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A preliminary study on light transmittance properties of translucent concrete panels with coarse waste glass inclusions

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Abstract

This paper investigates the potential reuse of coarse glass wastes as insert in a high performance cement matrix to produce translucent concrete panels for architectural applications such as interior walls. The effects of the addition of glass scraps on chemical and optical properties of concrete were studied. Alkali-silica reactivity resistance tests were carried out to evaluate the reactivity between amorphous waste glass and alkaline concrete pore solution. Light transmittance LT was evaluated through Radiance simulations and measurements on sample prototypes. The increase in the amount of daylight in a sample room and the reduction in the energy demand for lighting ED_l were investigated through Daysim simulations. Compared to two opaque side walls, the use of two translucent concrete walls with a LT of 5% allowed a reduction in ED_l up to 16% in Palermo (L=38.3°N).

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Keywords: Translucent concrete panels; glass waste reused; ASR expansion; light transmittance; energy demand for lighting; energy savings

1. Introduction

Glass has played an important role in modern architecture due to its aesthetical properties combined with transparency. The revolutionary invention of building glass blocks for design and architectural applications belongs to G. Falconnier in the late 1800's [1]. More recently, glass concrete walls were studied by combining opaque and transparent materials. Different composites were developed based on concrete or polymer matrix embedding light

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transmitting elements [2-6]. Early attempts to incorporate waste glass in concrete focused on aggregate replacement [7]. However, the amorphous nature of glass can promote alkali-silica reactivity (ASR) and concrete degradation [8].

In the present paper, translucent concrete panels, hereafter referred to as Beton Crystal (BC), were manufactured and characterized. They integrated the natural opacity of concrete with the light transparency of glass. Coarse flat waste glass inclusions were enclosed and surrounded with the concrete matrix and extended from one side to the opposite side of the panel to enabling the light transmission (LT). Despite the unique design of each prototype, due to the casualty of the geometries of the glass scraps, panels could be industrially produced. The panels could also be adaptive to a specific design and have different mechanical and LT properties, depending on the quantity of glass and on the mix design of the concrete. A mix design was defined to prepare non-load bearing panel prototypes. Fluidity of the high performance self-compacting cement mortar was optimized and alkali-silica reactivity (ASR) was tested. The mechanical properties of BC panels with and without reinforcing steel fibers were investigated in a previous study [9]. The present work was aimed at determining the LT of BC. Furthermore, since the most suitable application for BC seems to be in indoor spaces as partition walls dividing adjacent rooms, their impact was analyzed in terms of reduced energy demand for lighting (ED_l) in a target room. Two factors provide BC panels with a special appeal from the sustainability viewpoint: the increase in the indoor environmental quality (IEQ) concerned with enhanced daylighting admitted into indoor spaces and the reuse of glass waste. Enhanced daylighting improves the mood, the acceptance and the visual comfort for the occupants, reducing the ED_l. Even though the flat glass industry re-melts internal cullet in the float batch mix, thus decreasing the need for raw materials and the energy consumption of furnaces and the carbon dioxide emissions [10], reuse of glass scraps does not require re-melting or additional processes. Reuse could be a more sustainable option as the energy consumption of glass furnaces, normalized to a cullet level of 25%, is of 4-5.5 MJ per kg_{glass} [11], with an emission of 0.6-0.7 kg_{CO2} per kg_{glass} [12].

