Sunlight Permeability of Translucent Concrete Panels as a Building Envelope

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Abstract: An innovative building envelope was introduced for daylight permeability in an anidolic manner through the opaque parts of exterior façades and roofs. A prefabricated translucent concrete panel (TCP) with embedded optical fibers (OFs) was coupled with a layer outfitted with compound parabolic concentrators (CPCs). Such TCPs have been predominantly used for aesthetic purposes. Moreover, OFs and CPCs have been used in many industries, particularly for telecommunications and the concentration of solar energy, respectively. The goal of this study was to introduce a novel building-envelope construction solution that can transmit sunlight to the interior of a building. Because of the nature of the traditional building materials blocking the passage of natural light, artificial lighting was constantly required, even during daytime, which consumed a great deal of energy in the form of artificial electrical light. This proposed building envelope is a viable solution to alleviate this inefficiency. Experimental results show the effectiveness and limitations of the proposed solution discussed in this paper. **DOI: 10.1061/(ASCE)AE.1943-5568.0000321.** *© 2018 American Society of Civil Engineers.*

Author keywords: Anidolic concentrator; Building envelope; Light transmission; Optical fibers; Translucent concrete.

Introduction

Over the last 10–15 years, several companies have developed techniques for manufacturing light-transmitting concrete, such as LitraCon. These products typically used optical fibers (OFs) to transmit natural and artificial light through precast concrete blocks suitable for nonstructural applications. Although most of the current work has focused on decorative applications, there is a tremendous potential for light-transmitting concrete to provide daylighting in the interior of buildings. Little or no research has been conducted to quantify this potential or to compare the performance of OFs with other light-transmitting materials. An exception is the computational studies by Ahuja et al. (2015a, b) and Ahuja and Mosalam (2017). There is usually an excess of sunlight outdoors compared to the indoor lighting required in most buildings such as commercial buildings, apartments, and public buildings. This sunlight can be concentrated and transmitted to the inside of the building using OFs or acrylic rods (ARs), as conducted in this study. The substitution of electrical lighting by natural lighting effectively reduces the energy consumption in the building and accordingly the portion of the electricity bills associated with artificial lighting (André and Schade 2002).

The objective of this research was to introduce a novel building-envelope subsystem that allows lighting energy savings for different building types, such as residential, office, commercial, or public buildings. It is noteworthy that in architecture, *subsystem* refers to the collection of construction elements that work together for the same objective in the building system. Previous studies confirmed that daylighting can reduce artificial lighting consumption by 50–80%. Moreover, artificial lighting consumption could contribute 20–60% of the total electric consumption in an office building (Bodart and De Herde 2002). A building could achieve energy savings (i.e., reducing dependence on artificial or electrical lighting) by using passive solar lighting (Knight 1999) or light-emitting diode (LED) technology that contributes between 20 and 60% of the energy savings (Schubert and Kim 2005; Kalyani and Dhoble 2012).

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Background

Visual Effects of Lighting

Studies of the visual effects of lighting were started over 500 years ago by Leonardo da Vinci and Isaac Newton. The lighting quality should always be high enough to guarantee sufficient visual performance for the tasks a person is conducting at a specific time and place. Many codes have specified the lighting quality aspects for different interior types and associated activities. However, actual visual comfort depends also a person's own visual acuity, for which age is an important factor because lighting requirements usually increase with age (van Bommel and van den Beld 2004). Lighting has a powerful influence on the workplace by offering a stimulating environment for the workers. Moreover, daylight is an important factor determining the quality of living and human comfort and healthfulness.

Solar radiation or sunlight is a universal free source of renewable energy. The quality of life and maintenance of health as conditions of environmental comfort and prosperity are dependent on the effective use of these resources (Kittler and Darula 2002). Daylight penetrates into the building for only several hours each day as determined by the orientation and cloud cover in the sky. The dynamic, varying character of sunlight in both intensity and color contributes greatly to a good working environment and has a positive influence on people's mood and stimulation. However, dynamic artificial lighting is advantageous as well (van Bommel and van den Beld

2004). In 1997, a study conducted by Begemann et al. (1997) showed that people prefer artificial lighting in addition to the daylight present in an office environment (Fig. 1). Daylight is known to have beneficial health effects because the eye controls the biological clock and takes part in regulating some important hormones through regular light–dark rhythms. In the morning, light synchronizes the body's internal clock to the earth's 24-h light–dark rotational cycle. The absence of a normal light–dark rhythm can produce desynchronization, causing alertness and sleepiness during incorrect hours. Daylight has an important effect on the alertness and mood of individuals (van Bommel and van den Beld 2004). People spending their days in nondaylight-permeating buildings may, therefore, be in biological darkness, contributing to reduced performance (Kandilli et al. 2009). In summary, daylight offers health and psychological advantages, such as fewer absences at work (André and Schade 2002) and greater productivity.

There are many advantages of using sunlight, in addition to the partial replacement of electrical lighting and reduction in heating. It is important to illuminate inner spaces with natural daylight so that the indoors is connected to the outdoors. However, daylight may produce external or internal glare effects. Some ergonomic studies have discussed the proper positioning of work spaces to avoid glare. Too much glare has a negative impact on a person's productivity and may cause fatigue. However, the glare effect is out of the scope of the study presented in this paper.

Fig. 1. Office building lighting types: (a) artificial; (b) natural; and (c) both natural and artificial.

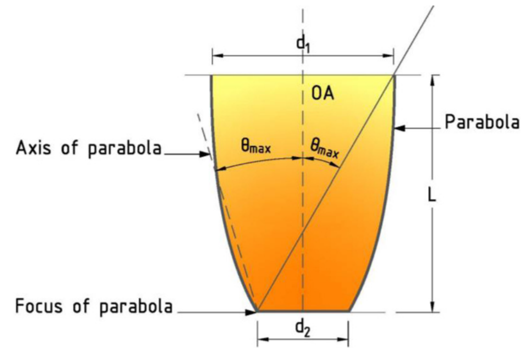


Fig. 2. CPC profile of an ideal concentrator (axis of the parabola is inclined at angle $\theta_{\max}$ to the optical axis, OA).

Compound Parabolic Concentrators for Interior Daylighting

The compound parabolic concentrator (CPC) is a geometric sunlight collector that can concentrate solar beams. Three different types of light concentrators have been described: (1) geometrical (passive), (2) fluorescent luminescent, and (3) hybrid systems (Smestad et al. 1990). The longitudinal cross section of the CPC, shown in Fig. 2, was used for light-ray tracking in nonimaging (anidolic) systems (Winston 1974), and the shape of it is similar to a truncated cone (Smestad et al. 1990). Usually, during the solstices, it is common to face problems in collecting solar radiation due to the sunlight inclination. Sunlight collection is possible only for few (approximately 6–8) hours of the day (Winston 1974), which can be exploited in generating power, heating of water, or air conditioning (Hamad 1988) with heat exchanger equipment. The first step of the research presented in this paper was to test a geometrical light concentrator together with a light-channeling element (i.e., an OF system) to transmit natural light from the exterior to the interior of a building in an anidolic manner, leading to energy savings, such as through the reduction in electricity used for lighting.

