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Cool, translucent natural envelope: thermal-optics characteristics experimental assessment and thermal-energy and day lighting analysis

Federica Rosso[a,*], Anna Laura Pisello[b,c], Franco Cotana[b,c], Marco Ferrero[a]

[a]*Sapienza University of Rome,Dept. Civil, Construction and Environmental Engineering, Via Eudossiana 18, Rome, 00184, Italy*
[b]*University of Perugia, Department of Engineering, Via G. Duranti 93, Perugia, 06125, Italy*

Abstract

Innovative construction elements are increasingly studied to improve the energy performance of new and existing buildings, to satisfy global regulations and societal needs. In this view, optimizing buildings energy efficiency and sustainability are crucial aspects, given their high energy saving potential with respect to the other sectors characterizing human activities. Natural materials are often preferred to artificial materials, thanks to their more sustainable production and to the reduced content of harmful substances. In particular, light, thin marbles have been recently analyzed as building envelope elements. Their cooling potential demonstrated how such envelopes have the threefold advantages of reducing solar heat gains into the building, accumulating and releasing less heat, reducing the Urban Heat Island (UHI) effect and consequently mitigating global warming. However, an important feature that has not yet been analyzed in literature and that is considered in this research is light passage throughout the translucent envelope, permitting an additional energy saving due to the contribution to artificial lighting. In this work, this feature of the translucent envelope is considered, by experimentally measuring thin, white marble panels' optic characteristics and implementing them in a thermal-energy dynamic simulation, to demonstrate the additional advantage of natural daylight to the overall building energy balance.

Keywords: Building envelope; thin translucent marble; cool materials; daylighting; thermal energy analysis; dynamic simulation; energy efficiency; electricity saving;

* Corresponding author. Tel.: +39 06 645 853 84;
E-mail address: federica.rosso@uniroma1.it

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1. Introduction

Nowadays world population has to face the environmental challenges of climate change and global warming, which lead to temperature increases up to +0.20 every ten years [1] and exacerbating its negative effects on human health [2]. A connection has been recognized between greenhouse gas (GHG) emissions and global-local climate change implications [2,3]: energy related emissions account up to the 70% of the total [4]. Therefore, saving energy, and consequently reducing CO_2 emissions, appears to be a fundamental priority to mitigate such phenomena.

To this aim, construction sector has a large impact on total energy demand [5], therefore it could play an important role in the reduction and optimization of emissions: in Perez-Lombard and colleagues' work [6] the authors assessed that the building sector represents almost 40% of the total primary energy consumptions, as confirmed by more recent data [7]. More in details, consumptions of the building sector are due to i) space conditioning (around 33% both for commercial and residential purposes), ii) lighting (4-16%), iii) domestic hot water (12-24%) and iv) other equipment and appliances (9 to 32%). While solutions for smarter and more efficient energy systems are sought [5,8], different strategies have been exploited to reduce each of the above mentioned drivers of consumptions, both in residential and commercial buildings. At the same time, optimal comfort conditions have to be maintained for occupants, with respect to their thermal and visual perceptions.

Passive strategies are defined as those solutions able to provide an increase in occupants' comfort conditions without any additional consumption [9,10]. An example is the conscious use of materials with determined thermal and optic characteristics, for thermal insulation or natural cooling applications [11], and in particular of natural materials [12,13], having the advantage of being less energy intensive to be manufactured and less harmful to deploy. In particular, *cool materials* are regarded as efficient construction materials to maintain lower surface temperatures and consequently absorb and release to the indoor or outdoor space less heat [14]. Many studies focused on cool materials employment in the built environment, for cool roof [15–18], urban paving [19,20] and cool envelope applications [21,22], assessing large decreases in surface and indoor temperatures.

