

Thermal and optical characterization of natural and artificial marble for roof and external floor installations

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Abstract. Some types of buildings need to use certain materials for aesthetic reasons, like churches or mosques. Marble is one of the most common materials usually installed on roofs and floors. The measurement of the thermal and optical characteristics can be useful to understand its behaviour when it is subjected to thermal loads such as solar radiation or high temperature winds. The paper shows a comparison study between natural and artificial types of marble, to investigate the thermal characteristics both in steady-state and transient conditions. Optical properties and surface emissivity were evaluated, in order to calculate the Solar Reflectance Index (SRI); the specific heat, the thermal conductivity and the density were measured to define the thermophysical properties useful for the dynamic analysis. Finally, a test bench was created to check the marble behaviour under known artificial irradiation.

1. Introduction

The constructions external layers, being exposed to solar radiation, are recently investigated with raising attention ([1], [2], [3], [4]) especially for applications in hot climates. For instance, the application of a layer of growing vegetation on the roof or on the walls of a building can lead to advantages from both thermal and acoustic point of view [5]. A different approach is to increase the ratio of the energy reflected and emitted from the building envelope through the application of cool coatings [6]. All the efforts directed to reduce the cooling load in the built environment must take into account the heat load deriving from the sun [7], [8]. Within this framework, marble plays the double role of fine and cooling material, if chosen with suitable thermal and optics characteristics [9], [10]. Many studies have been conducted to evaluate the change of aesthetic features of the marble caused by chemical reactions [11], the consequences of high temperatures and thermal cycling on structural properties [12], [13], [14]. The marble thermophysical performance assessment needs the knowledge of various parameters [15] whose combination could give a complete information also in dynamic conditions, the most common situation encountered in summer season [16].

Natural and an artificial marble samples were analysed in order to define the thermophysical properties describing the transient thermal behaviour and the marble response to solar irradiation. A set of several tests were performed on the two types of marble, according to the specific standard that rules each measurement. The characterization of the samples was useful to compare the natural and artificial composition, as well as to study two models for describing the transient thermal behaviour: an analytical approach and finite volume simulations; results were then compared with measured data, obtained by a laboratory experimental setup.



2. Thermal and optical characterization of natural and artificial marble

2.1. Thermal conductivity

The homogeneous materials thermal conductivity is commonly measured with a guarded hot plate equipment, where two large square-shape samples are used: 500 x 500 x 30 mm for both natural and artificial marbles. The device creates a temperature gradient on the sample surfaces with a known heat flux that passes through the sample itself. The apparatus can use single or double samples, according to the Standard EN 12664 [17]; for the analysed marble, a single specimen setup was chosen. The equipment is composed by a heating and a cooling unit (figure 1), in order to create the desired temperature gradient.

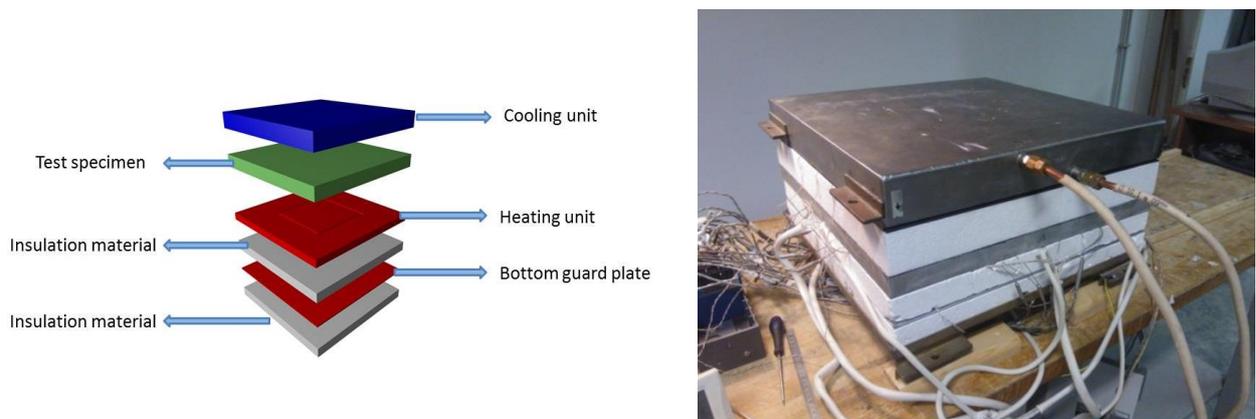


Figure 1. Guarded hot plate equipment.

