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Spectral light transmission measure and radiance model validation of an innovative transparent concrete panel for façades

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Abstract

This paper presents an approach to measure, characterize and simulate photometric performances of light transmission efficiency of an innovative transparent concrete panel for façades. The transparency was obtained by a texture of PMMA resin insertions in the fiber reinforced concrete panel.
In the first part of the paper integrating sphere measurements were collected to derive spectral optical properties of the panel. The optical properties of a specimen were measured for incidence angles between normal and 60° and the spectral results were reported.
The data collected during the measures were used to: create and validate a simplified Radiance model of the panel and to optimize simulation parameters to estimate properly the total internal reflections effects thought the PMMA resin insertions.

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1. Introduction

The study presents the first results of an innovative component for façade application. It is a precast concrete panel, made by combining an innovative mortar with PMMA resin insertions that give partial

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transparency to the panel providing daylighting to the built environment (Fig. 1.c). It was used for the first time as a façade cladding and shading system for the Italian pavilion for EXPO Shanghai 2011.

Light and transparency control are always important drivers of innovation for architecture design and new façade solutions. This panel satisfies the request to give the transparency to a well-known generally opaque material. Nowadays technological transfer processes also permits to architects and engineers to choose and use different kind of materials, and composite materials coming from various industry fields, and to apply them as day lighting or solar control system to response to an innovative building design idea (i.e. metal mesh grid or innovative materials texture inclusions in window panes etc.). Frequently, as in the early design stage as in implementation stage, the performances of the system is not well known or known at all. Nowadays it's necessary to develop an easy to apply procedure to measure or to simulate complex shading and daylight control system [1],[2]. It's also necessary the development of a large scale database of transparent and semi-transparent materials to help and guide the designer to choose the better solution, combining shape, design and functionality.

2. Panel description

The transparent concrete panel permits light to filter inwards and outwards, ensuring transparency combined with an adequate mechanical resistance that gives to the panel feasibility for different applications. The average standard panel is 1000 mm long and 500 mm wide with a 40 mm thickness and a weight of 40 kg. It can be used for façade or floor cladding, in addition or in substitution to other cladding solutions. Due to the mechanical resistance it can also be used to realize transparent floors, as a cladding secondary structure.

The cement is C CLASS 52.5 R, Type I to provide rapid hardening and a high strength. The mix design is obtained with a selected siliceous-calcareous sand/gravel with an appropriate granulometry to obtain a compact granular skeleton. Stainless steel fibers are added to the mix design to provide a high toughness and ductility. Polypropylene fibers are also added to minimize the crack risk at the early stages of production. There is also a suitable mix of admixtures to improve the rheology at fresh state and to reduce the stiffness of cementitious matrix.

The panel has a structural elastic limit of 1.92 Mpa and a peak stress of 7.70 Mpa with a plastic behavior after peak stress.

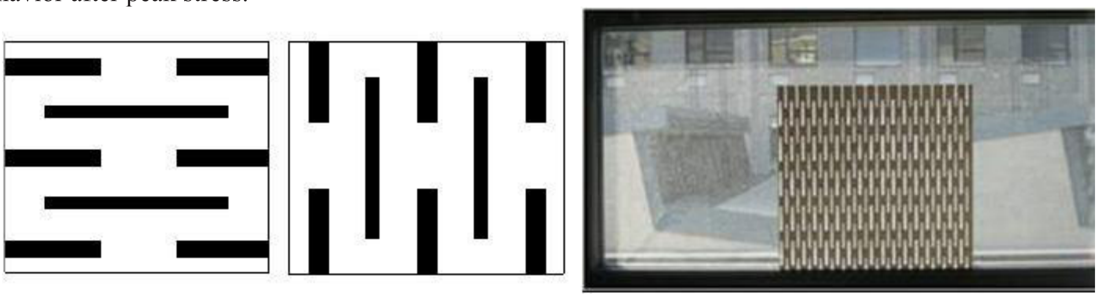


Fig. 1. (a,b) Resin insertion texture of a transparent panel. Depending on the orientation of the panel the texture can be horizontal or vertical. (c) The middle section of a transparent concrete panel

The resin insertions (Fig.1 a,b,c) are realized in polimetilmetacrilate (PMMA) because of its chemical compatibility and resistance to alkali contained in the cement matrix. Because of its transparency of at least 92% [3] (visible) and its good resistance to UV radiation PMMA is sometimes used as a glass substitute in curtain wall façades and windows.