In this work, a cool, translucent, natural material is considered as envelope material and its benefits on the thermal energy performance of buildings are assessed: moreover, an additional step is carried on to investigate the possible saving in electricity due to day lighting [23]. This aspect, due to the translucent feature of the construction element, has not been considered yet to the best of authors' knowledge, thus, the contribution of the paper is to have experimentally tested it and quantified its effects on energy demand. This possible saving is linked to the peculiar technology of the here considered cool construction element, i.e., a thin, translucent white marble panel for building envelope application. Such envelope element, apart from the architectural value, the cool behavior and also the light weight, permits light passage throughout its surface, illuminating with natural, diffuse light the indoor areas and therefore reducing the need for artificial lighting.

Many buildings have employed this technology in the last years, in particular religious or representative buildings, due to the evocative value of the light effects on the facade, changing throughout night and day accordingly to outdoor light conditions. Some examples are the Christ Pavillion, by architects von Gerkan Marg & Partners, Hanover, built in 2000 [24] as a religious construction, or Caja Granada savings bank in Granada, built in 2001 on a project by architect Alberto Campo Baeza [25].

Using a case study, we experimentally assessed the thermal and lighting energy performances of a building with such a cool, translucent envelope. We conducted in lab measurements of thermal and optic characteristics of the investigated construction element, followed by a year round dynamic simulation with Design Builder interface [26], implementing EnergyPlus software [27]. Existing work about thermal energy performance of a building with cool marble envelope performed a year-round dynamic simulation as well [22], but the innovative aspect of marble translucent behavior was not taken into account into such simulation, therefore the reduction in electricity due to natural light passage was not considered yet. In the present research, both the contributions toward energy saving, namely cool behavior and natural lighting, are considered into the assessment, leading to a broader evaluation of the energy related potentialities of white, translucent marble envelope. Such an assessment could lead to consider the promising features of a similar construction for office buildings, showroom and expositive areas, in consideration of the energy related potentialities, whereas until now it is almost exclusively employed for its evocative and architectural values in religious and representative buildings.

2. Materials

The considered white marble was Bianco Carrara marble, white with few grey veins, coming from the Apuan Alps of Carrara area, Central Italy. The marble panel was 0.01 cm thick, glued on a support layer of glass by mean of epoxy resin.

a b

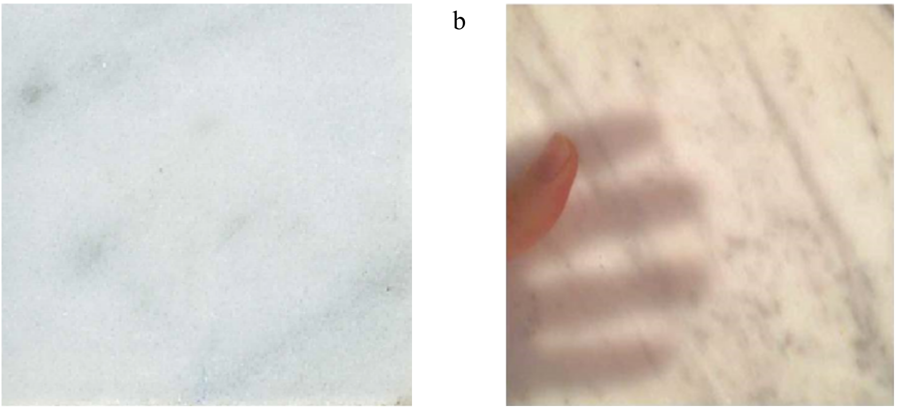


Fig. 1. (a) Bianco Carrara marble when light conditions are uniform; (b) Bianco Carrara marble when one side is more illuminated than the other.

The support layer has structural function and it is also required for low thickness (<0.01 cm) not to break the panel when cutting it into thin layers to achieve the desired thickness. Such structural support could be realized also with other materials, such as fiber glass or honeycomb, which are widely used for their reduced weight, for example in naval applications. However, since the present research deals with translucent envelope, it was fundamental that the panel resulted to be translucent, therefore the support layer had to be transparent.

