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Article

Integrated Thermal-Energy Analysis of Innovative Translucent White Marble for Building Envelope Application

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Abstract: Marble is a natural material, used in the construction field since antiquity. It has always been used to communicate monumentality and solidity. Nowadays new technologies permit marble to express new languages: particularly, translucent marble technology overturns the concept of solidity. The main issue to address is the lack of thermal-energy performance of such a thin stone layer as the only facade component. Conversely, Bianco Carrara and Statuario marbles, for instance, have intrinsic benefits as natural cool materials, due to their high solar reflectance and thermal emissivity. Thus, this paper analyzes the thermal-energy and environmental behavior of marble facade for a new designed building in New York City. An integrated analysis of the energy performance of the marble skin is performed through a preliminary experimental characterization, carried out for two different types of naturally white marble, for comparative purposes. Then, a dynamic simulation model of the building is developed to evaluate year-round benefits and drawbacks of the translucent marble envelope in terms of indoor thermal comfort and air-conditioning requirement. The analysis showed how the proposed marble facade is able to decrease the energy requirement for cooling up to 6%, demonstrating possible relevant perspectives for marble-based facades, even in energy-efficient buildings.

Keywords: thin translucent marble; building envelope; energy efficiency in buildings; cool natural material; optic-energy and thermal characterization; dynamic thermal-energy simulation of buildings

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1. Introduction

Energy efficiency of buildings appears nowadays as an essential field to analyze and improve upon. The aim to reduce the energy consumption of constructions is expressed also by the European program, Horizon 2020, the biggest EU research and innovation program addressing both academic and industry institutions [1]. This program is aimed at reducing greenhouse gas emissions by 20% before 2020, with the objective of a further reduction up to 80%–95% by 2050. Since buildings account for 32% of total final energy consumption and represent around 40% of primary energy consumption in most countries [2], the construction field has a high potential for energy savings. In this panorama, it is essential to reach the optimal energy performance for every building, considering its global combination of construction elements and connection with the surrounding environment, starting from the early design phase. For this reason, there is an increasing interest in dynamic simulations tools, which allow one to predict and assess building energy performance with varying dynamic boundary conditions: these tools have proven to be useful, both for new construction buildings [3] and for historic buildings [4]. Therefore, a tool for analyzing new technologies, applied as building construction materials, considering their dynamically variable energy performance and their innovative potential, appears a particularly current topic.

The purpose of this paper is to have a more robust understanding about translucent marble technology as an external envelope skin, since it is a recent and not widely used technology, due to its peculiar behavior. This technology is based on the properties of some marbles, especially the white ones, to be translucent when cut at a low thickness (below 2 cm). Bianco Carrara and Statuario marble were chosen for this research for their similar white color and grain type. The production of these materials is rather complex and expensive, so their use is extremely limited. Translucent marble is often paired with a support layer, which has also to be translucent. This reinforcement may be required by the manufacturing process or by the actions to bare when in service. The most frequently used solutions include glass slabs, honeycomb panels in polymeric resins (for example, styrene-acrylonitrile) or layers of epoxy resin, reinforced with glass fiber. Lab measurements in this study have concerned only marble slabs without support and with epoxy resin and glass fiber support. In fact, the presence of glass or alveolar panel supports significantly affects the characteristics of the panel and moves away from the behavior of real marble. In any case, both of the considered samples have been analyzed with attention to their real configuration when applied (*i.e.*, they do not need adjunctive supports for the application).

However, besides some disadvantages due to its reduced thickness, this application could bring many advantages thanks to its own peculiarity, if carefully and consciously applied. Actually, translucent marble’s capability of transmitting light towards the inner space permits one to have a natural and diffuse lighting, which is optimal for the determined functions (*i.e.*, artists’ labs, industrial spaces, shops). Moreover, the selected marble is a naturally cool material, with high reflectance and emissivity: these properties are highly requested qualities for envelope materials, in order to improve indoor comfort and contribute to urban heat island mitigation [5]. On the other side, this thin marble technology does not have intrinsically good thermal performance on its own, and it is sensitive to the polluted environment. The high cost of the material (approximately 80–140 €/m^2) needs to be dampened by its environmental benefits. By performing an integrated year-round thermal energy dynamic simulation, the performance of the translucent envelope is assessed. To better define the envelope parameters necessary to calibrate the simulation model, experimental characterization of the considered materials is carried out by mean of lab measurements. Two kinds of white marble are considered, to assess a direct comparison of the energy performance: Bianco Carrara (BC) and Statuario (S) marbles. If the advantages of this technology can be demonstrated and the problems can be overtaken with a careful design phase, this technology could gain competitiveness among other materials and technologies. Therefore, this study has relevant implications for marble producers, which could fabricate a competitive and innovative construction element, but also for designers, allowing them to place side by side the value of the architectural expression and of the operational value at the same time. For researchers, this is also a starting point to deepen translucent marble technology, bringing marble literally to a new and peculiar dimension.

2. Research Background and Purpose of the Work

Previous interesting works analyzed thermal-energy simulations of buildings as a tool to study building performance. In particular, Bouchlaghem [6] proposed a computer model to simulate building thermal performance, in order to automatically define the optimum design variables. In their work, Pisello and colleagues [3] pointed out the necessity to "remove the gap between building architecture, dynamic simulation procedures and energy systems design" and the necessity to evaluate the thermal performance of a building by integrating optimization strategies into a dynamic simulation tool. They analyzed three residential constructions' prototypes and defined performance levels with thermal deviation indexes (TDI), which are non-dimensional indexes able to describe building thermal behavior. With TDI, they described multiple optimization strategies and their impact. The input information is building characteristics (*i.e.*, envelope properties) and the specific climate environment; they supported the simulation by also measuring existing building envelope properties experimentally. The knowledge of the thermal performance of the building envelope is necessary from the early design phase, in order to optimize it with envelope shape and orientation and other passive techniques [7]. Therefore, many works focused on building materials for envelope application, deeply analyzing all of the aspect related to a particular or innovative technology used as a facade component. Kolokotsa *et al.* [8] examined mineral-based coatings, assessing how they contribute to buildings' energy efficiency. After developing mineral-based samples, they assessed the optical and thermal properties of these components. Then, they used the Transient System Simulation Tool, TRNSYS model [9], for a test building located in Greece, and with this simulation technique, the energy efficiency was assessed. Finally, they were able to state that mineral-based coatings as an envelope application are capable of improving envelope thermal performance as a passive cooling technique. Moretti and colleagues [10] analyzed, by means of experimental characterization and in-lab measurements polycarbonate systems, commercial and industrial building envelope applications. The authors compared polycarbonate systems with classic glazing systems for windows and facades, and they concluded that polycarbonate systems have a better thermal performance and a competitive and lower price. Similarly, in this work, a translucent marble envelope application is considered by analyzing if this innovative envelope technology could bring advantages in terms of indoor and outdoor thermal comfort: in fact, marble is a naturally cool material, characterized by high solar reflectance and emissivity. In recent years, numerous works analyzed cool material performance and applications; these are often considered for cool roof solutions, in order to reduce building energy demand and improve indoor thermal comfort; they are studied for cool pavement applications, in the field of the urban environment, for urban heat island (UHI) mitigation and outdoor thermal comfort. Pisello *et al.* [11] presented an innovative brick tile for a cool roof: the benefits related to this application were analyzed focusing on the roof thermal behavior and the indoor thermal performance of the environment adjacent to the roof. The monitoring showed that this roof system consistently reduced the peak overheating and the indoor temperature during summer, while the penalties during the winter season were negligible. The same clay tile was considered by Boarin and colleagues [12], specifically for historic building applications; with attention to the LEED® protocol, the suggested value for the solar reflection index is 29, while the prototyped tile was able to reach a value of 67, increasing the cooling potential of the roof surface. Regarding cool materials for outdoor solutions, Doulos *et al.* [13] set a comparison between materials, considering their surface texture, color and thermal properties, in order to find out which one better contributed to a lower ambient temperature during summer and fighting the UHI effect. One of the considered materials was marble, and they pointed out its suitability for cool applications. However, Doya and colleagues [14] observed that in a dense urban environment, cool horizontal components represent only a small part of the total envelope surface of the area, and cool roofs mainly impact the rooms immediately adjacent to the roof. Therefore, they considered the cool facade performance, by analyzing both the indoor and outdoor effects. The analyzed technology was a cool-colored coating, and its solar reflectivity was preliminarily measured. In this perspective, this study showed the decrease of temperature (both outdoor and indoor) thanks to the application of the cool technology. Similarly, the purpose of this work was to analyze the performance of an innovative thin marble facade, by means of a preliminary experimental characterization of the materials and, then, by performing a year-round dynamic simulation, in order to assess its thermal performance in varying boundary conditions [15]. A comparison and a statistical analysis between the two white marbles, *Bianco Carrara* (BC) and *Statuario* (S), characteristics are then stated, in order to establish if there is a sensitive difference between these two marbles, which are similar in color and surface finishing.