The resin insertion texture can be different in colors and in resin gap spacing to obtain a less transparent panel with a reduced openness factor.

The sample is obtained from the middle section of a standard panel of 1000 mm x 500 mm. A first qualitative analysis of the sample was made up with an incident laser beam moving over the external surface of the concrete panel with different incidence angles. The sample shows a specular (i.e. that is mirror-like) distribution of beam transmission with a definite angular dependency on the beam transmission (Fig. 2.a). The total internal reflection for the resin gap is complex to determine or estimate but affect the panel response to light. Depending on the solar radiation incidence angle and on the position of the observer a specular light reflection could be observed.

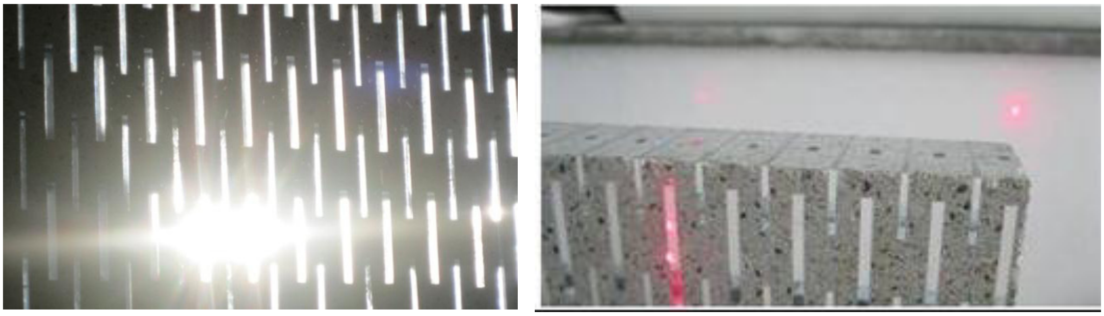


Fig. 2. (a) Internal edge reflection of a light source. (b) The Total internal reflection and transmission of a laser beam

3. Experimental

3.1. Experimental set-up description

The optical characterization of complex and bulk scattering samples cannot be carried out using commercial spectrophotometers, even if equipped with integrating spheres. The selected samples are characterized by an alternation of opaque and transparent area; hence the incident radiation beam area must be large enough to irradiate a significant portion of the sample itself. Large integrating sphere are needed to perform accurate measurements on such materials. The angular and spectral optical testing of thick assembled concrete/PMMA tiles was carried out by means of an optical bench consisting of the following parts:

- A 300 Watt xenon-ozone free halogen lamp. The collimated beam diameter can be modulates through a diaphragm according to the measurement requirements. Usual diameters range from 4 to 10 centimeters;
- The light source is mounted on a holder, which can rotate arm in order to vary the beam angle of incidence;
- An integrating sphere with a 100 centimeters diameter. The external shell of the sphere is made of aluminium, while the internal surface is made of barium sulphide, a white material with a reflectivity greater than 90% in the visible range (300-800 nanometers). The sphere is equipped with several ports and a central sample holder; the layout of the facility can be adjusted in order to perform transmittance, reflectance and absorbance measurements.
- Detection system consisting of three array spectrometers and the three following detectors: NMOS for the 250-1000nm range (dispersion 1.4 nm/pixel); InGaAs for the 900-1700nm range (dispersion 3.125

nm/pixel); ExtInGaAs for the 1600-2500nm range (dispersion 3.52 nm/pixel).Only the first detector was effectively used in this campaign, since only the sample characteristics in the visible range were investigated.