The presented application of the CPCs needed to account for the changing sky conditions of the climate (Arroyo 2012) and the incidence angle of the sunlight in the considered geographical location. This innovation did not avoid filtering, such as shading, of light or control the energy entering into and exiting from the building. Some other specific technologies were compatible and synergistic with CPCs, such as convertible structures (Knippers and Speck 2012), shading devices (Bessoudo et al. 2010), double façades (Shameri et al. 2011), new glazing technologies (Bahaj et al. 2008), kinetic devices (Suralkar 2011), water cooling systems (Tiwari et al. 1982), and electrochromic panels (Assimakopoulos et al. 2007). The interaction between the presented approach with natural ventilation (Liping and Hien 2007; Wong et al. 2002), acoustic effects (De Salis et al. 2002), and glare effect were not considered in this study.

The CPC equation was expressed in polar coordinates with the origin centered at the focus of the parabola. Defining ρ as the radial distance to a point on the parabola and ϕ as the angle between the tangent to the parabola at the focus and the radial distance, the three-dimensional (3D) geometry of a CPC is given as follows:

$$\rho(\phi) = 2f/(1-\cos\phi), \quad 2\theta_{\max} \le \phi \le \theta_{\max} + \pi/2 \qquad (1)$$

$$f = d_2(1+\sin\theta_{\max})/2 \qquad (2)$$

where d_2 is shown in Fig. 2. The CPC [Winston (1974); Jordan and Krennrich, unpublished data (2004)] was proposed as a nonimaging optical design to achieve the goals of the study. To the best of the authors' knowledge, most of the uses of CPCs have been limited to solar energy, light concentration, and optical signal measurements. Therefore, the present application tackles new frontiers in the use of CPCs in an anidolic manner for energy efficiency and sustainability of the built environment for all building typologies. Moreover, the present research allows building designers to use anidolic daylight concentrators in structural elements.

Optical Fibers for Interior Daylighting

The OF system follows Snell's law, which explains how to send light signals over any distance (Fig. 3), as follows:

$$n_1 \sin\phi_1 = n_2 \sin\phi_2 \qquad (3)$$

Because of the weakness of microwave transmissions, OF technology emerged as one of the preferred methods of digital transmission. Conceptually, an OF system is similar to a microwave system, but the former offers many benefits. OFs have been widely used for data transmission in telecommunications, but they can also be used for daylighting, harnessing solar power (Liang et al. 1998), and scattering light within a building, as shown in Fig. 4 with a translucent concrete panel (TCP). Basically, the OF is a thin and flexible

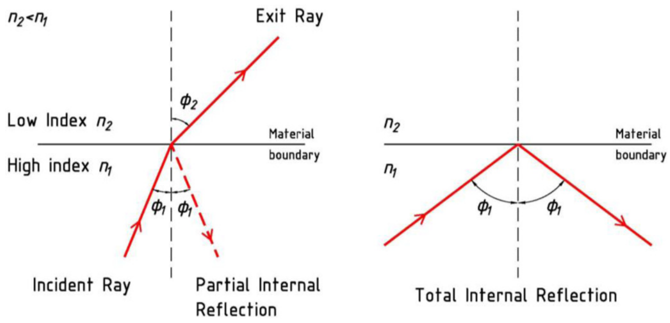
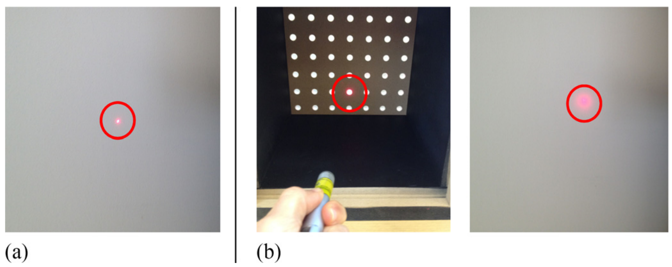


Fig. 3. Snell's law and light ray diagrams.



(a) (b)

Fig. 4. Light transmission in an OF: (a) collimated laser; and (b) laser through an OF in a TCP.

transparent cylindrical material that can transmit visible or infrared (natural or artificial) light through it. The core of an OF is either made up of plastic or glass. OFs are able to transmit ambient light constantly with low loss of light transmission properties even when they are bent less than 30°.

Proposed Building-Envelope Solution

Transporting concentrated solar energy by OFs was studied in 1980 by a group of French investigators (Cariou et al. 1982), who proposed placing OFs at the focus of a CPC such that focused energy was introduced into the fibers. The OFs in that research were of low quality and the design cost was high, limiting the study to a theoretical investigation. Nowadays, solar energy can be transmitted by high quality and inexpensive OFs with large diameters and large numerical apertures (NAs). The NA is a parameter that dictates the light-concentration ability of the OF. It is important to choose fibers with large NAs because they feature large differences in the refractive indices of the core and the outer shell of the fiber, called a *cladding* (Liang et al. 1998). The primary advantage of lighting systems with solar concentrators is the potential to reduce energy consumption to a greater extent than conventional systems can (Kandilli et al. 2009). Moreover, some studies have focused on the transmission of concentrated solar energy through single strands of OF or bundles of fibers, and it is noteworthy that an OF is a chemically resistant material that can be used in different environments. One of the architectural OF properties is transmitting light in an anidolic way such that one source of light can produce many light sources. Nowadays, in the market, some lighting systems allow sunlight to be brought into an interior room. For this situation, a receiver is located on the outside and the OF cables transport the light through the interior. Therefore, integrating OF lighting from solar energy is an energy-efficient option for illuminating interior spaces without enough natural daylight (Kandilli et al. 2009). Moreover, OFs have

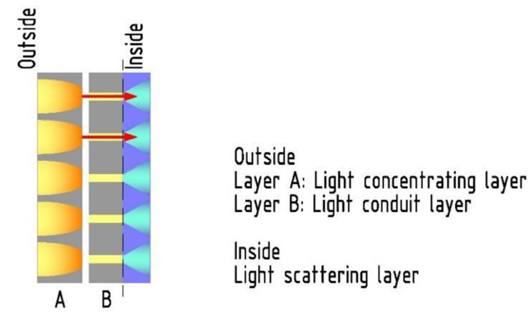


Fig. 5. Multilayer light concentrating structural subsystem.

the potential to eliminate the effect of ceiling light wells in the floor plan, giving much more flexibility to the architectural design and maximizing the use of the floor plan.

OF solar energy transmission and concentration provide a flexible way of handling concentrated solar energy (Liang et al. 1998). The high flux of solar energy transmission by a flexible OF bundle integrated with a specially designed CPC can offer many new applications for solar energy concentrators. The OFs transporting daylight from the outside to the inside of a building can vary in length, size, and configuration. It is important to pay attention to the placement of the light source because it determines the length and configuration of the fiber between the light source and a light fixture end. These parameters affect the output of an OF lighting system. Bundled small-core glass and plastic fibers and large-core plastic fibers are commercially available (Biermann et al. 1998). Knowing the OF performance, it is possible to optimize the design of an OF lighting system. Lighting designers using OFs consider two important parameters: (1) the quantity and (2) quality of the light (Biermann et al. 1998). OFs can be considered as a solution system for daylight transmission. Therefore, the research presented in this paper focused on the use of OFs for daylight transmission. Most previous studies on OFs were about data transmission, and very limited research has been available about OFs as daylight systems.

