction and 9 m in the east-west direction, which are connected by roof trusses made from T-beams (100 mm × 100 mm), L-beams (50 mm × 50 mm), and square pipe (50 mm × 50 mm) (Fig. 2). Shade screens are hung just below the trusses at 3-m intervals (200 mm wide when furled), and ribs (30 mm wide) hold the film together every 50 cm. Gutters (300 mm wide) are mounted in every valley.

We measured solar radiation in the horizontal plane inside the greenhouse (at 4.3 m height) and outside with 13 pyranometers (PCM-01(L), Prede, Tokyo, Japan; LI-200, Li-Cor, Lincoln, NE, USA), and readings were recorded by a datalogger (GL-220, Graphtech, Yokohama, Japan) every 1 min. The solar radiation outside above the greenhouse was also measured and recorded by a Ubiquitous Environmental Control System (Stella Green, Osaka, Japan) every 1 min. The sensors were calibrated against a pre-calibrated pyranometer (SR11, Hukse Flux, Delft, The Netherlands; r^2 = 0.99 in all regressions) from 22 to 26 December 2011.

With the shade screens furled, we measured the solar radiation for five days at six points each in compartments N4 and S4 of the greenhouse (8–12 March 2012) and at four points each in compartments N1 (21–25 February) and S2 (14–19 February) (Fig. 3). Each measurement period included both clear and rainy days. The daily cumulative solar radiation was 2.1–14.2 MJ•m^{-2} on 8–12 March, 1.1–14.4 MJ•m^{-2} on 21–25 February, and 2.5–14.6 MJ•m^{-2} on 14–19 February.

The light transmission (T_r) at each point was derived from the radiation at each point inside (R_i) and outside (R_o) as:

$$T_r = R_i / R_o \quad (1)$$

To avoid errors caused by the low sensitivity of the sensors at low radiation levels, we excluded data before 08:00 and after 16:00 (n = 481).

To obtain the light components inside the greenhouse, we divided the data between periods when each point was or was not shaded by the frames of the greenhouse on cloudless days (Fig. 4). With L_u as the transmission at unshaded points (due to both direct and diffuse light) and L_s as that at shaded points (due to diffuse light), the transmission due to direct light, L_d, was calculated as:

$$L_d = L_u - L_s \quad (2)$$

We estimated the light components in N4 and S4 on

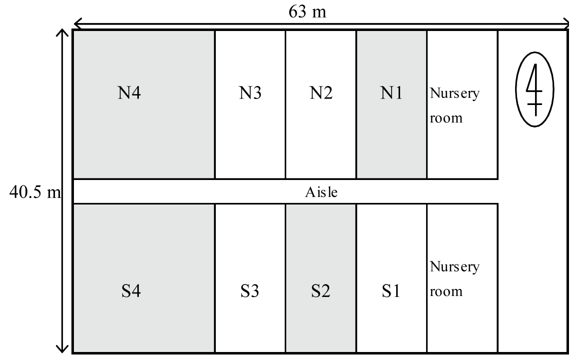

Fig.1 Plan of NARO Tsukuba greenhouse. Compartments N4, S4, S2, and N1 were used for this experiment.

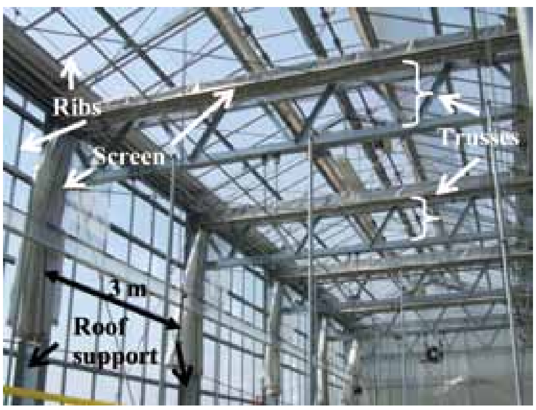

Fig. 2 Internal structure of the greenhouse. See text for description.