Fig. 3. (a,b)View of the optical bench including: the light source, the integrating sphere, the sample holder for the transmittance mode. (c) shows the experimental facility in the transmittance measurement mode. The spectral transmittance was performed on the selected samples

The procedures are following described:

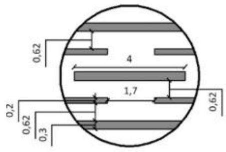
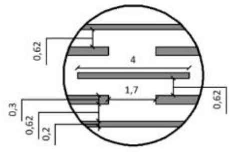
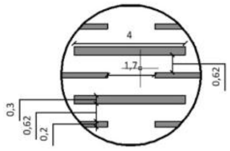
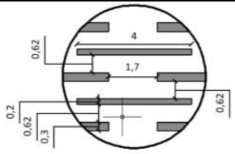
- The sample port is 25 cm in diameter and the incident beam diameter is optimized as described in the next paragraph.
- The transmittance is measured as the ratio of the energy transmitted by the specimen mounted on the sample port on the energy directly entering the sphere, see figure Fig 3. The measurement is corrected with the auxiliary port correction method [4],[5].
- The measurements are performed at the following incidence angles: 0°, 30°, 45°, 60°. An incidence angle greater than 60° was not significative for the measure because of the geometry of the panel.
- Measurements were performed between 350 and 1200nm, covering the whole visible range and the 75% of the whole solar range. The solar quantities were calculated starting from the spectral data using the reference solar spectrum defined in [6].

3.2. Optimal incident beam diameter definition

A preliminary analysis shows that the light transmittance value of the sample panel, with an incidence angle of the light beam of 0°, varies in accordance to different incidence points of the light beam on the sample and to different beam light diameter. Because of the particular texture and geometry of the sample is it possible to identify four areas which are the most representative incidence areas of a circular light beam on the sample.

All these areas have a different and significative ratio between the transparent surface (PMMA) and the opaque surface (mortar) as shown in Table 1. A beam incidence diameter of 7.11 cm is chosen to avoid all the problems due to positioning. With the chosen beam dimension the differences in ratio between two different incidence points on the surface are always under the 1.2%

Table 1. Beam incidence areas

A1	A2	A3	A4
			
Ratio between transparent and opaque portion of the incidence area			
30.33%	**25.90%**	**24.54%**	**23.44%**

3.3. Measurement results

The angular measured light transmittance values not only depend on the rectangular resin insertions percentage but also on their orientation (parallel or perpendicular to the light incidence angles plane). Hence the panel was measured for 5 different incidence angles and for 2 different orientations (V-Vertical and H-Horizontal).

Figure 3 present the spectral curves, measured at five angles of incidence for the two panel orientations. Figure 4 present the angular decay curves of the sample for the two orientations. Integrated values were calculated according to EN410.