3. Methods

Once the material and the construction elements were set, they were in lab characterized by mean of thermal and optics characteristics. A case study building was selected for analyzing the translucent envelope and modeled. The measured values were then inserted in the dynamic simulation software Design Builders implementing EnergyPlus to run the simulation with experimentally measured values, in order to provide a more realistic and coherent result. After the dynamic simulation, the obtained data were analyzed in order to draw the conclusions.

3.1. Construction element characterization

Thermal characteristics of the construction elements were measured in lab, by employing a portable emissometer [28] to measure emissivity, accordingly with ASTM Standard C1371-04 [29] and a hot disk [30] following the standard ISO 22007-2 [31] to assess conductivity.

Optic characteristics were measured with SolidSpec 3700 Spectrophotometer [32], in accordance with ASTM E903-12 [33]: solar reflectance, absorbance and transmittance were evaluated, as well as Color Rendering Index (CRI), which defines the extent of similarity of colors displayed by a light source with respect to the ones displayed by natural light. CRI appears as an important parameter to evaluate when considering a translucent envelope, where the stone construction elements acts as a light source, spreading natural light inside the indoor areas.

3.2. Case study selection and dynamic simulation

3.2.1. Architectural characterization

The selected case study is a building's project located in New York City, USA, as it is at an average latitude of European and USA cities and for its high rate of new constructions that may consider this study for future envelope materials decisions. The construction is designed as a 7-story, multipurpose building for artists, consisting in i) exhibition areas, ii) common laboratories areas and iii) common spaces, as well as iv) artists' residences. The area of each floor is around 450 m^2, for a total surface of around 3190 m^2. The multifunctionality of the building permits to exploit the potentialities of translucent envelope during all the hours when there is sunlight. Light passage permits a diffuse and natural lighting to the indoor spaces, suitable for labs, exhibition areas and common spaces. At the same time, residences are opaque, not showing the indoor activities of occupants and resulting as dark parallelepiped inside the translucent envelope. Finally, the choice was guided by possible future developments linked with further studies about marble envelope, and to serve as a comparison with past works [22].

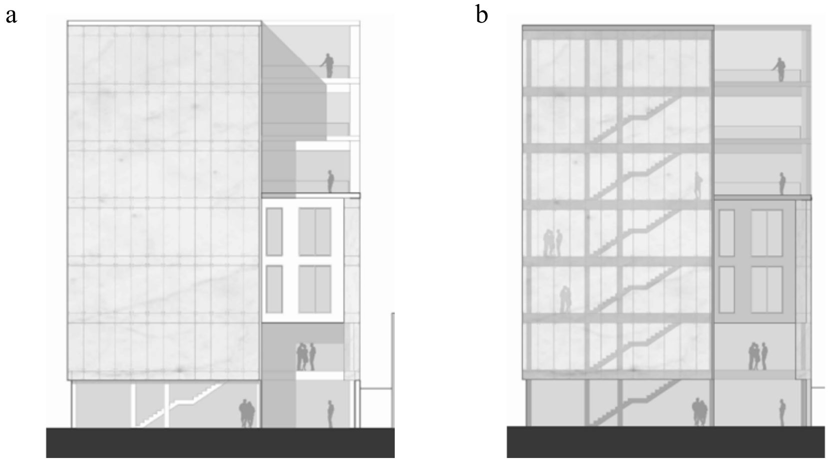


Fig. 2. Case study building's South-West facade: (a) during the day, absorbing daylight and (b) at night, emitting light a demonstrating its translucent feature.

3.2.2. Physical characterization and dynamic simulation

In order to run the dynamic simulation, the characteristics for building's i) envelope, ii) local climate boundary conditions and occupancy schedules as in [22] are described in the tables below.

The thermal and optic characteristics of the envelope's construction elements were previously measured in lab and then inserted in the dynamic simulation software, Design Builder interface implementing EnergyPlus tool. The physical characteristics of marble construction elements and of the envelope system are reported in Table 1.