An innovative building-envelope construction solution, shown Fig. 5, is proposed herein. It has been designed and tested. It consisted of a structural TCP consisting mainly of two layers: (1) Layer A was RC with embedded symmetric CPCs, which are nonimaging concentrators (Winston 1974), to concentrate maximum natural sunlight from the outside in a geometrical manner without mechanizing the panel, and (2) Layer B was RC with embedded OFs as a structural subsystem to act as a conduit for the natural sunlight from the outside to the interior space, which turns the TCP into a translucent construction solution for the opaque part of the building envelope. In addition, the TCP integrated two concepts: (1) Another form of TCP was presented in Ahuja and Mosalam (2017), showing that the proposed construction solution provided energy savings of approximately 20% of the energy cost, and (2) other studies (Ahuja et al. 2015a, b) have shown that the TCP through the OFs had daylight diffusion properties. The TCP was viewed as a novel wall technology with the property to transform an energy liability to an energy source providing daylight. Because the TCP needed sunlight to be used, the presented construction solution was dynamic. To optimize the design, an assessment of the proposed multilayer subsystem under exterior weather changes was conducted for several hours and during different days throughout the year. It is noteworthy that the proposed TCP construction solution was not designed as a replacement for windows; rather, it was an enhancement of the typically opaque part of the building envelop to allow light permeability.

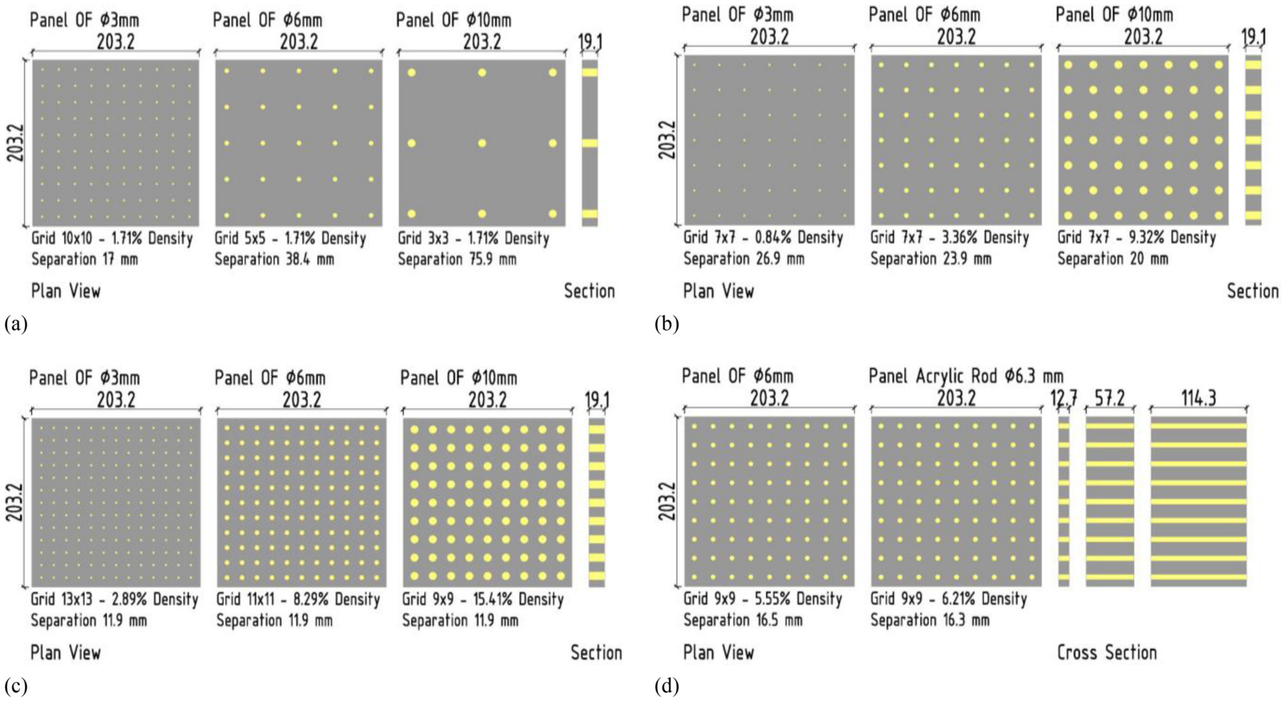


Fig. 6. Layer B test panels (in millimeters): (a) Test 1 panels (same OF density ~1.71%); (b) Test 2 panels (same OFs, 7 × 7 grid); (c) Test 3 panels (same OF spacing ~12 mm); and (d) Test 4 panels of varied thicknesses (OFs or ARs).

Experimental Study Approach

Fig. 5 shows that 15 opaque panels (made of wood to be replaced with RC in the future) in Layer B had embedded OFs and ARs that were fabricated and tested under direct sunlight conditions while the panels were placed in a horizontal position. For the presented research, four tests were conducted as divided into the following categories: (1) Test 1 for the same density of OF distribution [Fig. 6(a)]; (2) Test 2 for the same grid of OFs [Fig. 6(b)]; (3) Test 3 for the same spacing of OFs [Fig. 6(c)]; and (4) Test 4 for variable panel thickness [Fig. 6(d)]. For the construction of Layer A, in Fig. 5, six panels outfitted with CPCs and straight cones (SCs) were fabricated by a 3D printer and tested together with Layer B under direct sunlight conditions. In this case, two tests were conducted as follows: (1) Test 5 Layer A was outfitted with CPCs together with Layer B, and (2) Test 6 Layer A was outfitted with SCs together with Layer B.

Outdoor Portable Test Box

As shown in Fig. 7, a light-tight test box made of wood was designed to hold the test panels for different daylight tests. It was constructed from 19.1-mm-thick panels of medium density fiberboard (MDF) with interior clear dimensions of 203.2 × 203.2 × 203.2 mm. It was designed with construction details to prevent infiltration of exterior light. Side panels were rabbeted (i.e., they used wooden rabbet joints) to the top and bottom, and a back panel with an opening for the light meter was designed to be removable so that several sensors could be used during testing. The interior of the box was painted black to absorb light reflections from the walls.