2. Experimental procedure

BC panels (50x50x2.5 cm) (Fig. 1a) consist of a high performance self-compacting white mortar embedding 12-13wt. % of coarse flat glass scraps (thickness = 2.5 cm, maximum size $\leqslant$ 15 cm, aspect ratio varying from 4 to 1). The resulting openness factor OF (volume of glazed hollows to global volume ratio) ranged from 4.5 to 13.6%. Figg. 1b-d show three different lighting situations inside a real room, where an interior wall prototype (1:1 scaled) was realized. The maximum quantity of glass corresponds to 115 kg for a 4.5x3 m^2 wall. BC panels were manually prepared positioning the glass inclusions, extending from one side to the opposite side of the panel, inside the mold and placing the self-compacting mortar all around the flat glass scraps, wastes coming from Planibel® Clear Azure Line float glass production by AGC Flat Glass (Table 1). The mortar matrix consists of white cementitious high performing binder (FLOWSTONE® whiteline by Dyckerhoff), dry siliceous sand, potable water, superplasticizer (ADVA® Flow 342) and defoamer (OPTEC ® 960) by Grace (Table 1). The mortar was prepared in a horizontal rotary mixer and homogenization was guaranteed by 10 min low-speed mixing, followed by high-speed mixing for 10 min. The green density of the mortar was measured on three different samplings with the slump flow test according to the UNI EN 12350-8:2010 [13] (Table 1). Air entrained percentage and green density of the mortar have been measured on three different samplings by a Luftporengehalt equipment according to EN 12350-6 and 7:2009 [14]. The ASR was measured in accordance with the UNI 8520-22:2002 standard [15].

Table 1. Mix design and properties of the mortar matrix (values and maximum error) and optical properties of the flat glass.

Mortar mix design		Properties of the fresh mortar		Properties of hardened mortar (data from manufacturers)		Properties of flat glass (data from manufacturer)
Flowstone (kg/m^3)	1000	Green density (kg/m^3)	2211.5	Light transmission LT (%)	0	78
Sand (Ø = 0-2 mm) (kg/m^3)	1000	Entrained air (%)v	0.62±0.03	Luminosity Y (%) (with CIELAB D65/10°)	82	
Potable water (kg/m^3)	190	Slump flow		Light reflection LR (%)		7
Superplasticizer (kg/m^3)	18	SF (mm)	810± 8	Color Rendering Index – RD65 – Ra (%)		89
Defoamer (kg/m^3)	3.5	T500 (s)	5.6± 0.4			

The best way to measure the LT of BC panels would imply the use of a photo-goniometer, as done by Mainini et al. [16]. This measurement will be carried out at a future stage of the research. In this preliminary study, the LT of BC panels was determined using the following procedure, based on both measurements and simulations:

1) experimental measurements were carried out on one of the prototypes manufactured in the 'Daylighting Lab' facility, which consists of a sun simulator and a sky scanning simulator [17]. Different standard sun/sky conditions can be reproduced and repeated, which allows different configurations to be compared under the same boundary conditions, unlike what would happen under a real sun/sky. The sun simulator was used to verify the LT for the beam direct component (Fig. 1e): the 'sun' was positioned perpendicularly to the panel, to calculate the normal LT. The sky scanning simulator was used to verify the LT for the diffuse component: an overcast sky condition was therefore chosen (Fig. 1f). An array of 16 miniaturized illuminance-meters was used to measure the illuminance (E) distribution across the panel. Measures were taken with and without the panel, positioned ahead of the sensors, to measure the E values hitting and transmitted through the panel, respectively. For each sensor, the ratio of the transmitted to the incident E was calculated and assumed as LT value. In order to reduce the spacing between one sensor and another, the panel area (50x50 cm) was subdivided into four sectors, repeating the measurement procedure for each sector. The final spacing was 6.25x6.25 cm, resulting in 64 LT values: the mean of these values was eventually calculated and assumed as the LT value of the whole panel
2) an accurate 3D CAD model was built in Ecotect and then exported into Radiance for simulation. Consistently with experimental measurements, simulations were run for both a clear sky including the sun (positioned at the zenith to have perpendicular rays to the horizontal panel) and an overcast sky. The scope was to compare measured and simulated data to validate the numerical model. The LT values were calculated according to a grid of 20x20 points (spacing: 2.5 cm), then calculating the mean value for the panel. The relative difference between measured and simulated data was lower than 2% (see Table 2), which guaranteed that the simulation model was validated. A particular attention was paid to the Radiance simulations parameters: different simulations were run, consistently with what shown in the sensitivity analysis carried out by Mainini et al. [17]. Eventually, the following Radiance parameters were set: ab = 15; ad=16000; as=8000; ar=600; aa=0.05
3) after the validation of the numerical model, the LT of four more prototypes was determined through simulations.