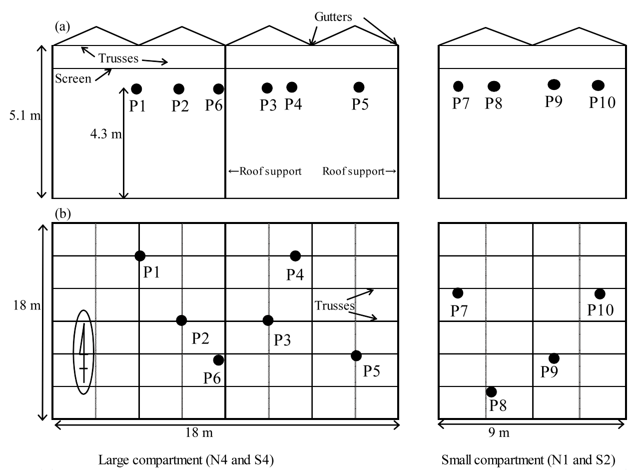

Fig.3 Measurement points in the large (N4, S4) and small (N1, S2) compartments. (a) Side view. (b) Plan view.

12 March (n = 35–127), in N1 on 21 February (n = 67–111), and in S2 on 19 February (n = 49–92).

We also estimated the light attenuation in the greenhouse due to the covering film and ribs (A_c) and to the structural frames (A_s) as:

$$A_c = 1 - L_u \quad (3)$$

$$A_s = L_u - T_a \quad (4)$$

where T_a = daily average transmission at the measurement point.

Ⅲ Results and Discussion

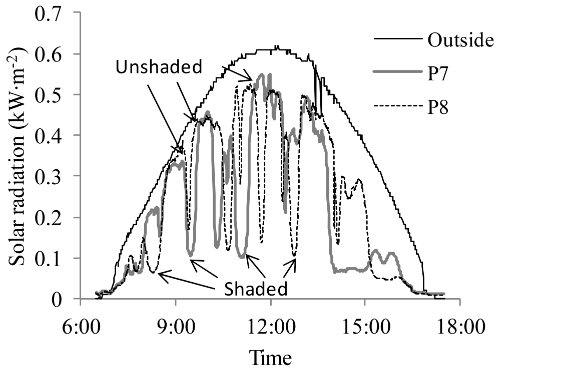

Fig. 4 Solar radiation outside and at points P7 and P8 in compartment S2 on a clear day (21 February 2012) at shaded and unshaded times [Eqn. 2].

In the large compartments, the light transmission was higher at pyranometers P3, P4, and P5 in N4 (0.50–0.75) and at P2, P3, and P5 in S4 (0.48–0.74) than at the other points (Table 1). The transmission at P6 was much lower than at the other points in both compartments on account of the support and the gutter above (Figs. 2, 3). As crops are not planted immediately beneath P6, we calculated the average transmission in each compartment without P6. Although both N4 and S4 faced outside to the west but inside to the east, the transmission on the western side of each compartment (P1, P2) was the same as or slightly lower than that on the eastern side (P3, P4,

Table 1 Light transmission measured at 6 points in the large compartments (N4 and S4), and solar radiation outside, from 08:00 to 16:00 for 5 days.