Prefabricated Test Panels

Fifteen panels from Layer B of the proposed construction solution (Fig. 5) were designed and fabricated from the MDF wood material instead of concrete because the main objective of this study was to

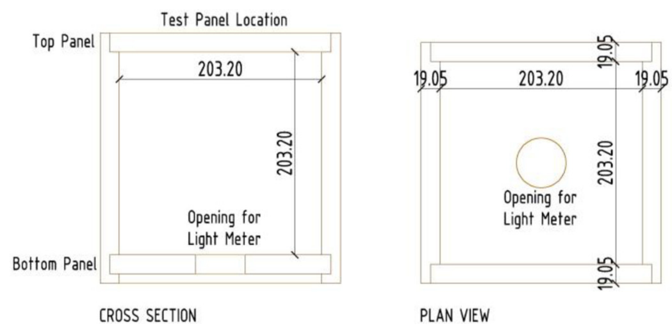


Fig. 7. Light-tight box design (in millimeters).

assess the light transmission. MDF is an opaque material and can be easily manufactured using basic woodworking tools. The panels were of 222.5 × 222.5 mm of varied thicknesses: Two panels were 12.7, nine panels were 19.1, two panels were 57.2, and two panels were 114.3 mm thick. They were constructed from 12.7- and 19.1-mm-thick MDF panels. Holes were drilled in the panels using a computer numerical control (CNC) flatbed router. OFs and ARs were cut to length with a miniature table saw. Once cut to length, these short segments were inserted into the predrilled holes of the test panels. To produce consistent results, a finishing operation was performed on the ends of the OF and AR segments. Therefore, several techniques for cutting and finishing the OFs and ARs were considered. After finishing, each of the samples was tested with a light power meter (DBTU1300 from General Tools, Secaucus, NJ with range of 2,000 W/m^2, resolution of 0.1 w/m^2, spectral response of 400–1,000 nm, and a silicon photodiode) to determine the light transmittance. This was an indoor test along the optical axis consisting of a panel with one OF-embedded or one AR-embedded sample. The light meter was placed perpendicular to the small-scale panel at a distance of approximately 5 mm. Test results, shown in Table 1, were obtained from 6.3-mm-diameter clear cast

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AR samples. The maximum center-beam results were achieved when the rods were cut with a laser, sanded, and finally polished with a buffing pad. Because the laser cutter was not strong enough to cut through the thicker 10-mm OFs, the second-best technique (cutting with a table saw before sanding and buffing) was chosen. The wooden panel fabrication consisted of the following steps: (1) sanding with 120-grit sandpaper to ensure that the length of the OF or AR was consistent with the thickness of the panel, (2) sanding with a sequence of 220-, 400-, and 600-grit sandpapers for greater smoothing, and (3) buffing with a lamb's wool polishing pad to give the panels and embedded OF or AR material a smooth and uniform finish.

The OFs and ARs were purchased from different sources. For the OFs, the core material consisted of polymethyl-methacrylate resin, and the refractive index profile was based on the step-index multimode. Because the intention was to cast the TCP ultimately from RC, the hole pattern in the wooden test panels accounted for RC design considerations; for example, the minimum distance between the OFs or the ARs was approximately 12 mm, which allowed for maximum aggregate and reinforcing bar size of apprxomately10 mm to provide sufficient strength for the most relevant applications. It is noteworthy that compliance with building code requirements was assumed in the selection of the building materials used. The TCP was recently manufactured at the University of California, Berkeley, California, as precast units using white ultralightweight cement composites (ULCCs) for an aesthetically appealing solution with low thermal conductivity (Rheinheimer et al. 2017) and involving polyethylene fibers for control of tensile stresses. The following subsections explain the different studies for Layer B of the panels.

Test 1: Same Density

Test 1 consisted of three panels with embedded OFs that were characterized by differences in grid pattern (i.e., diameter and spacing). The density of the OFs, defined as the ratio between the total cross-sectional area of the OFs and the planar area of the panel, was kept constant at 1.71%. The objective of the test was to determine the influence of the grid configuration of the OFs on the light transmission [(Fig. 6(a)].

Table 1. Test results for different finishing techniques of the OFs and ARs

Finishing techniques	(W/m^2)
1. Laser cut + sanding + buffing	200
2. Table saw cut + sanding + buffing	185
3. Laser cut without sanding or buffing	182
4. Table saw cut without sanding or buffing	170

Test 2: Same Grid

Test 2 consisted of three panels with embedded OFs of different diameter and spacing. The OFs in the panels were arranged in a 7 × 7 grid. The objective of the test was to determine the influence of the OF density by varying the OF diameters and OF spacing on the same grid for the light transmission [Fig. 6(b)].

Test 3: Same Spacing

Test 3 consisted of three panels with embedded OFs of different diameter. The edge-to-edge spacing between the OFs was kept constant at approximately12 mm, simulating the TCPs constructed with maximum aggregate and reinforcing bar sizes of approximately 10 mm. Because the minimum spacing between OFs was critical in TCPs, the objective of this test was to determine the influence of the OF density on the light transmission by varying the OFs diameters and grids with the same spacing [Fig. 6(c)].

Test 4: Varied Thicknesses

Test 4 consisted of six panels with thicknesses of 12.7, 57.2, and 114.3 mm and the same grid. Two panels were constructed for a specific thickness with embedded 6-mm OFs or 6.3-mm ARs. The objectives of the test were to determine the influences of panel thickness and material type (OF versus AR) on the light transmission [Fig. 6(d)].

Printed panels. Fig. 8 shows that for Tests 5 and 6, six panels of 222.5 × 222.5 mm were designed and fabricated using a 3D printer with a polylactic acid polymer (PLA) filament for Layer A of the proposed construction solution. Each panel was printed with 49 CPCs or SCs arranged in a 7 × 7 grid. They were painted with a layer of mirror-like coating. The external surfaces of the panels were painted black to absorb natural sunlight. The two independent variables of the CPC and SC were considered to be the maximum, d_1, and minimum, d_2, diameters (Fig. 2) that define the geometry of the concentrator. For the present design, the value for d_1 and d_2 was 25.4 and 10.2 mm, respectively. The three considered lengths, denoted L, for the CPCs and SCs were 40.7, 33.0, and 19.6 mm corresponding to the half acceptance angles, denoted asθ_{max}, equal to 23.6, 30, and 48.6°, respectively. The separation between the CPCs or SCs at the side with d_1 was taken as 4.6 mm.

Test 5: Layer B Plus CPCs Layer

Test 5 consisted of three Layer B panels with embedded OFs of different diameter and spacing but with the same 7 × 7 grid. The panels were outfitted with CPCs of the different half acceptance angles (Layer A) and tested together. The objective of the test was to determine the influence of the CPCs with the OFs on the light transmission (Fig. 8).

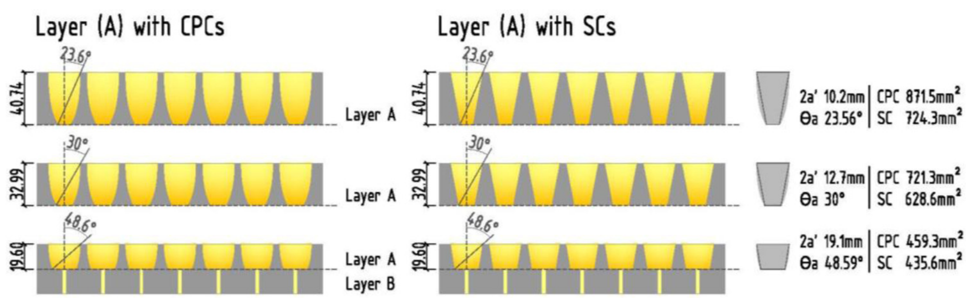


Fig. 8. Layer A plus Layer B test panels (in millimeters).