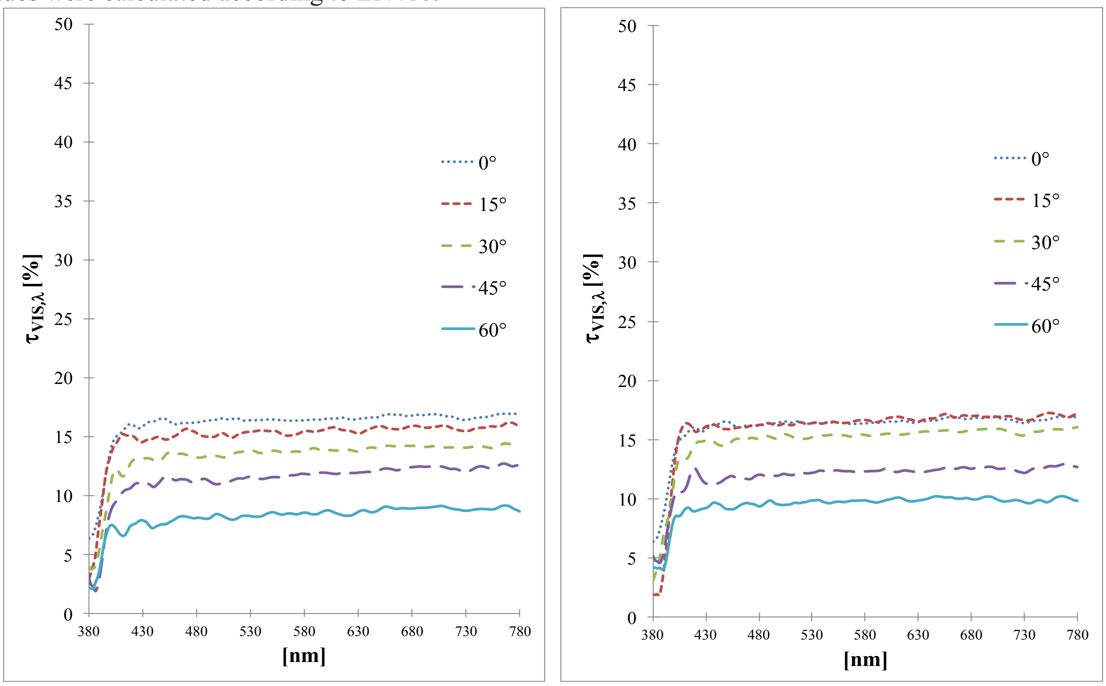


Fig. 4. (a) Spectral values of angular light transmittance (380-760 nm) of the (V) sample. (b) Spectral values of angular light transmittance (380-760 nm) of the (H) sample

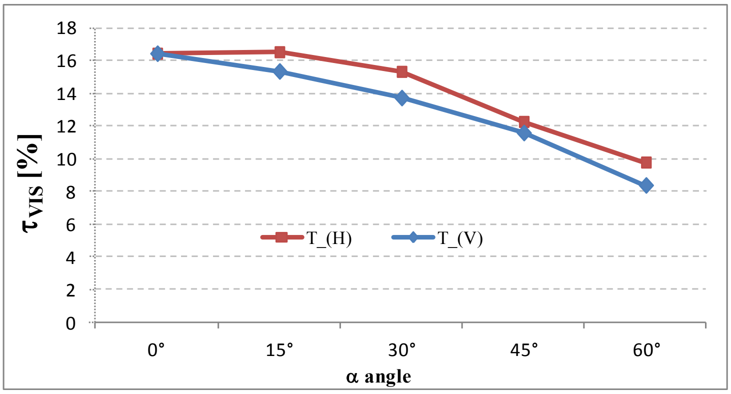


Fig. 5. (a) Integrated values of angular light transmittance (380-760 nm) of the samples (V) and (H)

4. Calculation

4.1. Calculation procedure

The main purpose of the calculation is to obtain with a simulated test case the simulation results in accordance with the integral angular light transmittance values measured. The secondary purpose of the calculation is to propose a simplified method to evaluate the light transmittance value of the panel.

A real size 3D panel was modeled with the Autodesk Ecotect Analysis 2011 geometry generator to generate an input for LBNL Radiance 2.0, due to its accuracy in simulating day lighting system [7], [8]. Because of its geometry and its particular texture it was not possible to evaluate a 2D dimension model. The angular dependency of the light transmittance measured with the experimental procedure shown in Cap. 3 depends not only on the panel texture, but also on its thickness. It was possible to subdivide and deconstruct the panel in a few number of similar small 3D components consequently repeated to obtain the whole geometry (Fig 6. a,b)