Reference temperature set points, in accordance with UNI EN 15251 [34] were selected for the HVAC system, which was modeled with unitary energy efficiency values. These set points are maintained constant in the different zones to achieve similar homogenous thermal behavior in the entire building: nonetheless, specific schedule and characterization for the different zones was provided in the model Table 2. All the thermal zones were simulated with 0.7 infiltration rate and minimum fresh air equal to 10 L/person.

The weather conditions were taken from JFK Airport weather files, to simulate New York City local climate.

Table 1. Envelope system characteristics

Envelope system	Thickness [m]		Thickness [m]		Thickness [m]
Vertical envelope		Roof		Ground floor	
Bianco Carrara marble layer	0.01	Asphalt membrane	0.01	XPS insulating panel	0.09
epoxy resin	0.001	mineral wool rolls	0.14	Cast concrete	0.2
glass	0.01	air gap	0.03	Floor screed	0.07
air gap	0.25	plasterboard	0.02		
internal glass	0.02	cement slab	0.2		

U-value	2.6 W/m2K	U-value	0.2 W/m2K	U-value	0.3 W/m2K

Table 2. Schedules for the activities of the different thermal zones of the case study building.

Thermal Zone Characteristics			
	Hall, lecture theatre	**Display and public areas**	**Museum galleries**
Density:	0.2 people/m2	0.15 people/m2	0.05 people/m2
Activity-metabolic rate:	standing-walking 140 W/person	light manual work 180 W/person	light work 160 W/person
Target illuminance:	300 lux	200 lux	300 lux
Equipment gain:	2 W/m2, radiant fraction 20%	2 W/m2, radiant fraction 20%	30 W/m2, radiant fraction 20%
Schedule:	8:00 am to 6:00 pm, 7 days/week	8:00 am to 6:00 pm, Sunday off	8:00 am to 1:00 pm and 6:00 pm to 9:00 pm, 7 days/week
	Domestic dining room	**Domestic kitchen**	
Density:	0.17 people/m2	0.05 people/m2	
Activity-metabolic rate:	eating-drinking 110 W/person	light work 160 W/person	
Target illuminance:	150 lux	300 lux	
Equipment gain:	3 W/m2, radiant fraction 20%	30 W/m2, radiant fraction 20%	
Schedule:	8:00 am to 1:00 pm and 6:00 pm to 9:00 pm, 7 days/week	8:00 am to 1:00 pm and 6:00 pm to 9:00 pm, 7 days/week	

4. Results

4.1. Optic and thermal characteristics assessment

The investigated optic characteristics were solar reflectance (SRI), transmittance (T) and absorbance (A), as well as Color Rendering Index (CRI), measured by mean of Spectrophotomer, in accordance with ASTM E903-12 [33]. Results are provided in Fig. 3 and Table 3, where the values have been averaged on multiple measurements carried out on different samples. CRI optimal values, as high as 85.8, demonstrated that light spread through marble envelope reveals colors as they are when illuminated by natural light.

With the above described methods, i.e., portable emissometer and hot disk, marble samples' thermal properties were assessed in Table 3.