The heating unit (figure 2) is composed by a metering section (250 x 250 mm) and a guard section, aimed at avoiding lateral losses; besides, another bottom guard hot plate is positioned to prevent the creation of vertical fluxes in the direction opposite to the specimen.

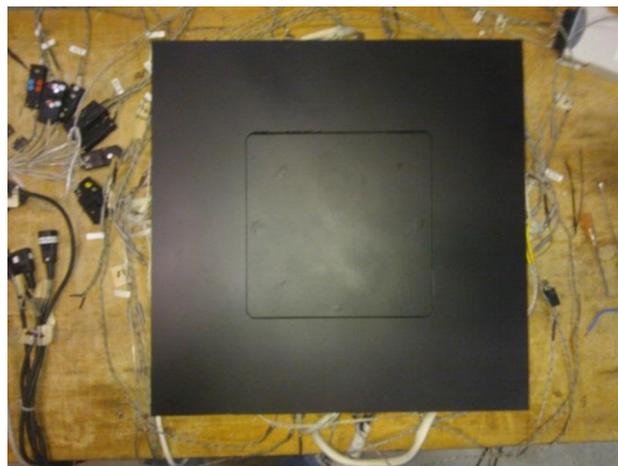


Figure 2. Guarded hot plate: metering section and guarding section.

The control and acquisition system were developed in the LabView environment [18], by a specific software that allows the control and acquisition of the various parameters, thanks to the reading and the recording of the 43 temperature probes and the current and voltage probes, installed to evaluate the heat flux. During the tests, when the system reaches the steady state conditions, the specimen thermal

conductivity is calculated by the one-dimensional Fourier expression, with the temperatures and the heat flux of the measuring zone.

Table 1 shows the thermal conductivities of the natural and artificial marbles, with the measured uncertainties, calculated according to the Standard ENV 13005 [19].

Table 1. Results of thermal conductivity tests.

	Thermal conductivity (W/m K)
Natural marble	1.46 ± 0.16
Artificial marble	1.08 ± 0.08

2.2. Specific heat

The specific heat of solid materials such as marble can be measured by a Hot Disk [20] setup, an instrument based on the Transient Plane Source (TPS) method [21], [22]. During the measurement, the hot disk sensor is sandwiched between two identical samples and it constitutes at the same time the heater and the recorder of the resistance increase as a function of time. An electrical current flows in the sensor spiral to increase the temperature between a fraction of a degree up to several degrees. With a specific algorithm based on the transient behaviour of the system, the instrument measures the thermal conductivity, the diffusivity and the volumetric specific heat. The volumetric specific heat was obtained and the specific heat in [J/kg K] has been calculated with the density measurement. Respect to the thermal conductivity assessment, different samples were used for this measurement: 100 x 100 x 10 mm square-shape for both types of marble. The natural marble has a density of 3020 kg/m³, with a specific heat of 773 J/kg K; the artificial one has a density equal to 2730 kg/m³ with the specific heat equal to 706 J/kg K. The uncertainty of the measurements is equal to 5% according to the Hot Disk specifications [20].

2.3. Emissivity and optical properties

2.3.1. Emissivity. The method for the measurement of the surface total emissivity is regulated by the Standard ASTM C1371 [23], that defines the procedures and the suitable instruments. The device consists of a circular head with a diameter of 50 mm, heated by an electric power supplier up to a temperature of 355 K. During the measurement, the sample surface and the measurement head surface remain separated by an air layer of about 4.3 mm, confined by the circular crown of the plastic cylinder that encases the entire head and facilitates its use. The instrument includes a heat flow differential gauge made of two pairs of sensors, that returns the difference between the voltage signals produced by the sensors themselves: one couple with the same surface treatment of the head (black-opaque, high-emissive), the other couple with a golden low-emissive treatment (figure 3).