3. Materials and Methods

In order to evaluate the thermal performance of the translucent marble envelope by dynamic simulation, primarily an in-lab characterization of the chosen white marbles is performed. The experimentally measured values are then compared and finally used for setting the required parameters in the dynamic simulation environment.

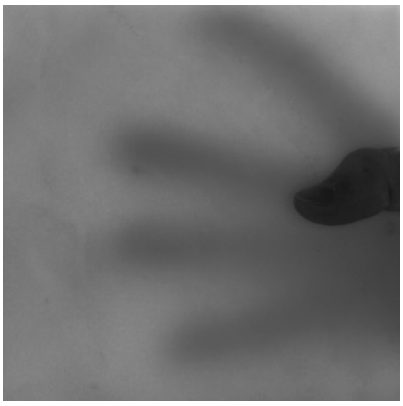
3.1. Research Procedure

i. Choice of the materials: two white marbles, similar in color and finishing, are chosen as prototypes for the experimental characterization and the following thermal-energy dynamic simulation;
ii. Marble in-lab characterization: the chosen samples are characterized through measuring their superficial optic-energy main properties, such as solar reflectance and thermal emissivity;
iii. Comparative statistical analysis;
iv. Development of the building thermal-energy model: the dynamic simulation model at the design stage of a multipurpose building is carried out;
v. Thermal-energy analysis of the effect of marble facades in both free-floating conditions and controlled temperature set point conditions;
vi. Analysis of the main results.

Two white marbles are analyzed: Bianco Carrara marble (BC) (Figure 1) and Statuario marble (S) (Figure 2). Both of the marbles have the same origin, in the Apuan Alps, near Carrara, located in the Northern Tuscany region, Italy. They both are white with few grey veins, with medium-fine grains. The materials are compact, with no or few surface porosity. The two samples are both thin and translucent, but with different stratigraphy: the BC sample is 0.5 cm thick, with an epoxy resin and glass fiber support layer, while S is single layer, only 1.0 cm thick. The surface of the samples has previously been polished to an ultrafine level (using a P2000 pad, manually finished) in order to be smooth. However, also another set of samples is taken, with an even more accurately polished surface (P2000 but with a mechanical instrument), in order to compare it with the still smooth, but less polished, set. P2000 is an ISO/Federation of European Producers of Abrasives (FEPA) designation for grit size [16], corresponding to the average size of the particles of the abrading material of the sandpaper: more precisely, P2000 is characterized by an 8.4-micrometer average particle diameter and is defined as an ultrafine level. One sample of each kind of marble is studied and experimentally characterized. Therefore, one sample of S, one sample of BC, one sample of S mechanically-polished (SP) and one sample of BC mechanically-polished (BCP) are analyzed. Each sample is characterized by three measurements to evaluate the variability of the performance along the sample structure.

Figure 1. Bianco Carrara (BC) marble sample.

Figure 2. Statuario (S) marble sample.



3.2. Marble Characterization

The samples are characterized within their optical energy parameters by using a spectrophotometer (Shimadzu, SolidSpec 3700 spectrophotometer, Japan, Kyoto [17]) with an integrating sphere, in order to assess the solar reflection and transmittance capabilities of each sample. These measurements are taken following the standard method [18]. For evaluating emissivity, an emissometer (Devices and Services Company, Emissometer with Scaling Digital Voltmeter Model AE1 RD1, Texas, Dallas [19]) is used, following the standard test method specified by [20].

In the tables below (Tables 1 and 2), the post-processed values of the measured data of reflectance, emissivity, transmittance and absorbance are reported. Moreover, the solar spectra of the samples are reported in Figure 3.

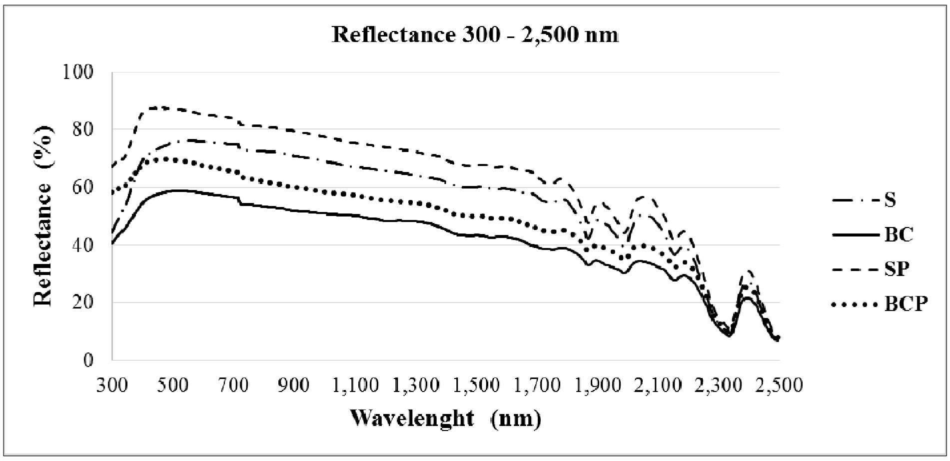
Table 1. In-lab measured values for emissivity, transmittance and absorbance characterization of marble samples.

Measured Value	**Marble Typology**	
	Bianco Carrara Polished (BCP)	**Statuario Polished (SP)**
Emissivity	0.83	0.88
Solar Transmittance (%)	7.4	4.4
Absorbance (%)	34.4	14.8

Table 2. In-lab measured values for solar reflectance.