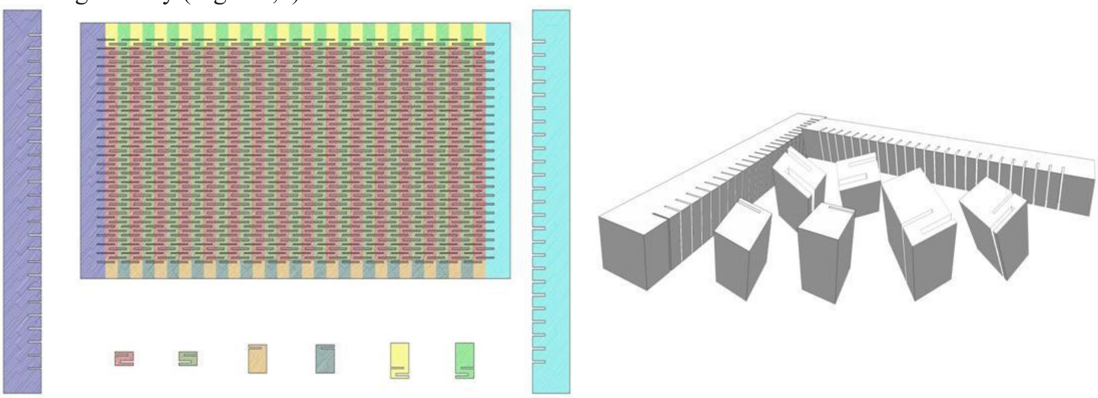


Fig. 6. (a,b) Panel geometry subdivision

In accordance with the optical behavior of the panel (Fig 1.) and to partially reproduce the total internal reflection in the resin gaps, the PMMA inclusions were modeled as small canyons with the internal vertical surfaces as a *mirror* material, with 99% reflectance, plus a *glass* surface planar to the external surface of the panel (Fig 7.), with a light transmittance value equal to 92% measured for PMMA. In this simplification it's also assumed that the Refractive index of PMMA is similar to float glass refractive index.

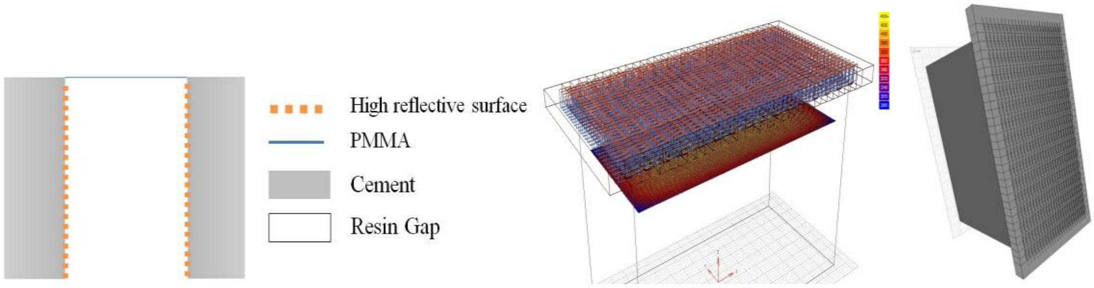


Fig. 7. (a)Resin "canyon" cross section: Simplification of the resin gap as a canyon with high reflective vertical surfaces. (b,c) simulation test facility

The virtual test facility is constituted by a real size panel and a box with a missing face. The panel is adjacent to the box on the missing face. On the back of the panel, inside the box, there is an analysis grid that detects the illuminance value inside the box, on the back of the panel on a parallel plane 10 cm distant (Fig.7 b,c). The inside surface of the box as a light absorbance of 100%.

The Autodesk Ecotect Desktop Analysis 2011 interface was used not only to create the geometry but also to edit Radiance data and to set up the simulation parameter. All the results obtained from Radiance calculation were back imported on Ecotect Analysis grid to evaluate the performance of the system.