Compartment	Position	Transmission[z] from 08:00 to 16:00 (W·m^{-2}·W^{-1}·m^{2})					
		8-May	9-May	10-May	11-May	12-May	Average for 5 d
N4	P1	0.40 b[y]	0.45 b	0.41 b	0.41 a	0.54 ab	0.44 ab
	P2	0.45 c	0.49 c	0.47 c	0.50 b	0.63 c	0.51 b
	P3	0.50 de	0.52 c	0.51 d	0.59 d	0.75 d	0.57 b
	P4	0.51 e	0.66 d	0.52 d	0.53 bc	0.62 bc	0.57 b
	P5	0.51 e	0.65 d	0.51 d	0.56 cd	0.73 d	0.59 b
	P6	0.26 a	0.20 a	0.30 a	0.38 a	0.46 a	0.32 a
	Average P1−5	0.48	0.55	0.48	0.52	0.65	0.54
S4	P1	0.43 b	0.49 b	0.44 b	0.44 a	0.57 ab	0.47 ab
	P2	0.50 de	0.56 c	0.51 d	0.56 c	0.73 c	0.57 b
	P3	0.50 e	0.54 c	0.51 d	0.55 c	0.73 c	0.57 b
	P4	0.48 c	0.60 d	0.49 c	0.49 b	0.60 b	0.53 b
	P5	0.48 cd	0.59 d	0.49 c	0.54 c	0.74 c	0.57 b
	P6	0.31 a	0.27 a	0.34 a	0.41 a	0.49 a	0.37 a
	Average P1−5	0.48	0.56	0.49	0.52	0.67	0.54
Outside solar radiation (MJ·m^{-2}·day^{-1})		5.4	2.1	4.6	11.2	14.2	7.5

[z] Daily average of transmission ($Tr = R_i$ (radiation at each point) / R_o (outside solar radiation) [Eqn. 1]) measured at 1-min intervals on 8–12 May 2012.

[y] Values within a column followed by the same letter do not differ significantly within a compartment (P < 0.05; ANOVA followed by Tukey's multiple-comparison test; n = 481 [daily] or 5 [5-d average]).

P5). This is unlikely to be due to outside influences, since we measured the radiation at 4.3 m height (whereas differences are more likely at floor level, on account of the lowering western sun in the evening). The overall daily average transmission at P1–5 over the five days was the same (0.54) in N4 and S4. The daily solar radiation was not significantly correlated with transmission.

Although the outside solar radiation on a cloudless day (21 February 2012) suggested a bell curve, the inside radiation at points P7 and P8 in S2 fluctuated wildly between peaks and troughs, indicating an alternation between full illumination and shading caused by the structural frames and their interaction with the sun at different angles (Fig. 4). The radiation at the peaks was due to both direct and diffuse light. The radiation at the troughs was due to diffuse light. This pattern was apparent at all points in all compartments, though it differed in the occurrence and degree.

In the large compartments on a cloudless day (12 May 2012), the transmission of direct light (L_d) averaged 0.65–0.67 (P1–5) (Table 2). The transmission of direct + diffuse light (L_u) was lower at P6 than at the other points, on account of the support and the gutter above (Fig. 3). The transmission of diffuse light (L_s) averaged 0.21–0.23 (P1–5). The attenuation by film and ribs (A_c) was lower at P2 and P3 (0.05–0.09) than at the other points, and was higher at P6. A_c averaged 0.11–0.12 (P1–5). The attenuation by structural frames (A_s) was higher than A_c at each point, and averaged 0.21–0.23 (P1–5). These results indicate that the frames blocked twice as much light as the film and ribs.

In the small compartments, the light transmission was slightly higher at P8 and P9 (Table 3). As in the large compartments (Table 2), L_u reached 0.90, and averaged 0.85–0.87. In N1, L_s averaged 0.23 and L_d averaged 0.62. In S2, L_s averaged 0.19 and L_d averaged 0.67. A_c averaged 0.13–0.15, and A_s averaged 0.28–0.30. The values of light transmission were slightly higher in S2 (14–19 February) than in N1 (21–25 February).

Table 2 Light components (transmission of diffuse light, L_s; of direct + diffuse light, L_u; and of direct light, L_d) and attenuation by film and ribs (A_c) and by structural frames (A_s) at 6 points in the large compartments (N4 and S4) on a cloudless day (12 May 2012).