Measured Value	**Marble Typology**			
	Bianco Carrara (BC)	**Statuario (S)**	**Bianco Carrara Polished (BCP)**	**Statuario Polished (SP)**
Solar Reflectance [%]	58.4	73.7	59.0	79.2
UV	53.0	60.9	62.7	73.1
Vis	63.5	78.6	66.5	85.1
NIR	69.0	78.6	70.2	54.1

Figure 3. Solar reflectance spectra for the 300–2500 nm wavelength.



3.3. Marble Statistical Comparison

A statistical comparison is performed in order to verify if there is a significant difference between the measured characteristics of the examined marbles. To this aim, data analysis and a statistical software, *i.e.*, STATA [21], are used. Every value taken for one marble type is compared with the correspondent value of the other marble type. For every comparison, the difference and the statistical significance is assessed (95% level of significance).

4. Case Study Building

4.1. Architecture

The dynamic simulation was performed on a multi-story building project located in New York City, USA (Figures 4–6). The building is multifunctional, containing residences, laboratories and expositive galleries specifically designed for artists, in the artists' neighborhood of Soho. The peculiar use of this building is highlighted by the translucent envelope: this thin marble film lets the shadows of what is happening inside shine throughout its surface. At the same time, the diffuse natural lighting allowed by this light envelope is ideal for artists' work and exposition. The total building surface is 3187 m^2, and each floor surface is about 450 m^2. The building consists of seven floors, each one composed of common and private spaces: the common spaces are utilities and lab areas; the private spaces are composed of the residences of each artist. The private residences result in opaque parallelepiped into the bigger translucent parallelepiped that constitutes common spaces. The choice of the building as a case study depends on the particularity and the variety of its functions, which are linked to the marble envelope. Moreover, it appeared useful to analyze this building in this precise location and with these functions in order to make a first analysis on a building that could be suitable for future developments (*i.e.*, analysis of marble characteristic changes caused by a dense urban environment, such as the one of New York City). To this aim, the inter-building configuration was taken into account in the thermal-energy analysis, and the architectural surrounding was modeled.

Figure 4. Plan type of the case study: the lightest space is common, and the gray-scaled parallelepipeds are private residences.

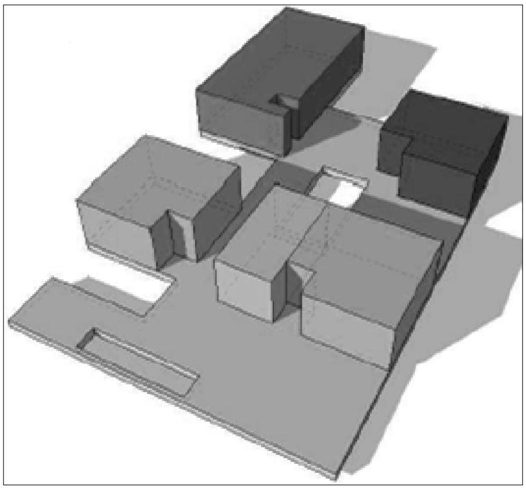


Figure 5. Northwest facade during the day.

Figure 6. Northwest facade at night.

4.2. Physical Characterization of the Building

The building's physical characteristics have been described within the dynamic simulation environment by modeling the envelope systems [11], the occupancy schedules [22], the local climate boundary conditions [23] and the inter-building dense urban surrounding [23]. This information was useful in order to investigate the thermal-energy behavior of the designed building in its real context of Manhattan, New York City, NY, by simulating also indoor realistic conditions about the possible use of the designed spaces and facilities. Free-floating conditions were assumed in order to investigate the natural indoor thermal performance of the spaces by comparing different envelope marbles and indoor use of the areas. In order to investigate also the possible effects of the considered marble envelope in terms of primary energy for cooling and heating, HVAC systems were modeled with unitary energy efficiency values and temperature reference set points in summer and winter. In particular, 20 °C and 26 °C were the temperature set-points, as suggested by Italian Organization for Standardization and *Comité Européen de Normalisation*, UNI EN 15251 [24], characterizing the 9200 m^3 of air-conditioned area of the multistory building. In particular, sedentary conditions and the II level of expectation were assumed as the "normal level of expectation and should be used for new buildings and renovations" [24]. Even if specific schedules characterization has been included in the model (Table 3), the indoor temperature set points were kept constant and homogeneous in the different thermal zones, in order to avoid differential thermal behavior in the building imputable to different temperature set points. Therefore, no specific technologies such as an HVAC (heating, ventilation and air conditioning) system, were considered in this study [25], since this is not the focus of the work. In order to investigate the building thermal-energy behavior, the climate of New York City was included into the simulation environment, and the weather file of JFK Airport was used in the EnergyPlus tool [26]. The specific indoor schedules of the activities are reported in Table 4, while the main thermal zones and functions are also described. All of the thermal zones were characterized with an infiltration rate of 0.7 air changes per hour and a minimum level of fresh air of 10 L/person. The detailed weather boundary conditions are reported in Table 4. The opaque envelope multilayer structure and its thermal properties are reported in Table 5. The optic-energy properties of the envelope marble surface were considered in the model, by taking into account experimentally measured values through a spectrophotometer and an emissometer, as reported in Section 3.

Table 3. Indoor activity schedules of the case study building.

Thermal Zone	Characteristics
1. Hall, lecture theatre	Density: 0.2 people/m^2 Activity-metabolic rate: standing-walking 140 W/person Target illuminance: 300 lux Equipment gain: 2 W/m^2, radiant fraction 20% Schedule: from 8:00 am to 6:00 pm, 7 days/week
2. Display and public areas	Density: 0.15 people/m^2 Activity-metabolic rate: light manual work 180 W/person Target illuminance: 200 lux Equipment gain: 2 W/m^2, radiant fraction 20% Schedule: from 8:00 am to 6:00 pm, Sunday off

Table 3. *Cont.*

Thermal Zone	Characteristics
3. Domestic dining room	Density: 0.17 people/m^2 Activity-metabolic rate: eating-drinking 110 W/person Target illuminance: 150 lux Equipment gain: 3 W/m^2, radiant fraction 20% Schedule: from 8:00 am to 1:00 pm and from 6:00 pm to 9:00 pm, 7 days/week
4. Domestic kitchen	Density: 0.05 people/m^2 Activity-metabolic rate: light work 160 W/person Target illuminance: 300 lux Equipment gain: 30 W/m^2, radiant fraction 20% Schedule: from 8:00 am to 1:00 pm and from 6:00 pm to 9:00 pm, 7 days/week
5. Museum galleries	Density: 0.05 people/m^2 Activity-metabolic rate: light work 160 W/person Target illuminance: 300 lux Equipment gain: 30 W/m^2, radiant fraction 20% Schedule: from 8:00 am to 1:00 pm and from 6:00 pm to 9:00 pm, 7 days/week

Table 4. Weather monthly boundary conditions of the simulated model.