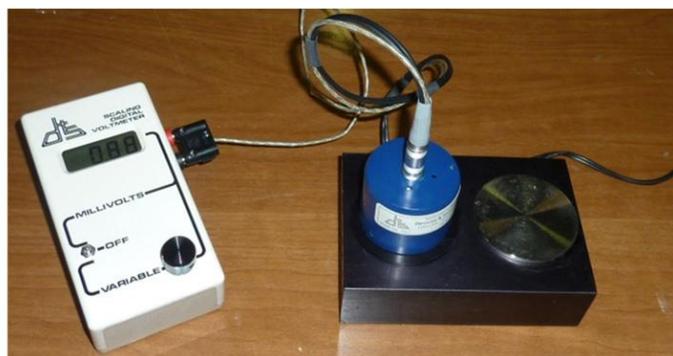
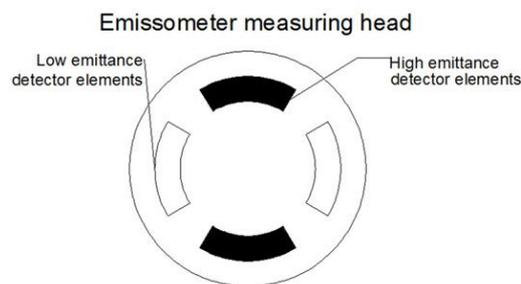


Figure 3. Calibration phase of the emissometer.

By means of this measurement it is possible to assess the radiation heat exchange, since the heat flux registered by the first pair includes both the conduction and radiation heat transfer, while the second pair evaluates contribution of the the only conduction; the small thickness of the cavity does not allow the activation of convection.

From the knowledge of the radiation heat flow and the surfaces temperatures (the sample temperature must be kept close to the ambient temperature), the emissivity of the sample can be determined.

The two tested samples (square-shape 100 x 100 x 10 mm) showed similar values of total emissivity. The emissivity for the natural marble is 0.88 and for the artificial one is 0.85, both with an uncertainty equal to ± 0.03 .

2.3.2. Optical properties. The optical characterization of marble samples (square-shape 100 x 100 x 10 mm) were carried out through specular gloss and reflectance. Specular gloss is used to evaluate the tendency of an object to reflect light in a specular (mirror-like) direction. This optical property was measured in terms of Gloss Unit (GU) using a ETB-0833 triple angle (20°, 60° and 85°) Gloss Meter in compliance with the ASTM D523-14 standard [24]. The instrumentation detects gloss between 0 GU (perfectly matte surface) and 200 GU (high gloss behaviour). Reflectance was evaluated using a double beam spectrophotometer in the wavelength range 300-2500 nm. The instrumentation allows to evaluate the amount of energy reflected by a solid sample, in comparison to a standard material. In this case, a BaSO₄ flat plate was used, which absolute reflectance coefficient is certified in the analyzed wavelength range. An estimation of the absolute reflection coefficient of the assessed samples was then calculated multiplying the absolute reflectance coefficient of the BaSO₄ reference sample with the measured reflection coefficient of the assessed samples. These elaborated data were used to calculate the single rating parameters solar reflectance ρ_s (according to ASTM E903-12 [25]) and light reflectance ρ_v (according to EN 410:2011 [26]). The first one allows to easily evaluate the sample reflection between the whole examined wavelength range, whereas ρ_v is calculated considering only the wavelengths perceivable to human eyes, fixed [26] in the range 380-780 nm. Several measurements were performed for each sample type to evaluate the uncertainty. The results are reported in table 2.

Table 2. Optical characterization of artificial and natural marble

Marble type	Parameter	Value
Artificial	20° Specular Gloss	101.0 \pm 7.0 GU
	60° Specular Gloss	95.7 \pm 8.4 GU
	85° Specular Gloss	91.9 \pm 11.9 GU
	Solar reflectance ρ_s	82.00 \pm 0.14 %
	Light reflectance ρ_v	86.90 \pm 0.12 %
Natural	20° Specular Gloss	0.9 \pm 0.1 GU
	60° Specular Gloss	1.7 \pm 0.2 GU
	85° Specular Gloss	0.8 \pm 0.3 GU
	Solar reflectance ρ_s	84.39 \pm 0.41 %
	Light reflectance ρ_v	87.26 \pm 0.18 %

Data reported in table 2 shows that artificial and natural marble reflect practically a similar quantity of light, but not in the same way. Solar reflectance and light reflectance values of the two assessed samples are quite similar, whereas specular gloss values are deeply different. Natural marble has a matte surface avoiding specular reflections; this aspect is crucial in some practical application, such as pavements of long corridors artificially illuminated. In this case, a specular gloss value close to 0 GU

is advisable, since it avoids uncomfortable luminaire reflections on people walking on the corridor. As far as reflection properties, both materials absorb less than the 20% of the energy in the 300-2500 nm wavelength range and reflect only above the 13% of the radiation perceivable to human eyes.