Compartment	Position	Light components[z] ($W \cdot m^{-2} \cdot W^{-1} \cdot m^2$)					Attenuation ratio[y] ($W \cdot m^{-2} \cdot W^{-1} \cdot m^2$)	
		L_s		L_u		L_d	A_c	A_s
N4	P1	0.22	a[x]	0.82	b	0.61	0.18	0.28
	P2	0.21	a	0.92	e	0.71	0.08	0.29
	P3	0.23	ab	0.93	e	0.70	0.07	0.18
	P4	0.25	bc	0.86	c	0.61	0.14	0.24
	P5	0.26	c	0.89	d	0.62	0.11	0.16
	P6	0.23	ab	0.74	a	0.51	0.26	0.28
	Average P1−5	0.23		0.88		0.65	0.12	0.23
S4	P1	0.20	b	0.83	b	0.63	0.17	0.26
	P2	0.21	b	0.91	c	0.69	0.09	0.17
	P3	0.21	b	0.95	d	0.74	0.05	0.22
	P4	0.22	b	0.84	b	0.62	0.16	0.25
	P5	0.22	b	0.89	c	0.67	0.11	0.16
	P6	0.18	a	0.71	a	0.53	0.29	0.22
	Average P1−5	0.21		0.89		0.67	0.11	0.21

[z] Average transmission at shaded (L_s) and unshaded (L_u) points; $L_d = L_u - L_s$ [Eqn. 2].

[y] $A_c = 1 - L_u$ [Eqn. 3]; $A_s = L_u - T_a$ (daily average transmission) [Eqn. 4].

[x] Values within a column followed by the same letter do not differ significantly within a compartment ($P < 0.05$; ANOVA followed by Tukey's multiple-comparison test; n = 35–127).

Table 3 Average light transmission over 5 days, light components (transmission of diffuse light, L_s; of direct + diffuse light, L_u; and of direct light, L_d), and attenuation by film and ribs (A_c) and by structural frames (A_s) on cloudless days at 4 points in the small compartments (N1 and S2).

Compartment	Position	Transmission[z] ($W{\cdot}m^{-2}{\cdot}W^{-1}{\cdot}m^2$)		Light components[y] ($W{\cdot}m^{-2}{\cdot}W^{-1}{\cdot}m^2$)					Attenuation ratio[x] ($W{\cdot}m^{-2}{\cdot}W^{-1}{\cdot}m^2$)	
				L_s		L_u		L_d	A_c	A_s
N1	P7	0.48	a[w]	0.21	a	0.80	a	0.59	0.20	0.27
	P8	0.52	a	0.26	b	0.85	b	0.59	0.15	0.27
	P9	0.57	a	0.26	b	0.90	c	0.64	0.10	0.29
	P10	0.48	a	0.19	a	0.85	b	0.66	0.15	0.35
	Average P7−10	0.51		0.23		0.85		0.62	0.15	0.30
S2	P7	0.57	a	0.18	a	0.89	b	0.71	0.11	0.32
	P8	0.60	a	0.21	c	0.89	b	0.68	0.11	0.26
	P9	0.60	a	0.20	bc	0.88	b	0.68	0.12	0.26
	P10	0.55	a	0.19	ab	0.81	a	0.62	0.19	0.28
	Average P7−10	0.58		0.19		0.87		0.67	0.13	0.28

[z] Average transmission ($T_r = R_i$ (radiation at each point) / R_o (outside solar radiation) [Eqn. 1]) measured at 1-min intervals during 08:00–16:00 for 5 days.
[y] Average transmission at shaded (L_s) and unshaded (L_u) points on 19 Feb (N1) or 21 Feb (S2) 2012; $L_d = L_u - L_s$ [Eqn. 2].
[x] $A_c = 1 - L_u$ [Eqn. 3]; $A_s = L_u - T_a$ (daily average transmission) [Eqn. 4].
[w] Values within a column followed by the same letter do not differ significantly within a compartment ($P < 0.05$; ANOVA followed by Tukey's multiple-comparison test; $n = 5$ [transmission], 67–111 [N1], or 49–92 [S2]).