The box and the panel were oriented to receive the light directly from a modeled Sunny Sky or a Uniform sky. The sun is the light source and the incident radiation on the external surface of the panel had incidence angles equal to the ones used for the laboratory measures. The Ecotect Riyhad (Saudi Arabia) weather file was used in this evaluation. For sunny sky simulations on 12:00 the 21st of June the sun is close to Zenith (Radiance approximate the sun elevation to 87°). With an additional 3° correction, because of a Radiance limitation, if the panel is oriented South all the incidence angles of the test facility could be obtained rotating the panel around x or y axis.

The ratio between the illuminance levels on the analysis grid calculated with and without the panel over the opened box to estimate the light transmittance of the panel. To reduce the boundary effect dependent to the box edges and their projection on the analysis grid caused by the test facility slope, the illuminance level were obtained from a middle section and from the whole surface of the analysis grid for both cases.

4.2. Calculation results

A sensitivity analysis of the optimal *–ad, –as,-lm* Radiance parameters (based on several simulations) and of the reflectance of the Radiance *mirror* material suggested to use really high values to obtain results consistent to the measures.

Figure 8 shows an example of the several trend analysis of the illumination level measured on the analysis grid inside the box, depending on the *–ad* radiance parameter variation. This parameter strongly influences the results and in this case all the values were obtained with *–as* parameter constant at 256 and 0° incidence angle: the illumination values in graph are indicative. High numbers of *-ad* were used for all the simulation in accordance with the asymptotic trend shown in the graph and in particular *–ad* 10240 for sunny sky simulations and *–ad* 25600 for uniform sky simulation. All the other simulation values were determined with several simulations, to optimize the results. Results for uniform sky conditions are obtained with a ratio between the *–as* and *–ad* values between 1/1 and 1/4. All the used values are summarized in Table 2.

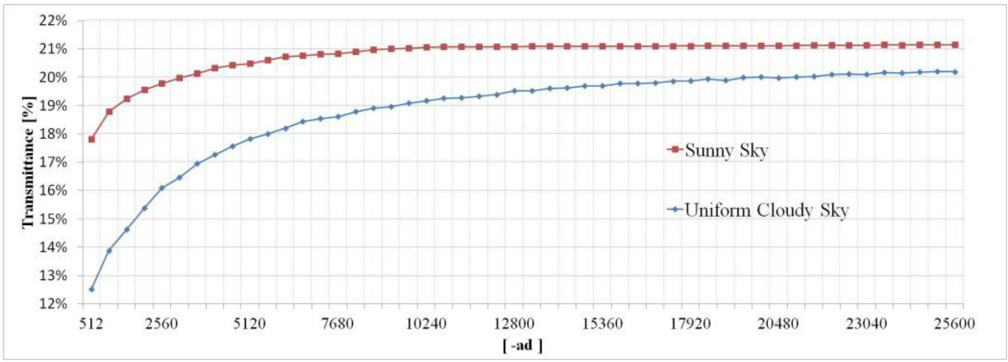


Fig. 8. Assessment of -ad Radiance parameter for one panel and for both sky conditions: Sunny Sky and Uniform Sky

The accordance between the simulated and measured values (Table 3 and Fig. 9a, b), with the analysis grid at 10 cm to the panel plane, is partially adequate for a simplified analysis for transparent panel with H - horizontal orientation and only for uniform sky sun conditions. There is an average difference of 10 to 12% between simulated and measured values. The angular light transmission values for V - vertical generally overestimate the measured transmittance values. The decreasing trend is not reproduced as clear as in the previous case and highlight some limits of a simplified analysis.