2.4 Solar Reflectance Index (SRI). According to ASTM E1980-11 [27], it is possible to calculate the Solar Reflectance Index from the measurements of total emissivity and solar reflectance. These parameters are related to the surface temperature of the specimen, since they represent respectively the capacity of the surface to emit energy to the environment and the effect of solar radiation on the surface itself. The Standard reports two different approaches for the calculation of *SRI*. The index in standard solar and ambient conditions (solar flux equal to 1000 W/m², ambient air temperature equal to 310 K and sky temperature equal to 300 K) is evaluated with the following equation:

$$SRI = 123.97 - 141.35\chi + 9.655\chi^2 \quad (1)$$

where:

$$\chi = \frac{((1 - \rho_s) - 0.029\varepsilon)(8.797 + h_c)}{9.5205\varepsilon + h_c} \quad (2)$$

ρ_s and ε represent respectively the measured solar reflectance and thermal emissivity. The term h_c is the convective coefficient that, according to the Standard, could assume three different values: 5, 12 and 30 W/m² K, to take into account of different wind conditions. Table 3 shows the results of *SRI* for the two marble samples with the final uncertainties calculated according to the Standard ENV 13005 [19].

Table 3. Results of the calculation of the Solar Reflectance Index (*SRI*).

Solar Reflectance Index (<i>SRI</i>)	$h_c = 5$ W/m² K	Uncertainty	$h_c = 12$ W/m² K	Uncertainty	$h_c = 30$ W/m² K	Uncertainty
Natural marble	105	± 0.79	105	± 0.70	105	± 0.63
Artificial marble	101	± 0.65	101	± 0.48	102	± 0.35

3. Models

3.1. Experimental setup

Thermal measurements were carried out in order to evaluate the surface temperature of marble under constant solar irradiation. The solar spectrum was provided using the Sun simulator Solar 2000, (ABET Technology, Model 11018) which generates a standard solar spectrum according to the IEC60904-9 (solar simulator performance requirements).

The sample (100 mm x 100 mm x 10) was placed into an insulated cylinder under the sun simulator lamp. The sample distance from the lamp was 25 cm, to obtain a radiation equal to the maximum value of 1200 W/m² on the sample surface.

Three thermocouples were attached on the sample surface, as shown in figures 4 and 5. At the same time, a fourth thermocouple was used to measure the air temperature at 10 cm from the marble surface.

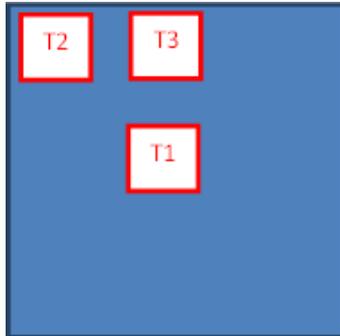


Figure 4. Positions of temperature probes on the surface sample.

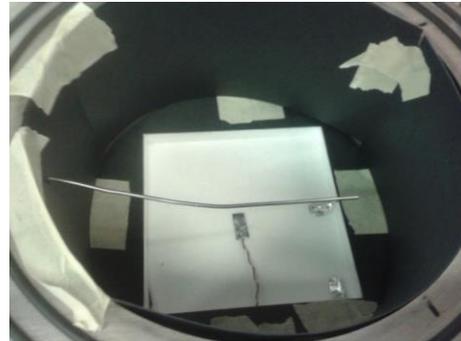


Figure 5. Temperature probes on the surface sample (with the thermocouple for air temperature measurement).

As soon as the shutter was opened, the radiation value was measured with a global radiation probe. Hence, the four values of temperatures were acquired each 10 seconds, until the average surface temperature reached a value that remained constant for at least 20 minutes. Afterwards, the radiation was verified at the end of measurement, in order to check its steadiness during the acquisition. Lower radiation values were obtained inserting a filter into the light beam.

3.2. Analytical model

The marble tile irradiated with a constant heat flux could be modelled, in first approximation, with the Lumped Capacitance Method [28]; the equations driving the phenomenon could be written as follows:

$$\frac{dU}{dt} = \frac{dQ}{dt} + \alpha W_i \quad (3)$$

$$\rho CV \frac{dT}{dt} = -hA[T(t) - T_\infty] + \alpha W_i \quad (4)$$

Where U is the internal energy of the entire tile, Q is the heat transferred to the external environment, t is the time, α is the solar absorbance, W_i is the incident radiation, ρ is the marble density, C is the marble specific heat, V is the tile volume, h is the heat transfer coefficient between the upper surface of the marble tile and the external air, hypothesizing that there are no thermal losses downwards, A is the tile upper surface, T is the tile temperature, T_∞ is the air temperature (supposed constant) and T_0 is the tile temperature at the initial instant.