The proportion of diffuse light increases as solar elevation angle decreases (Papadakis et al., 1998). Uchijima et al. (1976) measured the proportion in a greenhouse covered with PVC film as ca. 30% in Japan. We measured L_s as ca. 20% (Tables 2, 3), but the proportion is influenced by covering materials, latitude, solar elevation angle, and weather conditions (Kozai, 1977; Kurozumi and Kawashima, 1979).

Light transmission of greenhouses has improved (Critten, 1993; von Elsner et al., 2000a, b), reaching ca. 80% in The Netherlands (Hemming et al., 2011). In contrast, the value in the NARO Tsukuba greenhouse is still <60% (Tables 1, 3), similar to previously reported values in Japan (Kurata, 1994). These numbers indicate that crops in the NARO Tsukuba greenhouse receive at most 3/4 of the light in the Dutch greenhouse at the same outside light intensity. This lower light intensity will compromise crop yields (Cockshull et al., 1992; Higashide et al., 2012a, 2012b; Higashide and Heuvelink, 2009; Scholberg et al., 2000). The main cause of light attenuation in the NARO Tsukuba greenhouse was shading by the structural frames (Tables 2, 3). To improve light transmission of this greenhouse, we should give priority to improving the structure rather than the covering materials (Baeza and López, 2012). The number and size of the frames should both be decreased while still meeting earthquake standards. Alternatively, zoning provisions could be made to provide exceptions (i.e., different construction standards) for greenhouses.

Our results show that the light transmission of the greenhouse built to meet building and fire standards was only 50%–60%. The structural frames blocked >20%–30% of the light, and the film and ribs blocked >10%–15% on a cloudless day. Improvements to the frames retaining their structural strength could increase light transmission. Differences in transmission between compartment sizes and facing-orientations were minor.

Summary

We investigated light transmission in the NARO Tsukuba greenhouse, which was built to meet building and fire standards. Solar radiation was measured outside and inside large and small north- or south-facing compartments in February and March 2012. Light transmission averaged only 50%–60%. Differences in transmission between large and small compartments and between north- and south-facing compartments were minor. Measurement of light intensity during shaded and unshaded periods on cloudless days indicated that diffuse light accounted for >20% of transmitted light and direct light accounted for 60%–70%. Film and ribs blocked 10%–15% of the light, and the structural frames blocked 20%–30%. Improvements to the structural frames retaining their structural strength could increase light transmission in this greenhouse.