Table 2. Radiance simulation parameters for uniform sky conditions simulations

Radiance simulation parameters							
Analysis Quality	**-dp**	**-ar**	**-ms**	**-ds**	**-dt**	**-dc**	**-dr**
HD	2048	32	0.063	0.2	0.05	0.75	3
-st	**-ab**	**-aa**	**-ad**	**-as**	**-av**	**-lr**	**-lw**
0.01	30	0.1	25600	6400	0.001	96	0.0005

Table 3. Transparent panel uniform sky: comparison between measured integrated values and simulation results. The values are expressed for the center of the analysis grid for a 10x10 cm sub-grid (C), and as an average value on the whole analysis grid (A)

Angular light transmission t_{vis} – Vertical	**0°**	**15°**	**30°**	**45°**	**60°**
(V_M) Laboratory measures	16.40 %	15.30 %	13.70 %	11.60 %	8.40 %
(V_S_A) Radiance simulation results (average)	14.96 %	12.36 %	14.65 %	13.46 %	11.30 %
(V_S_C) Radiance simulation results (center)	14.81 %	13.47 %	14.50 %	13.11 %	10.54%
Angular light transmission t_{vis} – Horizontal	**0°**	**15°**	**30°**	**45°**	**60°**
(H_M) Laboratory measures	16.40 %	16.50 %	15.30 %	12.30 %	9.80 %
(H_S_A) Radiance simulation results (average)	14.97 %	14.98 %	13.58 %	11.41 %	10.16 %
(H_S_C) Radiance simulation results (center)	14.87 %	14.86 %	13.74 %	11.10 %	9.75 %

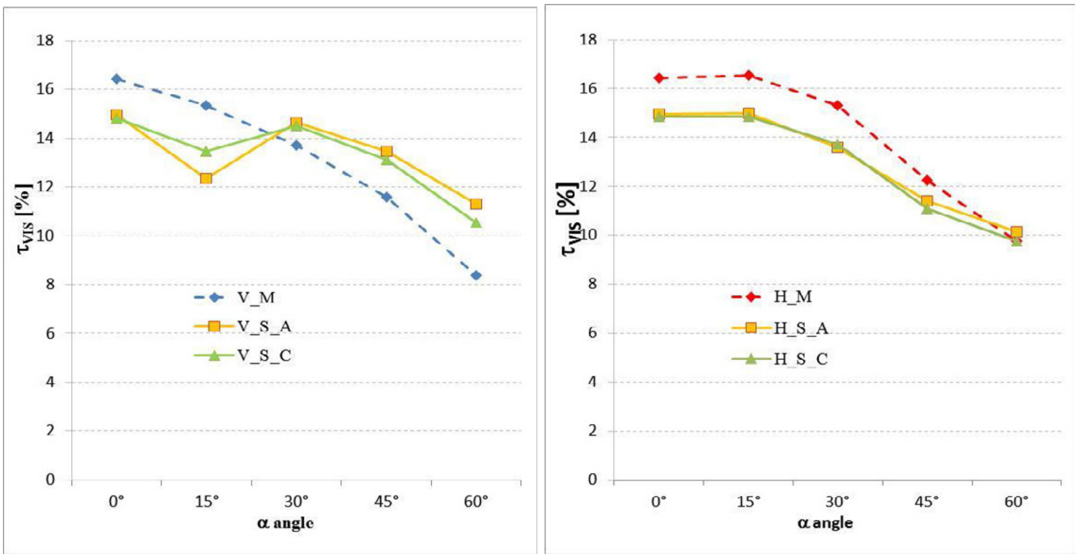


Fig. 9. Angular light transmittance for V-vertical (a) and H-Horizontal (b)

The simulated values are directly dependent to the distance of the analysis grid to the panel plane and to the light reflectance of the internal surfaces of the PMMA gaps (Fig. 10 and Table 4).