WMO Station Identifier 744860 **Details: TMY3**	**Latitude: 40.65; Longitude: −73.80**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Outside Dry-Bulb Temperature (°C)	1.17	−0.17	5.58	10.94	16.05	21.71	25.05	24.79	19.95	14.02	7.31	3.32
Wind Speed (m/s)	−4.35	−7.45	0.29	4.75	9.14	15.84	20.26	17.15	13.23	7.95	2.14	−2.82
Wind Speed (m/s)	5.64	5.07	5.58	4.99	4.42	4.92	4.06	4.19	3.91	4.86	5.61	5.64
Direct Normal Solar (kWh)	66.5	92.7	115.2	117.1	129.5	134.4	128.8	168.7	120.1	134.3	65.6	74.5
Diffuse Horizontal Solar (kWh)	27.6	31.7	51.0	59.7	81.5	81.0	85.3	71.4	53.2	45.8	34.8	22.7

Table 5. Thermal characteristics of the envelope systems.

S/BC Marble Vertical Envelope		**Flat Roof**	
Material	**Thickness**	**Material**	**Thickness**
S/BC marble layer	0.01 m	Asphalt membrane	0.01 m
Epoxy resin	0.005 m	Mineral wood rolls	0.14 m
Quartz glass	0.015 m	Air gap	0.03 m
Air gap	0.25 m	Plasterboard	0.02 m
Internal glass panel	0.02 m	Cement slab	0.2 m
Thermal transmittance: 2.6 W/m^{2}K		Thermal transmittance: 0.2 W/m^{2}K	
Internal heat capacity: 33 kJ/m^{2}K		Internal heat capacity: 189 kJ/m^{2}K	
Ground Floor		**Ground Floor**	
Material	**Thickness**	**Material**	**Thickness**
XPS insulating panel	0.09 m	Gypsum plasterboard	0.025 m
Cast concrete	0.20 m	Air gap	0.10 m
Floor screed	0.07 m	Gypsum plasterboard	0.025 m
Thermal transmittance: 0.3 W/m^{2}K		Thermal transmittance: 1.6 W/m^{2}K	
Internal heat capacity: 97 kJ/m^{2}K		Internal heat capacity: 23 kJ/m^{2}K	

5. Results and Discussion

The analysis of the results of the combined experimental-numerical study concerns: (i) the surface characterization of the material; and the (ii) thermal-energy assessment of its effect while applied as a facade finishing solution. The first part of the main results could be considered as a general characterization of the marble facade solution, while the second one is building-specific, since a case study has been chosen for this work. In this view, the general superficial properties of the marble facade can be found in Section 5.1, and the case study quantitative evaluations are reported in Sections 5.2 and 5.3. Even if the choice of the case study makes the results more difficult to extend to other cases, the building's precise modeling and simulation give a clear, realistic and quantitative impression of the performance of such an innovative material as applied in translucent facades.

5.1. Marble In-Lab Analysis and Statistical Observations

Many comparisons have been carried out between measured values of the different marbles. For every comparison, the standard deviation of the measurements is assessed, which is the dispersion around the average values. The compared measurements are the values of the solar reflection index (SRI), solar transmittance and absorbance, color rendering index (CRI) and emissivity, taken for Statuario (S) and Bianco Carrara (BC) marble. The comparison has been set between the same value of the two different marbles, in order to assess the different behaviors of the two samples, and states if this difference is significant. A linear regression has been performed to compare the different data sets: the measured values are considered as dependent variables and marble types as independent variables; *i.e.*, SRI measured values are dependent variables. The change of these values is analyzed whether the considered marble is S or BC, so marble type is considered an independent variable. If the Fisher test is significant (*p-value* < 0.05), then the linear regression model is considered representative. This happens for almost all of the analyzed data, meaning that the employed model is reliable, representing the considered phenomena. Moreover, considering the Student's *t*-distribution, *t*-value, it is possible to assess if the impact of the independent variable (*i.e.*, S marble or BC marble) is statistically significant (for a fixed confidence level of 95%) on the dependent variable (the measured value). If $|t| > 2.78$ and *p-value* < 0.05, the regression is 95% significant. Therefore, depending on the marble type, it is possible to assess the mean difference between the same value for different marbles, and moreover, it is possible to state if this difference is significant or not. In the next tables, the R-squared value (coefficient of determination) is also reported, which shows the reliability of the linear regression in predicting future values.

5.1.1. Solar Reflection Index (SRI), UV, Visible (Vis) and Near-Infrared Reflectance (NIR)

Regarding SRI, the difference between the measured values of the following samples is assessed:

i. Bianco Carrara (BC) and Statuario (S) marbles;
ii. Bianco Carrara polished (BCP) and Statuario polished (SP);
iii. Bianco Carrara (BC) and Bianco Carrara polished (BCP);
iv. Statuario (S) and Statuario polished (SP);

5.1.1.1. Bianco Carrara (BC) and Statuario (S)

From an examination of Table 3, it emerges that S has a higher SRI: this difference is significant, and the linear regression model is valid. The lowest difference between BC and S reflectance values is in the UV part: here, the mean difference is just half of the one in the other spectra parts. However, also here, the difference is significant. See Table 6 for the values.

Table 6. Bianco, Carrara and Statuario solar reflection index (SRI) measured values and statistical comparison.

Marble Type	**Solar Reflectance**			
	Mean	**SD**	**Min**	**Max**
BC	58.7	3.1	52.7	61.0
S	75.6	2.9	69.7	77.3
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BC on S	−16.9	0.0	0.0	0.92
Marble Type	**UV Reflectance**			
	Mean	**SD**	**Min**	**Max**
BC	52.8	3.3	47.4	55.8
S	61.6	2.6	56.3	63.2
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BC on S	−8.8	0.0	0.0	0.72
Marble Type	**Vis Reflectance**			
	Mean	**SD**	**Min**	**Max**
BC	63.9	3.6	57.1	66.6
S	80.3	2.9	74.4	82.1
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BC on S	−16.4	0.0	0.0	0.90
Marble Type	**NIR Reflectance**			
	Mean	**SD**	**Min**	**Max**
BC	53.2	2.8	47.5	55.1
S	70.0	2.6	64.7	71.4
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BC on S	−16.8	0.0	0.0	0.93

significant or non-significant.

5.1.1.2. Bianco Carrara Polished (BCP) and Statuario Polished (SP)

It appears clearly from Table 7 that SP has higher reflectance than BCP. The difference between the two marbles is emphasized by the polishing, since the mean difference is greater than the one assessed in the comparison between manually-polished BC and S. Furthermore, here, the difference is significant, except in the NIR part of the spectra. The highest difference is noticeable in the Vis part.

Table 7. BCP and SP SRI measured values and statistical comparison.

Marble Type	**Solar Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	59.5	1.7	57.5	61.8
SP	78.8	0.4	78.4	79.6
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	−19.3	0.0	0.0	0.99
Marble Type	**UV Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	61.1	1.9	58.9	63.0
SP	71.8	1.4	70.4	73.7
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	−10.8	0.0	0.0	0.99
Marble Type	**Vis Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	64.0	3.0	60.6	67.4
SP	84.5	0.7	83.8	85.3
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	−20.5	0.0	0.0	0.99
Marble Type	**NIR Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	62.0	9.5	52.7	71.0
SP	63.1	9.9	53.9	72.6
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	−1.1	0.9	1.0	0.00

significant or non-significant.