Literature Cited

1) Baeza, E. and J.C. López (2012): Light transmission through greenhouse covers. *Acta Hort.*, **956**, 425-440.
2) Cockshull, K.E., C.J. Graves and C.R.J. Cave (1992): The influence of shading on yield of glasshouse tomatoes. *J. Hort. Sci.*, **67**, 11-24.
3) Critten, D.L. (1993): A review of the light transmission in to greenhouse crops. *Acta Hort.*, **328**, 9-31.
4) Hasegawa, T. 2013. Introduction to the Building Standard Law - Building regulation in Japan. 1-212. Building Center of Japan, Tokyo.
5) Hemming, S., F.L.K. Kempkes and V. Mohammadkhani (2011): New glass coatings for high insulating greenhouses without light losses-energy saving, crop production and economic potentials. *Acta Hort.*, **893**, 217-226.
6) Higashide, T. and E. Heuvelink (2009): Physiological and morphological changes over the past 50 years in yield components in tomato. *J. Am. Soc. Hort. Sci.*, **134**, 460-465.
7) Higashide, T., K. Yasuba, K. Suzuki, A. Nakano and H. Ohmori (2012a): Yield of Japanese tomato cultivars has been hampered by a breeding focus on flavor. *HortScience*, **47**, 1408-1410.
8) Higashide, T., I. Gotoh, K. Suzuki, K. Yasuba, K. Tsukazawa, D. Ahn and Y. Iwasaki (2012b): Effects of pinching and lowering on cucumber yield and yield components. *Hort. Res. Jap.*, **11**, 523-529 (in Japanese with English abstract).
9) Kozai, T. (1974): Numerical experiments on light transmission in greenhouses (2). *J. Agric. Meteorol.*, **4**, 239-247 (in Japanese with English abstract).
10) Kozai, T. (1977): Direct solar light transmission into single-span greenhouses. *Agric. Meteorol.* **18**, 327-338.
11) Kurata, K. (1994): Light environmental control. p. 233-242. In: Nishi, S., M. Amano, T. Itagi, T. Ito, I. Ueno, S. Okitsu, I. Kurata, T. Kozai, Y. Odaka, R. Sakiyama, K. Seike, T. Takakura, H. Hakura, T. Murai, (eds.). Greenhouse horticulture handbook 3rd edition (In Japanese). Japan Greenhouse Horticulture Association, Tokyo, Japan.
12) Kurozumi, T. and N. Kawashima (1979): Model experiments on the light transmission in the greenhouse. 2. The influences of covering-materials and structural elements. *Bull. Nara Agric. Exp. Sta.*, **10**, 1-9 (in Japanese with English abstract).
13) Nakano, A., T. Higashide, K. Yasuba, H. Ohmori, S. Kaneko and K. Suzuki (2012): Research centers for intelligent plant production systems in Japan (5) National Agriculture and Food Research Organization (NARO) Institute of Vegetable and Tea Science, Tsukuba plant factory. *J. Soc. High Technol. Agric.*, **24**, 219-223 (in Japanese with English abstract).
14) Papadakis, G., D. Manolakos and S. Kyritsis (1998): Solar radiation transmission of a single-span greenhouse through measurements on scale models. *J. agric. Eng. Res.*, **71**, 331-338.
15) Scholberg, J., B.L. McNeal, J.W. Jones, K.J. Boote, C.D. Stanley, and T.A. Obreza (2000): Growth and canopy characteristics of field-grown tomato. *Agron. J.*, **92**, 152-159 (doi: 10.2134/agronj2000.921152x).
16) Uchijima, Z., K. Inoue and S. Kimura (1976): The climate in growth chamber: (6). Diffuse radiation environment in vinylhouses. *J. Agric. Meteorol.* **32**, 117-125 (in Japanese with English summary).
17) von Elsner, B., D. Briassoulis, D. Waaijenberg, A. Mistriotis, Chr. von Zabeltitz, J. Gratraud, G. Russo and R. Suay-Cortes (2000a): Review of structural and functional characteristics of greenhouses in European Union countries: Part I, Design requirements. *J. Agric. Eng. Res.*, **75**, 1-16.
18) von Elsner, B., D. Briassoulis, D. Waaijenberg, A. Mistriotis, Chr. von Zabeltitz, J. Gratraud, G. Russo and R. Suay-Cortes (2000b): Review of structural and functional characteristics of greenhouses in European Union countries: Part II: Typical designs. *J. Agric. Eng. Res.*, **75**, 111-126.

建築基準法および消防法に準拠した植物栽培施設（つくば植物工場拠点）における施設内への光透過特性

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摘　　要

建築基準法および消防法に準拠して建設された植物栽培施設（つくば植物工場拠点）における施設内への光透過特性を調査した．大きさや位置の異なる区画内の日射を測定し，屋外日射と比較した．その結果，屋外日射に対して施設内に入った日射の割合を示す日射透過率は，約 50 ～ 60％であった．日射透過率において区画の大きさや南北の位置による大きな違いは確認できなかった．雲のない晴天日に測定点が骨材などの陰になる場合とそうでない場合に分けて計測したところ，施設内の光成分は，散乱光が 20％以上，直達光が 60 ～ 70％であった．施設による日射の減衰は，10 ～ 15％がフィルムとその留め具によるものであり，20 ～ 30％が骨材等の構造によるものと推定された．したがって，この施設の日射透過率の向上には，施設の強度を維持したままで骨材等の構造を改良することが効果的であると考えられる．

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