Table 2. Illuminance results for Tests 1–3

Civil time	Test 1 same density (lux)			Test 2 same grid (lux)			Test 3 same spacing (lux)		
	3 mm	6 mm	10 mm	3 mm	6 mm	10 mm	3 mm	6 mm	10 mm
10:30	175.3	296.6	228.4	87.7	750	1,003	345	1,354	1,509
10:45	276.6	363.4	366.6	107.7	678	1,341	520	1,769	2,201
11:00	436	449	544	159	861	1,898	778	2,373	3,402
11:15	589	557	524	303	1,054	2,770	1,085	3,333	5,450
11:30	798	655	666	367	1,254	3,589	1,387	4,280	6,500
11:45	997	748	625	425	1,450	4,220	1,530	5,190	7,700
12:00	1,118	838	453	463	1,618	4,300	1,750	5,700	8,700
12:15	1,168	933	360	528	1,785	5,300	1,960	6,190	9,280
12:30	1,198	997	340	535	1,865	4,860	2,040	6,540	8,660
12:45	1,218	1,055	368	487	1,889	5,410	2,020	6,700	8,000
13:00	1,228	1,062	334	483	1,914	4,680	2,030	6,740	8,080
13:15	1,233	1,025	306	473	1,905	4,980	2,000	6,920	8,470
13:30	1,245	997	313	480	1,869	4,600	1,940	6,770	8,200
13.45	1,208	962	360	536	1,797	4,580	1,860	6,380	8,230
14:00	1,148	888	435	558	1,655	4,860	1,710	5,850	8,870
14:15	1,020	797	573	495	1,477	4,170	1,490	5,180	8,020
14:30	830	698	632	398	1,266	3,514	1,309	4,470	7,310
14:45	678	601	600	304	1,070	2,745	1,081	3,722	4,880
15:00	519	501	476	223	875	2,024	773	2,714	3,133
15:15	343.2	404	280	154	714	1,420	518	1,966	2,082

Table 3. Illuminance results for Test 4

Civil time	OFs with different panel thicknesses (lux)			ARs with different panel thicknesses (lux)		
	12.7 mm	57.2 mm	114.3 mm	12.7 mm	57.2 mm	114.3 mm
11:00	1,674	1,578	1,586	1,194	700	1,137
11:15	2,700	2,403	2,485	2,205	990	1,768
11:30	3,620	3,100	3,433	3,082	1,345	2,585
11:45	4,190	3,710	3,930	4,060	1,720	3,090
12:00	4,680	4,360	4,650	4,620	2,350	3,540
12:15	4,900	4,650	5,200	4,280	2,980	3,840
12:30	5,160	4,710	5,400	4,980	3,180	3,990
12:45	5,220	4,880	5,380	5,000	3,580	4,250
13:00	5,280	5,050	5,380	5,000	3,920	4,400
13:15	5,340	5,100	5,420	5,230	3,680	4,360
13:30	5,140	4,980	5,300	5,030	3,430	4,200
13:45	5,130	4,790	4,940	5,820	3,030	3,980
14:00	4,740	4,380	4,580	4,150	2,480	3,670
14:15	4,390	3,930	4,190	3,660	1,780	3,180
14:30	3,890	3,518	3,515	3,422	1,501	2,768
14:45	2,860	2,670	2,200	2,200	1,030	1,830
15:00	2,165	2,020	1,582	1,460	804	1,297
15:15	1,461	1,405	1,113	913	598	877
15:30	1,000	977	821	618	463	598

Test 6: Layer B Plus SCs Layer

Test 6 was the same as Test 5, but in the latter case, the three Layer B panels were outfitted with SCs of three different half acceptance angles (Layer A) and tested together. The objective of the test was to determine the influence of the SCs with the OFs on the light transmission (Fig. 8).

Light Transmission Test Results

The ultimate goal of the conducted tests was to demonstrate the light transmission effectiveness of the proposed building envelope using TCPs. The results could be used as a first step toward the optimization of the light conduit diameter and spacing (i.e., the density and panel thickness) for the maximum daylight transmission through the panels. The tests took place outdoors on the University of California, Berkeley, California campus.

Outdoor Test Results for Layer B

Fifteen panels were tested under direct sunlight over the course of two days. The panels were held in a horizontal position on the test box, and measurements (in lux) were taken with an illuminance meter that was placed at the back (bottom) of the box. The purpose of this test was twofold: (1) to observe the behavior of the test panels with embedded OFs under direct beam radiation from a daylight source and (2) to observe the effect of the solar incidence angle on the amount of light transmitted through the test panels.

The tests were conducted on two different days. Tests 1–3 were conducted on July 1, 2013, from 10:30 to 15:15 civil time (Table 2), and Test 4 was conducted on June 7, 2013, from 11:00 to 15:30 (Table 3). The test box was placed on a bench to raise it approximately 0.40 m above nearby obstructions and facing a wall that had never blocked the capture of sunlight during the hours of the tests. The illuminance meter was inserted into a hole at the bottom of the test box to measure the light transmission from outside to inside the box (in lux). The illuminance readings were recorded every 15 min. for each test panel. The test setups are shown in Fig. 9. For both days, the weather conditions were relatively consistent throughout the tests. According to the Florida Solar Energy Center (Michalsky 1988), the maximum solar incidence angle at solar noon in San Francisco on the day of Tests 1–3 and 4 was 75.46 and 75.24° at 13:15 and 13:10 civil time, respectively.

Test 1 Results: Same Density

Fig. 10 shows that, at the beginning and end of the test duration, the three panels transmitted approximately the same amount of light. The highest illuminance readings were recorded with the 3-mm-OF panel and were observed at around solar noon (i.e., 13:15 civil time). In contrast, the readings from the panel with 10- mm-OF decreased during the middle of the day and were highest at 11:30 and 14:30 civil time. The panels with 3- and 6-mm OFs showed a similar trend in the variation of light transmission over the course of the day. Unlike the panels with 3- and 6-mm OFs, the panel with 10-mm OFs showed a decrease in light transmission in the middle of the day. The maximum light transmission through the 10-mm panel was observed at 11:30 and 14:30 civil time. As expected, this test was biased toward the smaller OFs for which more of the transmitting area was near the center of the test box where the measurements were taken. However, for the larger OFs, positioning several fibers close to the corners led to emitted light striking the black walls without being measured.

(a) (b)

Fig. 9. Overall images of the setup for Tests 1–4: (a) setup; and (b) illuminance meter.

Test 2 Results: Same Grid

Throughout the second test, the illuminance readings were greater in panels with larger OF diameters (and larger cross-sectional areas of the OFs). The results from the three panels deviated significantly, and the maximum values were observed in the middle of the day (Fig. 11). At every point throughout the day, the quantity of light transmission per unit of cross-sectional area was greatest in the panel with 3-mm OFs.

Test 3 Results: Same Spacing

Fig. 12 shows that the illuminance readings were greater in the panels with larger OF diameters (and larger cross-sectional areas of the OFs). The results from the three panels deviated significantly, and the greatest deviation was observed in the middle of the day, but did not remain proportional throughout the test duration. The panel with 10-mm OFs exhibited a behavior similar to that of Test 1, with readings decreasing in the middle of the day. The light transmission through the 10-mm-OF panel was greatest at 12:15 and 14:00 civil time. At every point throughout the day, the quantity of light transmission per unit of cross-sectional area was largest in the panel containing the 6-mm OFs.