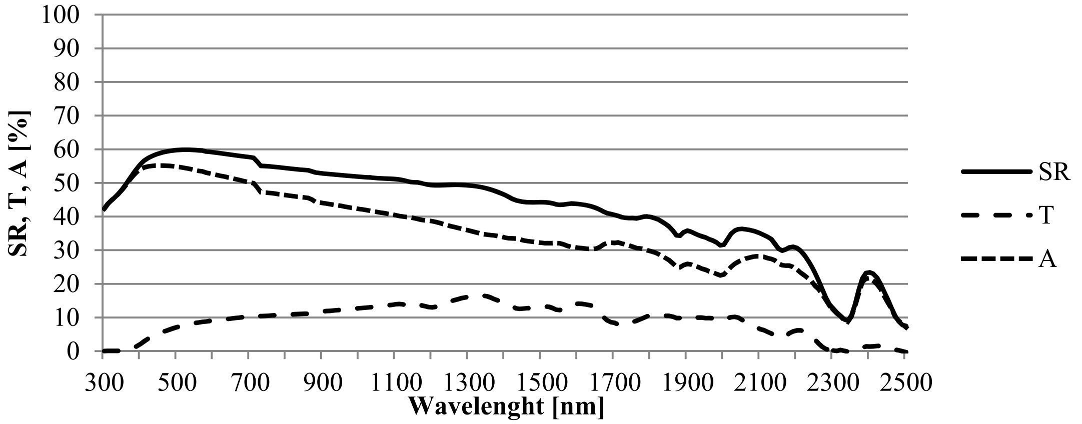


Fig. 3. Solar Reflectance (SR), Transmittance (T) and Absorbance (A) along the solar spectrum, from wavelength 300 to 2500 nm.

Table 3. Optic and thermal characteristics measured in lab on Bianco Carrara marble samples.

	Optic properties		Thermal properties	
Bianco Carrara marble	Solar Reflectance (SR)	0.58	Thermal emittance (ε)	0.83
	Solar Transmittance (T)	0.07		
	Solar Absorbance (A)	0.35	Thermal conductivity (λ) [W/mK]	2.40
	Color Rendering Index (CRI)	85.80		

4.2. Building energy analysis and comparisons

Different investigations and comparisons were set for the integrated analysis of building's performance due to marble envelope.

The first analysis, referred to as *building thermal analysis*, dealt with indoor temperature when HVAC systems are not operating, to highlight the effect of SRI on it. A comparison was set between cool marble envelope and more traditional, non-cool, cement-based tiles' envelope.

The second analysis, *building lighting analysis*, had the objective of assessing the impact that translucent feature of marble envelope had on electricity use in the building. To highlight this impact, a comparison was set with equivalent, but not translucent, marble envelope.

4.2.1. Building thermal analysis

Considering Bianco Carrara marble envelope, a comparison with non-cool cement-based tiles envelope is set. Cement-based elements are considered with values of SR=0.3 and ε=0.9. Fig. 4 displays surface and radiant temperatures both for cement-based and marble panels, showing a slight decrease in marble radiant temperature, equal approximately to 0.5 °C. Fig. 5 shows how marble envelope is able to decrease primary energy for cooling by 9% in August.

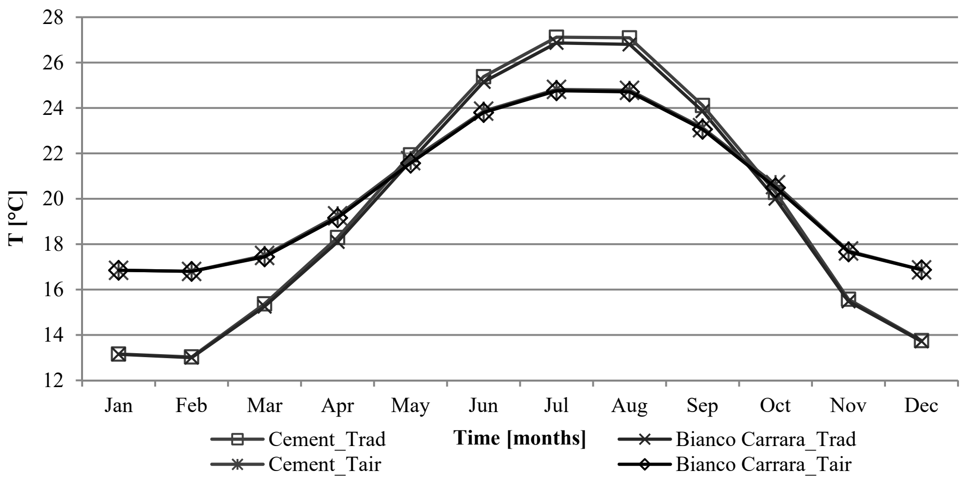


Fig. 4. Surface and radiant temperatures with marble and cement-based panels.