5.1.1.3. Bianco Carrara (BC) and Bianco Carrara Polished (BCP)

The difference between BC and BCP values appears not significant regarding SRI (see Table 8). However, it appears significant in the UV and NIR regions of the spectrum (see Table 8), but with lower values than the ones between BC and S or BCP and SP.

Table 8. BC and BCP SRI measured values and statistical comparison.

Marble Type	Solar Reflectance			
	Mean	**SD**	**Min**	**Max**
BCP	59.5	1.7	57.5	61.8
BC	58.7	3.1	52.7	61.0
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on BC	+0.8	0.6	0.3	0.73
Marble Type	**UV Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	61.1	1.9	58.9	63.0
BC	52.8	3.3	47.4	55.8
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on BC	+8.2	0.0	0.0	0.77
Marble Type	**Vis Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	64.0	3.0	60.6	67.4
BC	63.9	3.6	57.1	66.6
Marble Type	**Statistical Comparison**			
	Mean difference	**P > t**	**Prob > F**	**R-squared**
BCP on BC	+0.1	1.0	0.6	0.12
Marble Type	**NIR Reflectance**			
	Mean	**SD**	**Min**	**Max**
BCP	62.0	9.5	52.7	71.0
BC	53.2	2.8	47.5	55.1
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on BC	+8.7	0.0	0.0	0.55

significant or non-significant.

5.1.1.4. Statuario (S) and Statuario Polished (SP)

Conversely, the values of SP are higher than the values of S regarding SRI (see Table 9), and this difference is statistically significant. However, also regarding S and SP, the comparison assesses smaller difference than the ones obtained by comparing the two different marbles values.

Table 9. S and SP SRI measured values and statistical comparison.

Marble Type	**Solar Reflectance**			
	Mean	**SD**	**Min**	**Max**
SP	78.8	0.4	78.4	79.6
SP	75.6	2.9	69.7	77.3
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
SP on S	+3.2	0.0	0.1	0.48
Marble Type	**UV Reflectance**			
	Mean	**SD**	**Min**	**Max**
SP	71.8	1.4	70.4	73.7
SP	61.6	2.6	56.3	63.2
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
SP on S	+10.2	0.0	0.0	0.88
Marble Type	**Vis Reflectance**			
	Mean	**SD**	**Min**	**Max**
SP	84.5	0.7	83.8	85.3
SP	80.3	2.9	74.4	82.1
Marble type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
SP on S	+4.2	0.0	0.0	0.57
Marble Type	**NIR Reflectance**			
	Mean	**SD**	**Min**	**Max**
SP	63.1	9.9	53.9	72.6
SP	70.0	2.6	64.7	71.4
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
SP on S	−6.9	0.0	0.0	0.65

significant or non-significant.

5.1.2. Solar Transmittance

Regarding solar transmittance, the difference between Bianco Carrara polished (BCP) and Statuario polished (SP) marble (Table 10) is assessed:

Table 10. BCP and SP solar transmittance values and statistical comparison.

Marble Type	**Transmittance**			
	Mean	**SD**	**Min**	**Max**
BCP	8.3	1.4	6.0	9.5
SP	4.2	0.3	3.8	4.7
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	+4.1	0.0	0.0	0.85

significant or non-significant.

BCP has a higher transmittance value, and the difference is statistically significant. However, the different thickness and stratigraphy of the elements have to be considered: BC is thinner, but it has an epoxy resin and glass fiber support, while S is thicker, but it does not have any support. The light transmittance is also measured in order to evaluate the effective capability of the thin marble to allow the sunlight to enter the building. Measured values are between 5% and 8% for BCP and around 3.5% for SP. The SP type is indeed more compact and it seems to be less transparent to sunlight and the naked-eye, as well. The BCP type presents several variances producing a wider variability of the measurements and the white part of the samples, in particular seeming to be more translucent than the SP, even by comparing two samples with the same thickness.

5.1.3. Solar Absorbance

The solar absorbance value is measured and compared for BCP and SP marbles (Table 11).

BCP appears to have the highest absorbance, although SP has more consistent values, with a lower standard deviation. The difference between the two marbles is significant and the linear regression model valid.

Table 11. BCP and SP Solar absorbance measured values and statistical comparison.

Marble Type	**Absorbance**			
	Mean	**SD**	**Min**	**Max**
BCP	31.7	3.7	27.3	36.7
SP	15.6	1.0	14.5	16.8
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	+16.1	0.0	0.0	0.93

significant or non-significant.

5.1.4. Color Rendering Index

The color rendering index value (CRI) is a measure of the capability of a light source to reveal the colors according to those shown by natural light. It represents a relevant characteristic to consider, since the marbles are typically translucent and the light is spread by the envelope towards the internal space. A value in the range of 85%–100% is considered optimal, while the range 70%–85% is considered good. Both SP and BCP have optimal CRI, meaning that they are good in transmitting light that shows colors almost equal to the ones revealed by natural light. BCP appears to have a slightly better performance regarding CRI, but the values are really similar, and the difference is confirmed as not significant. See the Table below (Table 12) for the results.

Table 12. BCP and SP CRI measured values and statistical comparison.

Marble Type	Color Rendering Index			
	Mean	**SD**	**Min**	**Max**
BCP	85.8	1.2	84.0	87.0
SP	85.7	3.1	81.0	89.0
Marble Type	**Statistical Comparison**			
	Mean Difference	**P > t**	**Prob > F**	**R-squared**
BCP on SP	±0.2	0.9	0.5	0.13

significant or non-significant.

5.2. Building Thermal Analysis

This section concerns the analysis of the indoor thermal performance of the building with varying marble typology. These results refer to the free-floating conditions, when the HVAC plants are considered as not operating. These simulations were specifically performed in order to investigate those thermal profiles in several thermal zones that could be affected by the application of the proposed marble facade solution. Therefore, the simulations are run with the HVAC systems turned off, since the active technologies are not the focus of the work. Figure 7 deals with the year-round primary energy requirement analysis of the building configuration with BC marble applied as the external coating. It is possible to note that in summer, the difference between air and mean radiant temperatures is around 1 °C, while in the winter, the same difference is negligible, given the low intensity of the solar radiation heating the envelope external layer. Additionally, the graph reports the monthly energy requirement of the building in order to address its functionalities. In fact, the values of general lighting, room electricity and solar gains through the windows are supposed to be not affected by the marble type, in the preliminary hypothesis not considering the translucent property of marbles.

Figure 7. Primary energy monthly requirement of the free-floating building with BC marble.