Test 4 Results: Varied Thicknesses

All the panels with OFs transmitted the greatest amount of light at solar noon (readings taken at 13:15 civil time). The highest readings in the AR panels were less consistent and observed within 35 min. from solar noon. The maximum value in light transmission occurred when the solar incidence angle was at the highest position. As shown Fig. 13, at most points in time, the highest readings were observed with the panels that were 12.7 mm thick, for which the panel with ARs gave higher readings for every test and that with the OFs gave higher readings only at the beginning and end of the day. In contrast, the lowest readings were observed in the 57.2-mm-thick

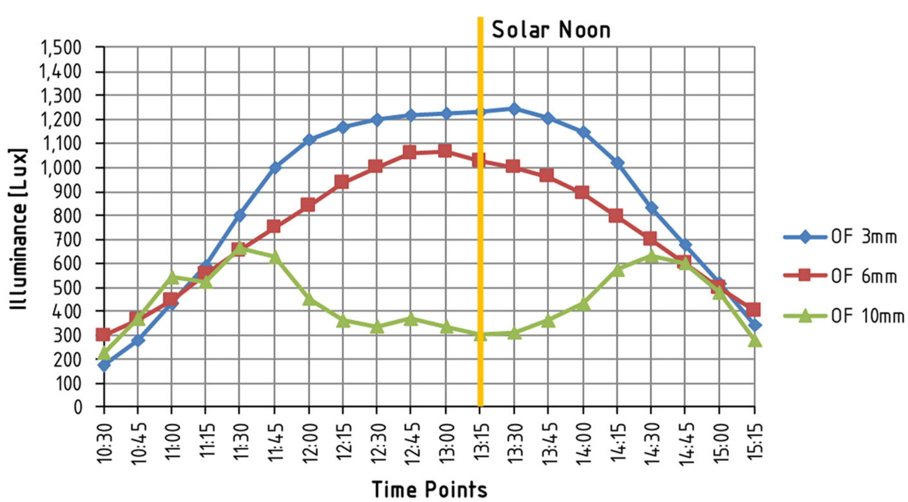


Fig. 10. Illuminance results from Test 1 (same density).

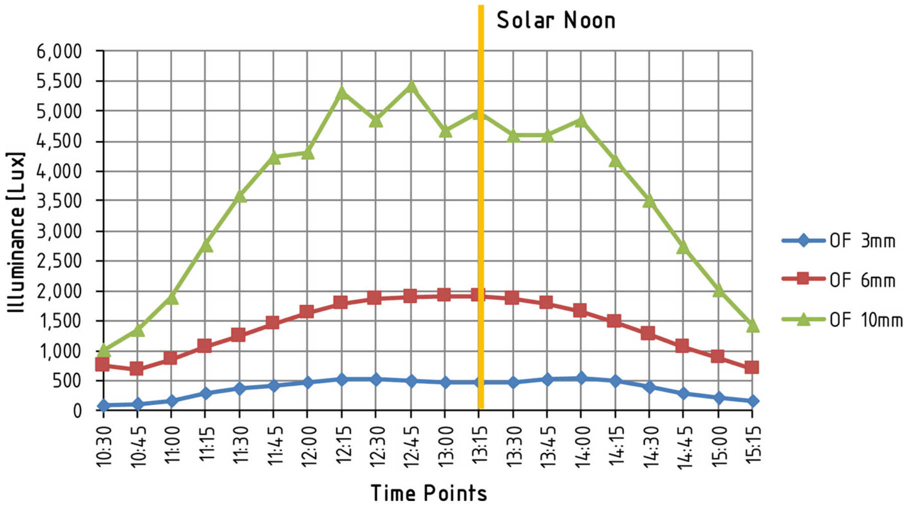


Fig. 11. Illuminance results from Test 2 (same grid).

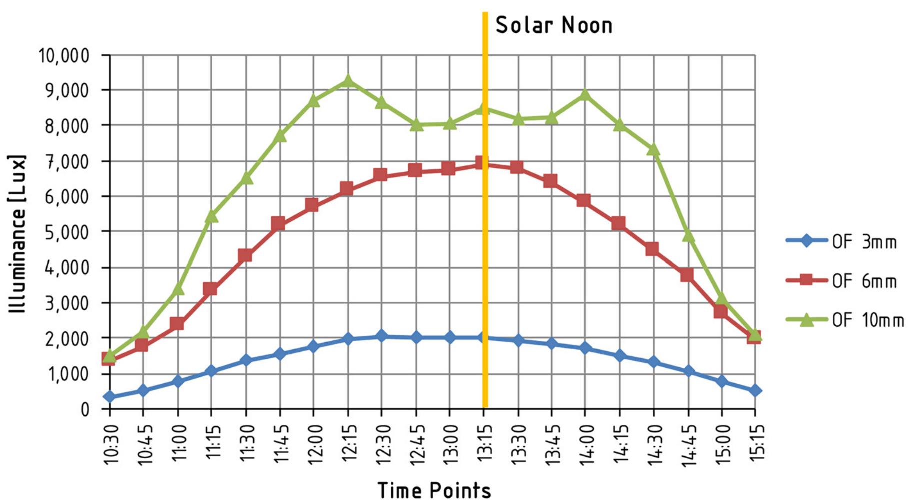


Fig. 12. Illuminance results from Test 3 (same spacing).

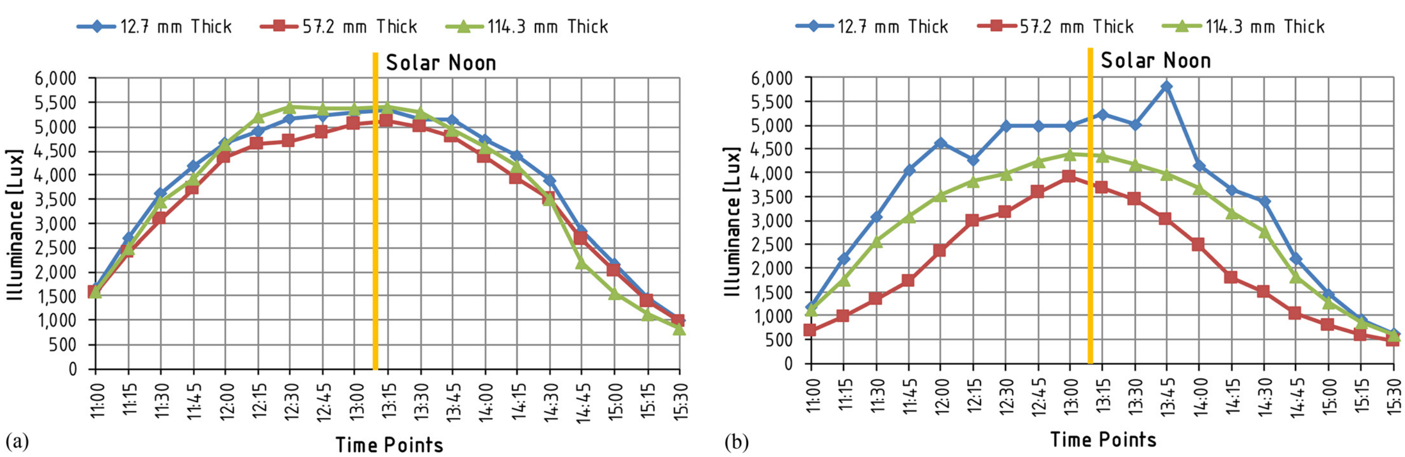


Fig. 13. Illuminance results from Test 4 (varied panel thicknesses): (a) embedded OFs; and (b) embedded ARs.