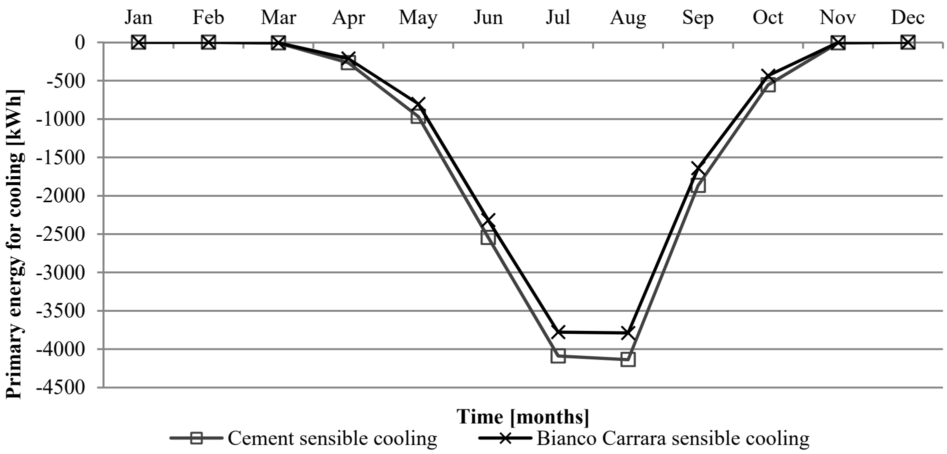


Fig. 5. Primary energy requirement for cooling with cool marble envelope and cement-based panels envelope.

4.2.2. Building lighting analysis

In order to assess the contribution of natural light passage throughout the entire envelope, a second comparison was performed between i) Bianco Carrara marble translucent envelope and ii) Bianco Carrara marble opaque envelope, by varying just the solar transmittance of the construction element. To simulate the translucent envelope with specific solar transmittance and other optic and thermal characteristics, it had to be built as a multilayer opening in the model: therefore, the software permitted to modify the above mentioned characteristics. Differently, for the case of opaque envelope case, the multilayer envelope was designed. Then, for the dynamic simulation, lighting control was turned on, in order to account for natural light passage in both the compared cases: illuminance levels were calculated by the software at every hourly time step, determining how much the electric lighting can be reduced. The difference between the two cases was then just solar transmittance value. By considering Fig. 6, it is noticeable how translucent envelope decreases the need for electricity for lighting purposes in July, while in Fig. 6. Daily electricity for lighting in July, for opaque and translucent marble envelope.

, assessing January demand, this difference is lower. The peaks of savings are during the morning, equal to 5 kW.