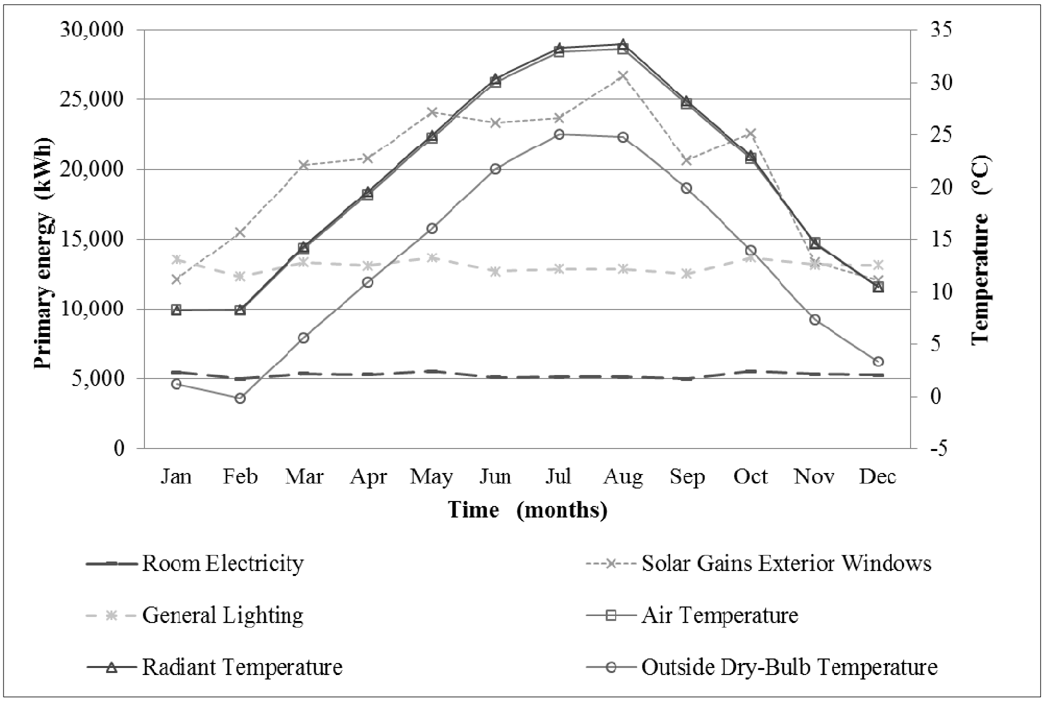
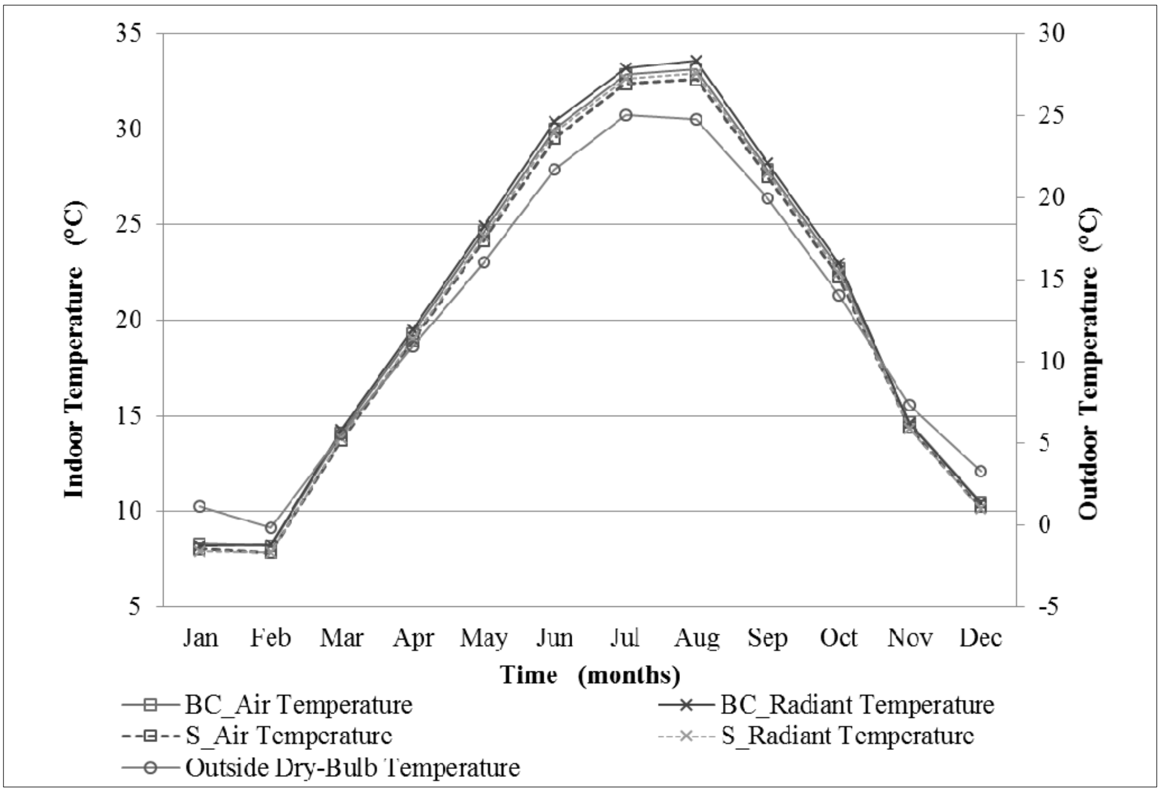


Figure 8 reports the general building-level thermal comparison between the two marbles when simulated as the external skin of the building envelope. The analysis showed that in summer, as expected, the general effect of higher reflectance marble (S) is able to produce an indoor temperature decrease of about 1 °C on average for all of the indoor thermal zones of the buildings. In winter, the same effect is negligible, showing that the application of cool marbles is not responsible for a notable overcooling penalty.

Figure 8. Thermal comparison at the building-scale of the two modeled marble envelopes.



Now, a specific thermal zone was selected in order to be representative of the marble behavior. In fact, such a thermal zone is located on the top floor of the building, it could be considered as not affected by inter-building effects, and it is surrounded by marble facade elements in all of the four orientations. The indoor occupancy was characterized in Table 3 (3. Domestic dining room). Focusing now on that central zone of the sixth floor of the building, chosen as a representative area to determine the overall indoor thermal effect of marble application, Figure 9 reports the daily analysis in winter (January 10 has been chosen for the analysis as a typical cold day). As expected, the night's effect is almost negligible, while a major effect is observed for the radiant temperature difference, around 0.6 °C in the hottest afternoon hours.

Figure 10 reports the results of the same indoor zone, but on a summer day (July 10). Consistently with annual observation, the effect of varying the marble is very much larger in summer than in winter. In fact, it determines a temperature decrease of around 1 °C, with a slightly higher effect for the radiant temperature difference. The same difference is not negligible in night hours when the marble envelope still determines a different thermal behavior, even if the visual difference between the two chosen marbles is not so notable.

Figure 9. Daily winter thermal comparison in the reference zone with varying the marble.