The initial boundary condition of $T = T_\infty$ for $t = 0$, brings to the solution:

$$T(t) - T_\infty = (T_0 - T_\infty - \frac{\alpha W_i}{hA}) e^{-\frac{hAt}{\rho CV}} + \frac{\alpha W_i}{hA} \quad (5)$$

It is therefore possible to follow the transient of the marble tile temperature, once the parameters above described are known.

3.3. CFD Analysis

The marble transient behaviour was also studied by a finite volumes method by means Ansys Fluent [29]. The analysis was carried out with the definition of the 2-D geometrical model of the marble and a gridding process with hybrid meshes (figure 6). The thermophysical properties of the two types of marble, measured by the methods showed in the previous paragraph, were inserted in the material properties of the virtual domain.

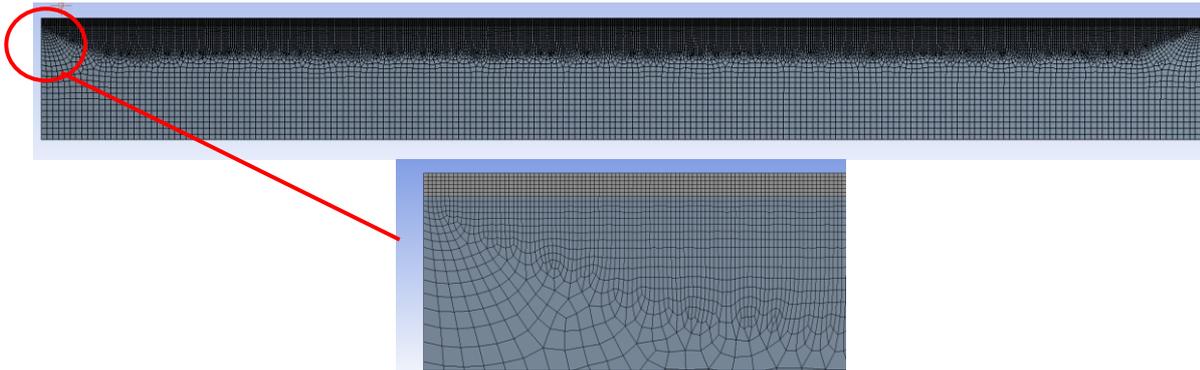


Figure 6. Grid of the 2-D marble model for CFD analysis.

At the aim of simulating the heat flow density (W/m^2) that hits the surface of the model, a thin layer of marble was created on top of the domain. An internal heat source was generated in this thin layer with the same value of the radiation heat flow, reduced by the solar reflectance index of the considered marble sample.

The initial temperature of the simulation was chosen by the values retrieved from the experimental analysis, to make the temperature transient comparable. Furthermore, the convective boundary conditions on the top surface of the marble were assigned (and considered constant during the simulations), hypothesizing that the marble in the CFD model reaches the same asymptotic temperature of the experimental data after two hours of simulation. Adiabatic boundary conditions were given for the other three sides. It is necessary to underline that for the comparison between the numerical analysis and the experimental setup, the density of the marble in the CFD model was increased to take into account of the thermal inertia of the polystyrene and the metal structure positioned under the test sample. The time-step of the simulations was setup to 1 second, with a complete transient analysis of around 6300 seconds.

4. Comparative analysis of the different approaches

The two models were compared to assess the transient thermal behaviour of the marbles. In particular, on the basis of the experimental approach, the aim of the work consists of evaluating the agreement of the models with measured data. Figures 7 and 8 show the trend of temperature on the top surface of the marbles, according to the three approaches, when a heat flow density equal to 1100 W/m^2 hits the sample. The boundary conditions of the two marbles were defined by the experimental analysis in the final steady state conditions and they were assigned to the analytical and numerical models. The two models need to define the same boundary conditions, but they have different approaches to the phenomenon: the analytical model - Lumped Capacitance Method [28] applies the heat transfer coefficient h to the whole marble perimeter and it considers the entire solid at the same temperature each time-step. On the other hand, the numerical model applies the heat transfer coefficient to the top surface of the marble, according to the real behaviour of the experimental test, creating a temperature gradient inside the solid. Therefore, the numerical analysis needs to define the boundary conditions in the other three sides, which, according to the experimental setup, were considered adiabatic. Table 4 shows the convective boundary condition parameters.