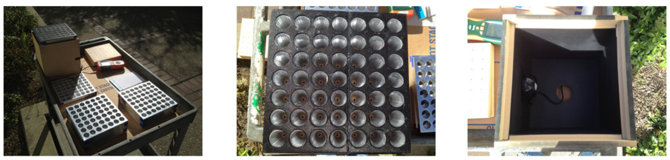
panels. The relationship between the readings from the three panels remained consistent in the AR tests but varied significantly in the OF tests. The 114.3-mm-thick panel with OFs gave the highest readings in the middle of the day but performed worse than the thinner panels when the sun incidence angle was lower (at the beginning and end of the day).

Table 4. Illuminance results for Tests 5 and 6

Civil time	TCPs with 3-mm OFs (lux)						TCPs with 6-mm OFs (lux)						TCPs with 10-mm OF (lux)					
	CPC 23.6°	SC 23.6°	CPC 30°	SC 30°	CPC 48.6°	SC 48.6°	CPC 23.6°	SC 23.6°	CPC 30°	SC 30°	CPC 48.6°	SC 48.6°	CPC 23.6°	SC 23.6°	CPC 30°	SC 30°	CPC 48.6°	SC 48.6°
09:30	5.9	5.0	8.8	6.2	16.2	11.1	41.7	37.0	64.1	44.6	84.3	69.6	90.0	71.8	139.7	96.3	220.5	169.0
09:45	6.4	5.9	9.8	6.7	20.4	13.5	93.8	72.7	58.4	45.1	93.8	72.7	96.1	76.4	158.8	103.3	233.7	176.9
10:00	0.0	0.0	0.0	0.0	10.0	3.0	33.0	20.0	62.0	35.0	96.0	74.0	91.0	66.0	166.0	104.0	258.0	202.0
10:15	0.0	0.0	0.0	0.0	12.0	7.0	39.0	34.0	73.0	43.0	121.0	119.0	108.0	86.0	204.0	130.0	301.0	253.0
10:30	0.0	0.0	2.0	0.0	27.0	13.0	54.0	52.0	93.0	58.0	149.0	145.0	130.0	107.0	241.0	156.0	365.0	325.0
10:45	0.0	0.0	4.0	0.0	30.0	18.0	60.0	52.0	109.0	80.0	176.0	157.0	152.0	133.0	275.0	191.0	433.0	390.0
11:00	0.0	0.0	4.0	2.0	37.0	25.0	69.0	69.0	102.0	92.0	185.0	182.0	176.0	160.0	325.0	229.0	552.0	429.0
11:15	1.0	0.0	16.0	7.0	39.0	26.0	78.0	86.0	123.0	94.0	253.0	219.0	196.0	188.0	365.0	290.0	654.0	548.0
11:30	23.4	20.7	41.3	33.7	52.0	26.0	101.0	109.0	163.0	135.0	219.0	163.0	225.0	247.0	393.0	350.0	854.0	1,150.0
11:45	12.0	4.0	36.0	35.0	65.0	24.0	124.0	135.0	210.0	200.0	265.0	244.0	264.0	277.0	425.0	400.0	1,241.0	1,194.0
12:00	19.0	8.0	43.0	43.0	114.0	38.0	145.0	156.0	202.0	221.0	443.0	457.0	304.0	327.0	473.0	508.0	1,184.0	1,304.0
12:15	29.0	18.0	60.0	73.0	95.0	92.0	166.0	191.0	247.0	280.0	422.0	458.0	319.0	366.0	545.0	630.0	1,712.0	1,530.0
12:30	42.0	31.0	68.0	73.0	106.0	70.0	192.0	208.0	256.0	305.0	708.0	782.0	394.0	430.0	583.0	680.0	2,000.0	1,869.0
12:45	48.0	43.0	70.0	77.0	133.0	90.0	215.0	235.0	282.0	334.0	733.0	718.0	437.0	452.0	645.0	769.0	2,022.0	2,040.0
13:00	45.0	38.0	64.0	72.0	120.0	94.0	213.0	237.0	268.0	342.0	582.0	785.0	462.0	477.0	658.0	786.0	1,793.0	1,910.0
13:15	43.0	47.0	59.0	82.0	142.0	83.0	207.0	239.0	268.0	350.0	658.0	625.0	445.0	487.0	610.0	813.0	1,753.0	1,885.0
13:30	37.0	38.0	63.0	75.0	139.0	78.0	194.0	225.0	240.0	340.0	703.0	737.0	435.0	480.0	599.0	850.0	1,813.0	1,959.0
13:45	29.0	30.0	48.0	72.0	121.0	63.0	178.0	208.0	224.0	314.0	752.0	674.0	418.0	450.0	545.0	784.0	1,780.0	1,570.0
14:00	21.0	24.0	29.0	50.0	43.0	59.0	157.0	173.0	196.0	287.0	610.0	579.0	363.0	374.0	498.0	681.0	1,661.0	1,674.0
14:15	18.0	17.0	28.0	46.0	46.0	52.0	136.0	140.0	170.0	245.0	482.0	425.0	342.0	353.0	440.0	570.0	1,422.0	990.0
14:30	10.0	8.0	25.0	30.0	30.0	25.0	107.0	126.0	146.0	206.0	242.0	337.0	282.0	285.0	381.0	467.0	790.0	881.0
14:45	4.0	6.0	19.0	13.0	18.0	15.0	89.0	104.0	123.0	165.0	117.0	161.0	240.0	228.0	332.0	336.0	543.0	496.0
15:00	1.0	0.0	11.0	5.0	14.0	15.0	78.0	77.0	102.0	98.0	134.0	137.0	212.0	189.0	289.0	292.0	255.0	375.0
15:15	0.0	0.0	6.0	2.0	9.0	20.0	63.0	60.0	82.0	71.0	116.0	142.0	167.0	158.0	247.0	225.0	350.0	437.0
15:30	0.0	0.0	1.0	0.0	6.0	19.0	43.0	44.0	70.0	63.0	94.0	135.0	144.0	122.0	214.0	182.0	243.0	343.0
15:45	0.0	0.0	0.0	0.0	5.0	16.0	35.0	34.0	58.0	41.0	93.0	132.0	114.0	87.0	180.0	138.0	257.0	336.0

Outdoor Test Results for Layer A Plus Layer B

In the outdoor test series, six panels outfitted with CPCs and SCs were tested under direct sunlight throughout the day together with the panels outfitted with OFs (the same test panels from Test 2). As explained in "Experimental Study Approach," the test panels were placed horizontally on the test box and measurements were taken (in lux) with an illuminance meter that was placed on the south side of the testing box facing directly opposite to the sun. The purpose of this test was twofold: (1) to observe the behavior of both layer A and layer B, working together under direct beam radiation with a sunlight source and (2) to observe the effects of the incidence angle on the amount of light that was transmitted through the test panels.