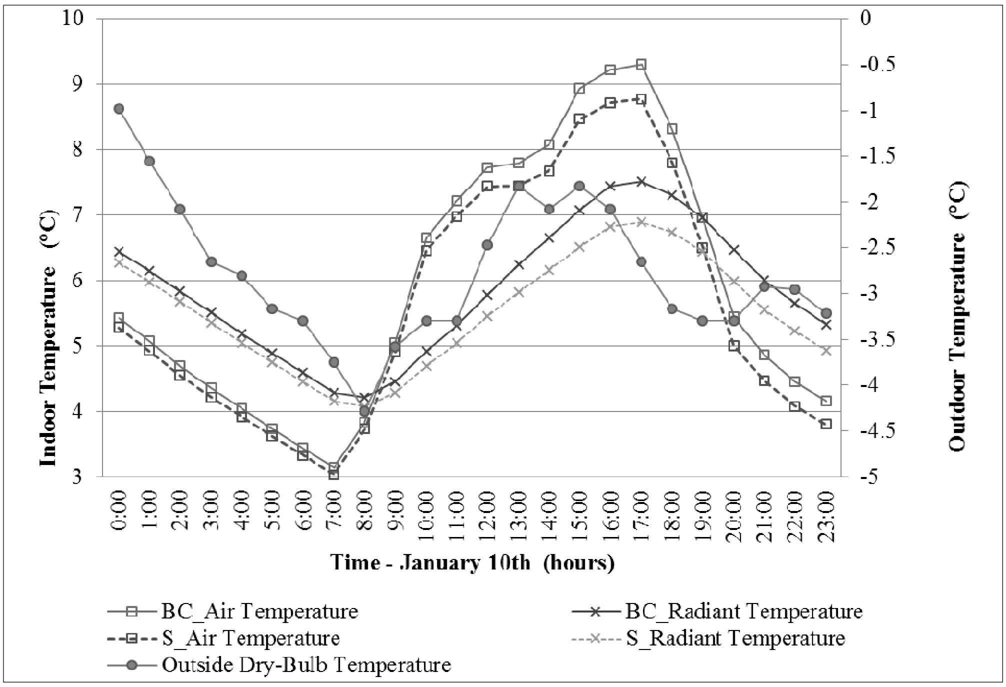
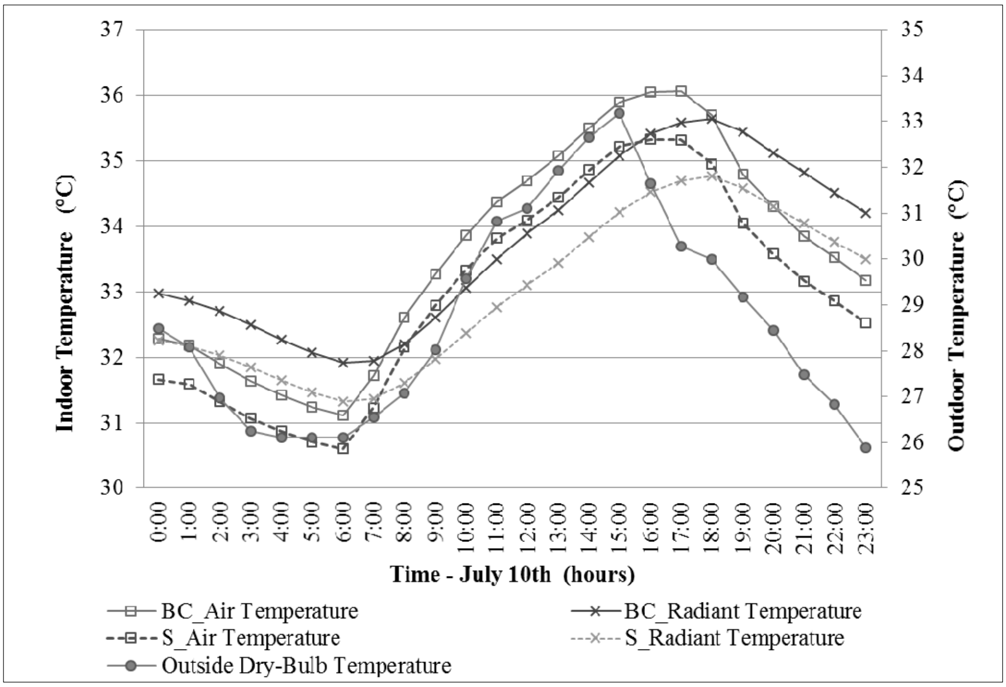


Figure 10. Daily summer thermal comparison in the reference zone with varying the marble.



5.3. Building Energy Analysis

As previously mentioned, the energy comparative assessment between the two marble configurations is carried out in order to estimate the primary energy requirement for cooling and heating of the building. To this aim, the ideal HVAC system was simulated and the energy demand for heating and cooling analyzed, by considering hypothetical technologies having a unitary energy efficiency value, in order to take into account primary energy data. Figure 11 shows that the increasing reflectance is able to reduce the energy requirement for cooling up to 6% in July, while the corresponding winter maximum penalty is around 3%.

Figure 11. Daily summer thermal comparison in the reference zone with varying the marble.

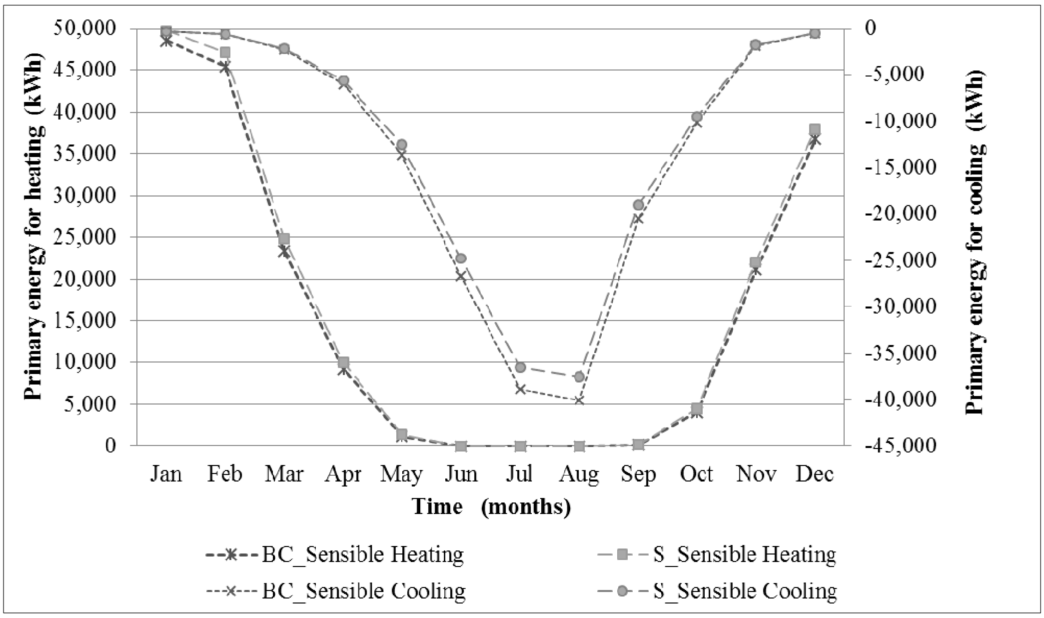
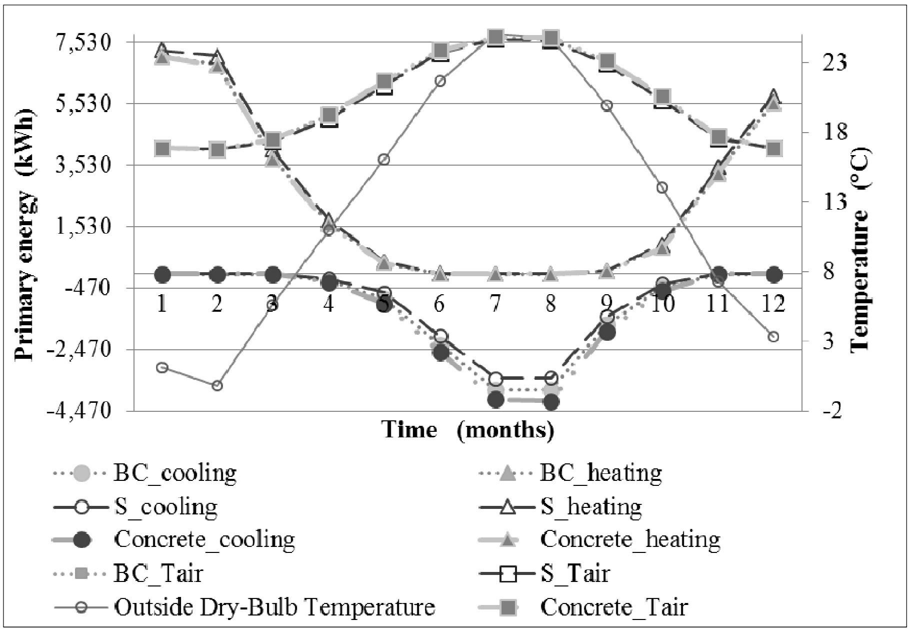