(a) (b) (c) (d) (e) (f)

Fig. 1. LT effect of a single BC panel (50x50x2.5 cm) in a clear sky day (a); LT of an interior real BC wall during a clear sky day (b), an afternoon sky day (c) and in an electric lighting condition at night (d); illuminance measurements under the sun simulator (e) and the sky scanning simulator (f).

An analysis of the IEQ, in terms of visual comfort perceived by occupants and of the ED_l which may get reduced by using BC panels instead of opaque interior walls, was carried out through Daysin simulations. For this investigation, a sample room was considered, 4.5 m long, 4.5 m deep and 3 m high (net sizes). Some characteristics of the room were changed to assess the variation of the daylight amount in the room and of ED_l.

The characteristics which were kept constant were (Fig. 2):

- presence of a window in one of the walls, equipped with a double pane selective glazing with a LT of 72%
- light reflectance (LR) values of walls, floor and ceiling, set to 60%, 30% and 70%, respectively
- presence of one floor upstairs and of one floor downstairs the considered room

- orientation of the room: south and north; for the case of south-facing rooms, the presence of a venetian blind was also considered to shade the direct sun component (this was a blind with a LT of 25%, pulled down whenever during an annual simulation any point of the work plane was hit by an irradiance higher than 50 W/m^2)
- target illuminance over the work plane E_{wp} (covering the whole floor area minus a peripheral stripe of 50 cm): 500 lx (typical value required for VDT office activities) and 300 lx (typical value required for reading)
- lighting power density (LPD) in the room: 10 W/m^2 and 6 W/m^2 (for a E_{wp} of 500 lx and of 300 lx, respectively).
- presence of two identical rooms, adjacent to the considered one, to allow a daylight admittance from these rooms into the target room through the side shared walls, when made of BC panels; these rooms were assumed at the same temperature as the target room, which means that no thermal exchange occurred through the shared walls
- control system for electric lighting: a photodimming sensor combined with a switch off occupancy sensor.

The characteristics which were changed were:

- site: the room was located in Turin, northern Italy (lat.: 45.1°N) and Palermo, southern Italy (lat.: 38.3°N)
- window area; two room geometries were defined (Fig 2):
  - room type 1: window area = 7.65 m^2 (window-to-wall ratio=WWR=0.57; window-to-floor ratio=WFR=0.38)
  - room type 2: window area = 3.825 m^2 (WWR=0.285; WFR=0.19)
- materials of the side internal walls (Fig 2): a) **R**: opaque walls with LR=60%; b) **T1**: BC panels with LR=60% and LT=5%; c) **T2**: BC panels with LR=60% and LT=8%; d) **T3**: BC panels with LR=60% and LT=11%. Configuration T1 corresponds to one of the actually manufactured BC panels, whilst T2 and T3 are theoretical.

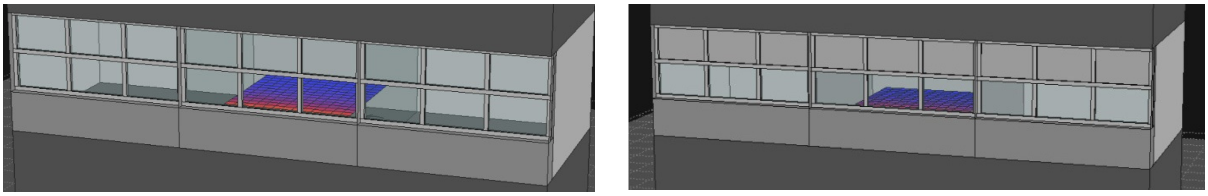

Fig. 2. 3D Ecotect models of room type 1 with BC walls side walls (left) and room type 2 with opaque (right).