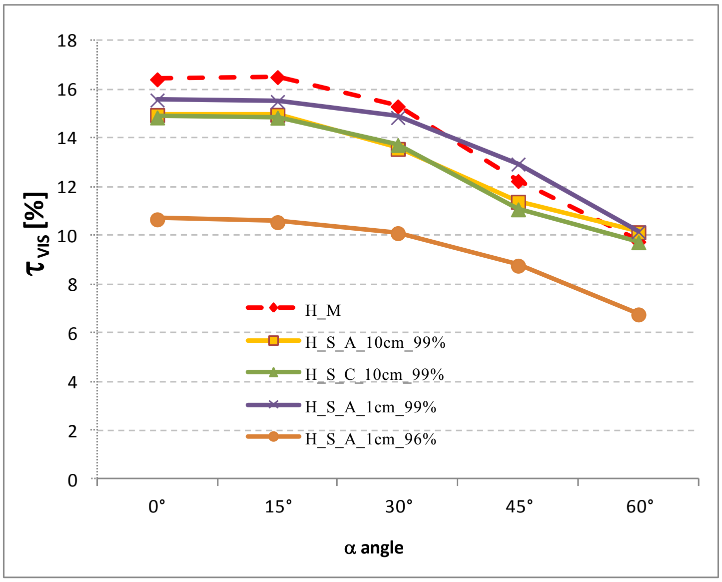


Fig. 10. Comparison between simulated angular light transmittance values for H-Horizontal with 10 cm and 1 cm distant analysis grid and with 99% and 96% reflectance of inside surfaces of resin gaps

In Fig10 and Table 4 the differences between a 10 cm and a 1 cm distant analysis grid are presented. The simulated results with a light reflectance of 96% instead of a 99% are also presented. Grid analysis distance partially affects the results, but light reflectance is the most important variable that strongly affects the result because of the sky type definition. With an analysis grid plane at 1 cm distance from the panel the light transmittance simulated values for both direction (H and V) with uniform sky appeared to be similar.

Table 4. Transparent panel uniform sky: comparison between measured integrated values and simulation results. The values are expressed for the center of the analysis grid for a 10x10 cm sub-grid (C), and as an average value on the whole analysis grid (A). The difference between an analysis grid at 10 cm and 1 cm are presented. Are also presented the difference in measures valued of a reduced reflectance value from 99% to 96%

Angular light transmission t_{vis} – Horizontal	**0°**	**15°**	**30°**	**45°**	**60°**
(H_M) Laboratory measures	16.40 %	16.50 %	15.30 %	12.30 %	9.80 %
(H_S_A_10cm_99%) Radiance simulation results (average)	14.97 %	14.98 %	13.58 %	11.41 %	10.16 %
(H_S_C_10cm_99%) Radiance simulation results (center)	14.87 %	14.86 %	13.74 %	11.10 %	9.75 %
(H_S_A_1cm_99%) Radiance simulation results (average)	15.59 %	15.52 %	14.87 %	12.96 %	10.18 %
(H_S_C_1cm_96%) Radiance simulation results (average)	10.69 %	10.57 %	10.12 %	8.79 %	6.79 %

Accordance between the simulated and measured values, is not fully adequate in case of sunny sky conditions. Despite of the different simulation time that is four times higher the results are not fully in accordance with the measured ones, especially for high incidence angles (45°), obtaining values that are approximately a half than the ones expected. Sunny sky simulations are still under optimization and not here presented.

5. Conclusion and further developments

The procedures assessed in this article permits to estimate, with a simplified method, the light transmission of a complex scattering bulk sample of transparent concrete. To ensure more reliable simulations preventive measure campaigns are necessary, to set up all the simulation variables, to understand the complexity of the geometry modeled. Hence, because of its simplicity the model itself should help designer in the early design stages, but the operational time needed to simulate a single panel, using Ecotect Radiance interface, does not permit to easily simulate rooms and buildings with a large amount of panels. A more simplified and more efficient discretization should be developed.

The transmission values and the illumination levels presented for the test case need to be verified with a real test facility, despite of the accordance between measured and simulated values obtained with the calculation procedure. The simplified method proposed could not permit to express the real light and shadow distribution in a room, especially for sunny sky conditions. Also the bi-directional transmittance behavior of the panel could not be fully reproduced. A fully BTDF of the sample should be obtained [9] and reproduced directly in Radiance to better estimate light values and distribution [10].The research developments plan a series of in the field measures of a sample room box with one of the wall made up by a transparent concrete façade system.

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