Figure 12. Monthly comparative analysis between marble solutions and cement-based tiles in the reference zone.



Now, the comparative thermal-energy analysis between marble solutions and more traditional solutions is performed in order to evaluate the possible benefits and penalties of the proposed material compared to traditional tiles. To this aim, a cement-based tile is chosen, and the primary energy for heating and cooling is evaluated for the reference thermal zone at the top floor of the building, which is surrounded by the building facade in all orientations, as explained before. The optic-energy characteristics of the cement-based tile are: (i) solar reflectance of 0.3; (ii) thermal emittance of 0.9;

and (iii) visible absorbance of 0.7. These typical values are assumed from other previous works characterizing several construction materials. The other properties of the tiles are basically very similar to the ones of the marble slabs; therefore, the most interesting comparison is operated in terms of the superficial natural properties of the chosen construction materials. Figure 12 reports such a comparison, where it is possible to observe that the marble solution is able to reduce the cooling energy demand up to 18% in summer, with relatively low penalties in winter, *i.e.*, around 3%. Since we are studying the controlled regime, *i.e.*, with a working HVAC system, the indoor temperature difference is not much impacted by the facade material, even if a weak non-negligible difference is shown. In fact, the cement-based solution presents a higher air temperature in July (the hottest month) by about 0.1 °C, with negligible differences in winter.

6. Conclusions and Future Developments

In this paper, an integrated thermal-energy and optic experimental analysis of innovative translucent marble for a building envelope application is presented. Marble slab is cut into thin layers, and its reduced thickness permits the light to pass throughout the element itself. This solution is not so common nowadays, given the cost of the material and the disadvantages that this technology brings in terms of thermal-energy performance. However, there are also some advantages to consider (*i.e.*, diffuse natural light illuminating internal areas and cool natural performance of the marbles). For this purpose, this preliminary analysis focused on the optical and thermal-energy characterization of two different white marbles. Moreover, a comparison was set between Bianco Carrara (BC) marble and Statuario (S) marble, to assess the differences in their thermal energy performance and optical characteristics. A dynamic simulation was performed, considering a case study building project located in the dense urban environment of New York City. The application of such a naturally cool material is evaluated as a passive solution to reduce the building energy requirement for cooling. The corresponding winter penalties are also assessed.

The results of the optical and thermal experimental characterization indicated that both of the marble samples (Bianco Carrara and Statuario) have a natural cool performance, since they are characterized by high solar reflectivity and emissivity, with respect to standard construction materials. Moreover, the more polished the surface of the marble is, the higher the solar reflection index (SRI) is, mainly in the UV. However, by statistically analyzing the measured data, the BC sample shows a significant difference compared to the S sample regarding SRI: SRI values of BC are −16.90% smaller than the S values. The greatest difference in the reflectance is located in the NIR and Vis parts, while it is smaller in the UV. Differently, by comparing BC and BCP and, then, S and SP, the results show that this difference is not significant or slightly significant regarding SRI.

In terms of solar transmittance, the values are assessed given the different stratigraphy and thickness of the samples. The BCP sample is 0.5-cm thick and has an epoxy resin and glass fiber support, with a mean of 8.32% solar transmittance. The SP sample is 1.0-cm thick, without any support, and the mean solar transmittance value of 4.25% is assessed. The difference between these marble samples is significant, BCP has a +4.07% solar transmittance. Further investigation about the possibility to use such material in order to save energy for lighting will represent a future perspective of this research.

The same result is given by absorbance measurements, where BCP has a mean value of 31.7%, significantly greater (+16.08%) than the SP sample one, which is 15.61%.

Furthermore, the color rendering index is assessed, and the measured values indicated that the light that passes throughout the BCP and SP sample surfaces reveals colors according to those shown by natural light. This is an important aspect, confirming that this could be a good technology for naturally lighting internal spaces. The CRI values are over 8, both for BCP and S, which is considered an optimal CRI index.

Finally, regarding experimental measurements of emissivity, S marble shows a slightly higher value of 0.88, while BC is 0.84.

Thermal-energy numeric analysis shows that the marble facade presents very high values of thermal transmittance, and further investigation should be done in order to integrate marble finishing with a higher thermally-insulating layer. Nevertheless, the effect of the higher reflectance of S marble produces important benefits in reducing indoor air and radiant temperature and in reducing the energy requirement for cooling up to 6%. Relatively lower winter penalties are registered as overcooling production due to the implementation of S marble instead of BC marble. The comparative analysis between marble solutions and more traditional cement-based tiles showed how the marble is able to reduce the cooling energy demand by around 17%–20% with relatively low penalties in winter, *i.e.*, around 3% with respect to the cement-based solution.

In this panorama, a combined dynamically variable solution integrating extra-insulating layers in winter and the natural marble cool behavior in summer could represent a further development of the work. However, the movable extra insulation layer could compromise the translucent properties when the daylight benefits are relatively low, *i.e.*, in winter, when the solar radiation is weak and of short duration during the course of the day.

However, as a preliminary study, the analysis carried out in this paper provides key insights in this research and design field. Future developments of the research will take into account the effect of weathering phenomena in varying marble optic-energy properties, by considering the effect of acid rain in the city of Manhattan. Finally, the capability of translucent layers to save energy for lighting in the same case study building will be evaluated. Moreover, in this work, two important types of marble have been analyzed: it would be interesting to consider a wider variety of marble typologies, different in color, texture and origin, and to compare their characteristics.

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Author Contributions

Federica Rosso is a Ph.D. student, whose main research interest is the analysis of marble solutions for energy savings; she is the main author of the work. Anna Laura Pisello is an assistant professor leading the work development and the experimental activities. Franco Cotana and Marco Ferrero are the full professors supervising the energy and the architectural analyses, respectively.

Conflicts of Interest

The authors declare no conflicts of interest.

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