The analysis was run using Daysim. An Ecotect model for each configuration was built and used to assign Radiance-compatible materials and to lunch Daysim. The different geometry to be analyzed (a whole room in a building vs. a single BC panel) made it necessary to change the simulation approach: as the two translucent walls measure 4.5 m * 3 m each (i.e. each wall consists of 54 BC panels of 50 cm * 50 cm), generating for the backward ray-tracing calculation all the rays which were used to characterize a single panel in Radiance would have been far over the computation capabilities of the available workstation. For this reason, the BC walls were simulated taking advantage of the properties of trans materials in Radiance: these actually allow modeling both LR and LT of BC panels (measured for the real panel T1) as well as the OF and the direct vs. diffuse transmission and reflection properties (which are different for the various BC panels investigated). A validation test was also carried out for panel T1: using the same configuration of the validation phase of single panels, panel T1 was modeled as a trans material, then comparing the LT value to the value found with high resolution Radiance parameters. The difference was found to be lower than ±5%.

The amount of daylight in the room was quantified through the average daylight factor (DF_m) over the work plane (under an overcast sky) and through some climate-based daylight metrics CBDM: these latter account for both sunlight and skylight dynamically entering an indoor room throughout a year for the considered site. The following CBDM were used: Annual Light Exposure (ALE) [18]; spatial Daylight Autonomy ($sDA_{300/50\%}$) [19]; continuous Daylight Autonomy (DA_{con}) [18]. Unlike the $sDA_{300/50\%}$ and the DA_{con}, which use the E_{wp} as a threshold to analyze the daylight performance of a room, the ALE quantifies this daylight amount in absolute terms and is therefore particularly useful to compare the different configurations of translucent/opaque walls. On the other hand, the $sDA_{300/50\%}$ and the DA_{con} are used in technical standards and recommendations [20,21], unlike the ALE.

The ED_l was calculated in [kWh/m^{2}yr], consistently with what is done for other energy demands (for cooling, heating). ED_l values accounted for the parasitic power due to stand-by of the sensors (assumed to be 0.12 W/m^2) and to the luminaires' ballasts (10% of the luminaire nominal power).

3. Results and discussion

The glass with a light azure tint showed an insignificant expansion, lower than 0.01%, under the accelerated ASR test. This result implies that the glass should be classified as not-alkali-reactive.

As for LT, Table 2 shows the difference between measured and simulated LT values found for one prototype of BC and which led to the validation of the simulation model; the Table also summarizes LT values found for all the prototypes from simulations. The Openness Factor OF is also reported.

Table 2. LT values simulated for the 5 prototypes manufactured. Prototype 1 was the one also measured for the validation of the process.

prototype #	OF	**clear sky with sun**			**overcast sky**		
		simulated $LT_{s,c}$	measured $LT_{m,c}$	$\Delta=(LT_s-LT_m)/LT_m$	simulated $LT_{s,o}$	measured $LT_{m,o}$	$\Delta=(LT_s-LT_m)/LT_m$
1	10.6%	4.91%	4.96%	-1.11%	3.87%	3.80%	+1.82%
2	8.4%	3.81%			2.51%		
3	11.5%	4.84%			3.65%		
4	9.9%	4.07%			3.03%		
5	1.3%	1.75%			1.32%		

Table 3 summarizes the results obtained. In short, the following main considerations can be drawn:

- DF_m: for both room types 1 and 2 (which all show a DF_m over 3%) the progressive increase in the LT value for cases T1, T2, T3 resulted (compared to case R) in an increase in the DF_m value in the range 6.3 to 10.1%
- ALE: an increment of values was also observed, in the range 7.3 to 13.4% for Turin and 11 to 14.7% for Palermo
- $sDA_{300/50\%}$: an increment in these values was observed for both sites; this increment was appreciable for the case of room type 2 only, as the presence of large windows of room type 1 fulfilled the requirements for all cases ($sDA_{300/50\%}$ = 100%), thus not allowing the effect of the BC walls to be assessed
- DA_{con}: an increment of values was also observed, in the range 0.8 to 6.2% for Turin and 0.5 to 5.6% for Palermo
- all static and climate-based metrics reveal, even though to a different extent, that the daylight availability within the two room types increases as the LT value of the translucent concrete wall increases
- ED_l: with respect to the case with opaque walls, ED_l decreases as the LT value of the BC walls increases: this decrease was in the range -6.1 to -20.6% for Turin and -6 to -21.7% for Palermo.

Table 3. Results from Daysim simulations for the two sites considered. Configurations: E = 500 lx ; LPD = 10 W/m^2.

Room type	orientation	side walls	DF_m [%]	ALE_m [luxh]		sDA [%]		$DA_{con,m}$ [%]		ED_l [kWh/m^{2}yr]	
				Turin	Palermo	Turin	Palermo	Turin	Palermo	Turin	Palermo
1	S w/blinds	R	6.23	4350636	4414362	100	99	75.9	78.0	11.3	11.2
		T1	6.62	4668931	4900448	100	100	77.8	81.3	10.6	9.6
		T2	6.68	4711838	4951723	100	100	78.1	81.6	10.4	9.4
		T3	6.75	4765640	5016708	100	100	78.5	82.1	10.0	9.1
1	N	R	6.22	4621552	4616838	100	100	88.8	93.0	6.3	4.8
		T1	6.63	5013275	5156609	100	100	89.5	93.9	5.9	4.3
		T2	6.70	5081393	5230877	100	100	89.7	94.0	5.7	4.1
		T3	6.75	5146840	2100737	100	100	91.5	94.1	5.0	4
2	S w/blinds	R	3.07	2942450	2950001	41	41	55.5	58.3	18.6	16.8
		T1	3.32	3208316	3254695	43	43	58.3	61.2	16.8	15.8
		T2	3.36	3249984	3301660	45	45	58.7	61.6	16.7	15.9
		T3	3.38	3275411	3332785	46	45	59.0	61.9	16.6	15.7
2	N	R	3.09	2398005	2458564	95	100	74.7	80.8	14.1	10.6
		T1	3.34	2639253	2734207	100	100	78.3	84.3	11.0	8.9
		T2	3.36	2660650	2757001	100	100	78.3	84.3	10.8	9.1
		T3	3.41	2719443	2820889	100	100	79.2	85.2	10.2	8.3

(1) calculated for a target E_{wp} of 300 lx, according to [19] and [20].

4. Conclusions and future work

Concrete panels obtained through the combination of a high resistance self-compacting mortar with coarse waste glass scraps coming from the flat glass industry were manufactured and analyzed. Glass inclusions were classified as non-reactive under the accelerated ASR test. The prototypes were then characterized in terms of light transmittance performances. The LT resulted in the range 1.3 to 4.9%, as a function of the glazed hollows. The simulations carried out to calculate the daylight amount in a sample room, with two side internal walls made of BC with a LT of 5%, showed, with respect to two side opaque walls, an increase in the DF_m and in the ALE. As a consequence, the ED_l decreased by up to 12.7% for the site of Turin and up to 16% for the site of Palermo. Even better results were found simulating BC panels with LT values up to 11%: the ED_l was reduced in this case by up to 20.6%. The characterization showed a good potentials concerned with the application of BC in buildings: this use is more suitable for internal walls rather than for envelope components, due to the difficulty in coupling them with insulating and other materials of an envelope. The work is still on-going: further study is being made to investigate mechanical properties of BC panels with more glass for higher transparency, as well as other properties such as sound insulation performances.

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