(a) (b) (c)

Fig. 14. Setups for Tests 5 and 6: (a) setup; (b) Layer A + Layer B panels; and (c) illuminance meter.

The test was conducted on September 4, 2013, from 9:30 to 15:45 (Table 4). The test box was placed on a cart to raise it above the nearby obstructions. The illuminance meter was inserted into the hole in the south-facing panel of the test box and was used to measure the light transmission to the inside of the box (in lux). The illuminance readings were recorded every 15 min. for each test panel. The test setup is shown in Fig. 14. For both tests, the weather conditions were relatively consistent throughout the tests. According to the Florida Solar Energy Center (Michalsky 1988), the maximum solar incidence angle in San Francisco on the day of Tests 5 and 6 was 59.30° at solar noon (13:08 civil time).

Results of Tests 5 and 6

All the panels transmitted the maximum amount of light at solar noon (readings taken at 13:15 civil time). However, as shown in Fig. 15, the tests using only the Layer B panels transmitted more light into the box than did Layers B and A when tested together. In another scenario, the panels with SCs that formed Layer A

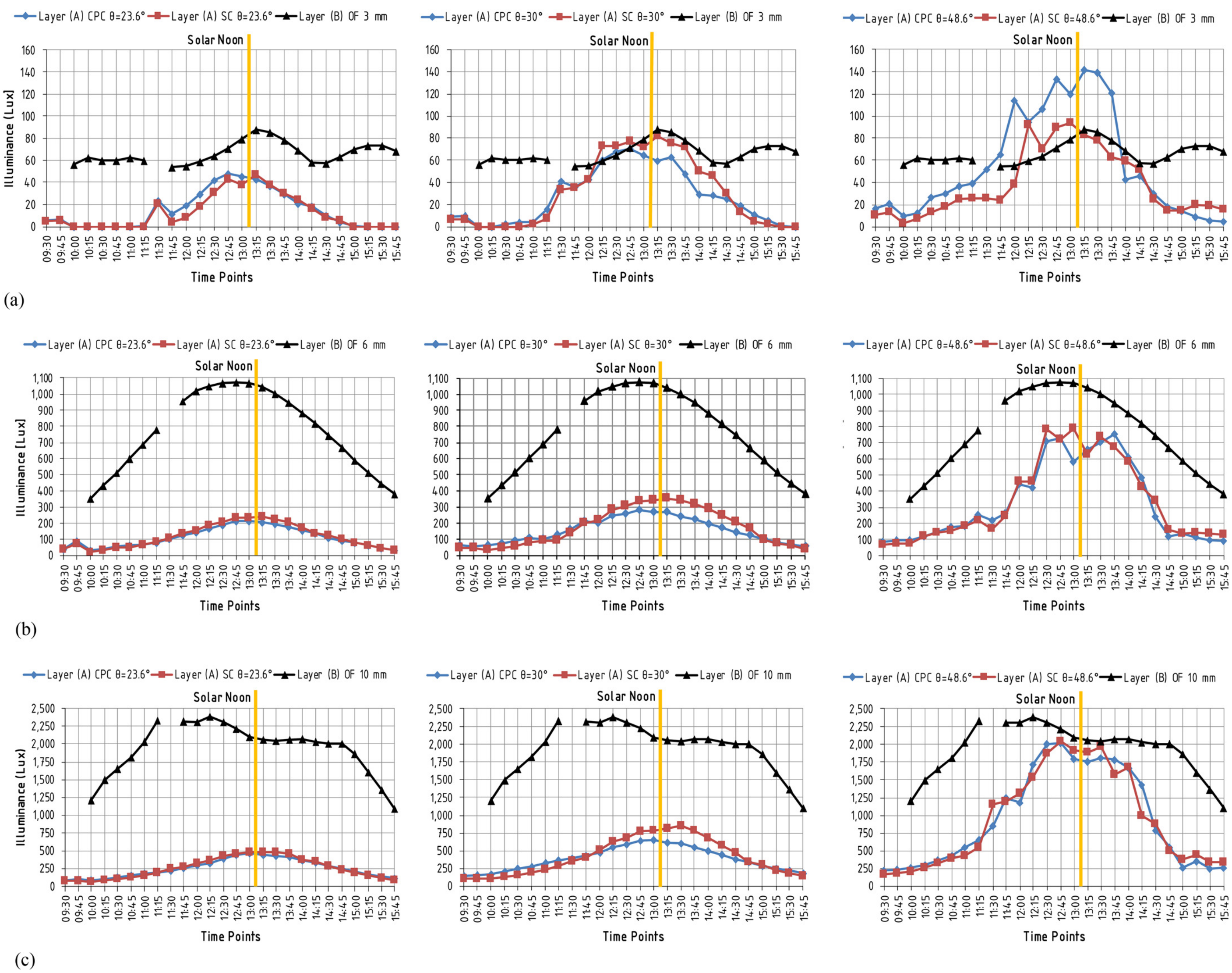


Fig. 15. Layers A + B outdoor results: (a) OF 3 mm; (b) OF 6 mm; and (c) OF 10 mm.

transmitted more light through the OFs into the testing box than did the panels with CPCs. The graphs in Fig. 15 show that a system of CPCs or SCs and OFs, with a half acceptance angle of 48.6° for the cones, allowed more transmission of light. This finding was the result

of the big acceptance angles capturing sunlight over larger solar altitudes than did CPCs or SCs with small half acceptance angles. All the cones accepted the same amount of light because all of them had the same maximum value for d_1. Therefore, for all the panels, the same amount of light affected the top surface where part of that light was either transmitted or reflected.

Concluding Remarks

The present study faced different physical limitations, such as real overcast scenarios, but all the readings took place when the sunlight incidence angle was highest: June, July, and beginning of September. However, from outdoor Tests 1–4, one concludes that the OFs provided more light transmission than did ARs. In spite of this, the light transmission behavior was similar for both cases. For Layer B tests, it was confirmed that the distribution and separation from edge to edge of the fibers were important for getting more light delivered to the floor of a space; for example, for the Test 1 panel with 3-mm OFs embedded, more light was received at the floor than was received with the other panels of larger OF diameters and greater OF densities. This finding was attributed to the transmitting area being concentrated around the center of the test box while the daylight emitted by larger OFs at the perimeter of the box struck the black walls without being measured. In general, apart from the OF density in the panel, OFs with small diameters worked better during noon time than did OFs with larger diameters. Therefore, it is necessary to (1) explore other inclinations of the panels and (2) improve the OF geometry for transmitting more natural sunlight in vertical or horizontal orientations without the necessity to incline the panel.

It was observed that cones with bigger acceptance angles could transmit more sunlight through the OFs than cones with smaller angles could. Initially, the results seemed inconsistent, but for maximum efficiency, it was necessary that the rays of sunlight fall within the NA of the OF. In this case, the cones had acceptance angles similar to the NAs of the OFs. Therefore, a major part of the sunlight was lost and not able to exit from the other end. It is necessary to (1) explore other CPCs and SCs with an appropriate half acceptance angle that is compatible with the one from the OF and (2) improve the cone distribution for transmitting more natural sunlight in vertical or horizontal orientations without the need to incline the panel.

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