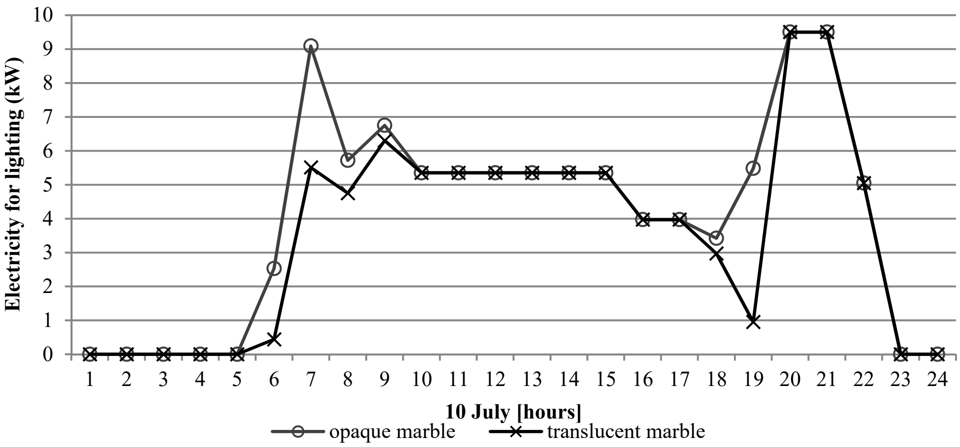
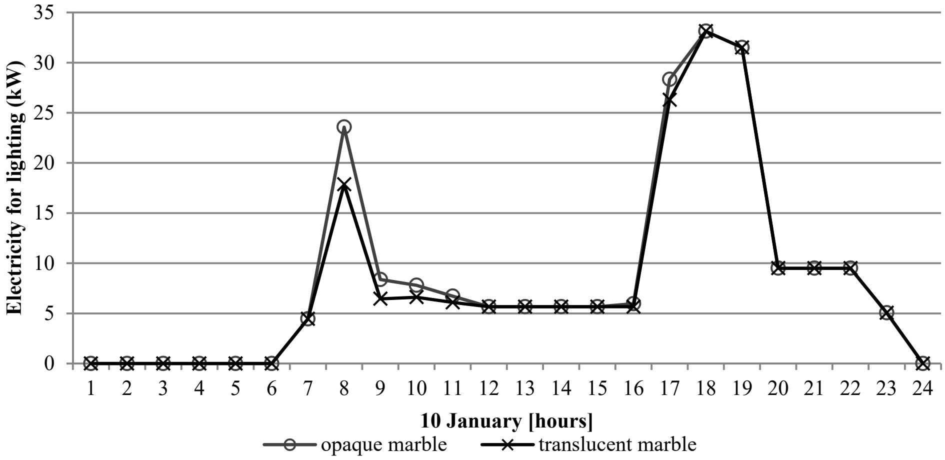


Fig. 6. Daily electricity for lighting in July, for opaque and translucent marble envelope.



. 7. Daily electricity for lighting in January, for opaque and translucent marble envelope.

By gauging the yearly need for interior lighting in opaque/translucent cases, it is possible to notice that translucent envelope permits to save 10.7% of energy for interior lighting, while this saving is reflected in the total energy reduction of almost 4%.

Table 4. Comparison of opaque/translucent case study building's energy demand and savings assessment.

Yearly analysis	Total site energy [kWh]	kWh/m^2	Electricty for interior lighting [kWh]
Opaque marble	147190	48.8	57353.0
Translucent marble	141481	46.9	51207.2
yearly savings due to light passage	**-3.9%**	**-3.9%**	**-10.70%**

5. Conclusions

This study took into consideration a cool, translucent, natural building envelope, i) by experimentally measuring optics and thermal characteristics of the marble construction element, applied as façade, and ii) by performing a yearly dynamic simulation of a case study building with such an envelope, employing materials' characteristics as measured in lab. While previous studies analyzed the thermal benefits of marble envelope, the contribution of the present research was to assess the possible savings in electricity demand for lighting due to natural light passage throughout marble surface, due to the translucent intrinsic property of the material (T=7.4%).The contribution to the literature regarding translucent marble applications [22,35] is thus to consider also the light passage in the energy savings assessment.

The cooling effectiveness of white Bianco Carrara marble façade (SR=58%) is confirmed as able to decrease summer demand of energy for cooling of almost 10%, when compared to more traditional cement-based panels with SR=30%. With respect to natural lighting, the yearly assessment of electricity for interior lighting permitted to observe savings equal to almost 11% when compared to opaque, same marble façade. Such saving is reflected in a yearly total site energy demand decrease of almost 4%. The magnitude of the energy savings should be of interests of new builders and policy makers. Therefore, the considered white, translucent marble façade, apart from the architectural value, demonstrated a potentiality in reducing not only primary energy requirement for cooling, as a cool material, but also a reduction due to its translucent feature. Future developments of the work will consider the durability of the assessed performance, given the modification of optics characteristics due to degradation caused by acid environment [35,36].

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