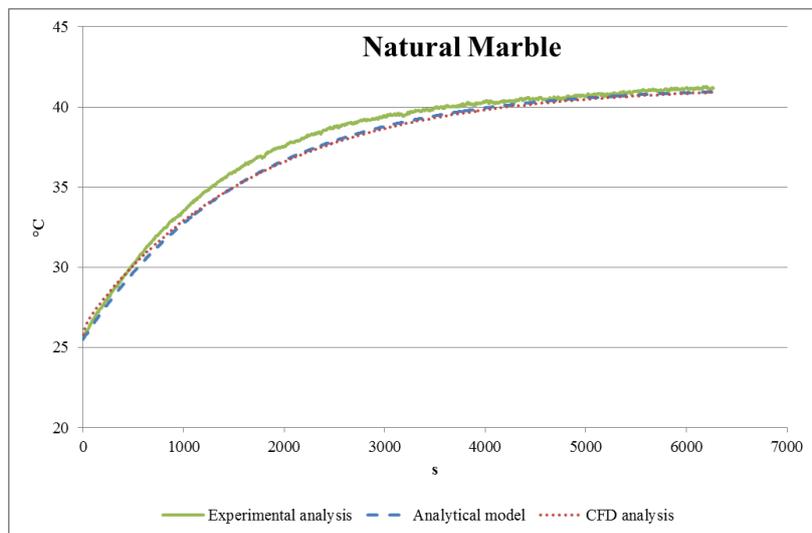


Figure 7. Temperature trend on the natural marble surface hit by a radiation of 1100 W/m².

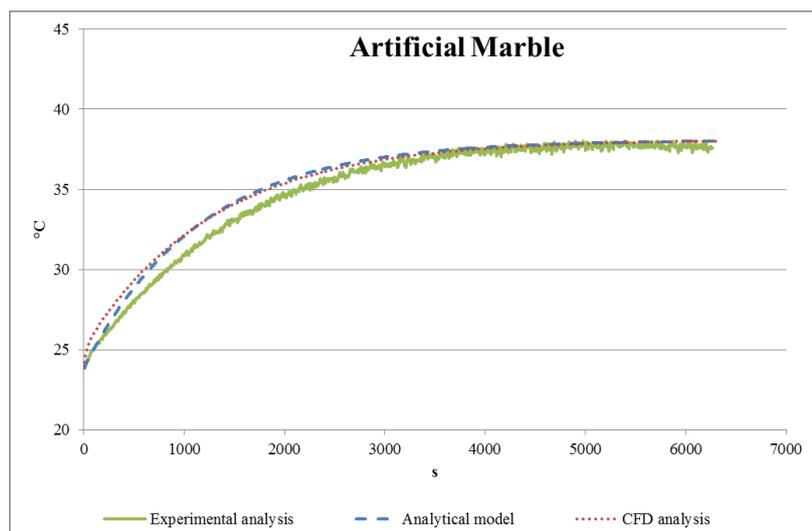


Figure 8. Temperature trend on the artificial marble surface hit by a radiation of 1100 W/m².

Table 4. Boundary conditions measured during the experimental analysis.

	Heat transfer coefficient (W/m ² K)	Free steam temperature (°C)
Natural marble	27.58	34.90
Artificial marble	33.67	32.19

The trend of the analytical and numerical models are generally comparable with the experimental results for both types of marble. The slight differences are linked to the models approximations and to the definition of the intrinsic materials properties. In particular, the analytical and numerical models consider a constant heat transfer coefficient value for each time-step of the analysis, whereas in actual conditions the heat transfer coefficient varies with time. The other factor that may contribute to the trend differences is the definition of the material thermal properties that, as previously seen, are evaluated with tests affected by a level of uncertainty.

5. Conclusions

An experimental and numerical comparative analysis on natural and artificial types of marble was conducted. The characterization of the samples properties was performed with several methods, in order to evaluate the main parameters that can affect the thermal behaviour of the materials hit by solar irradiation. The samples steady-state and transient thermal response depend on the thermal conductivity, the specific heat and the density; all these properties were measured according to the corresponding Standards. By means of these parameters it was possible to calculate the thermal diffusivity, which resulted equal to $6.25 \times 10^{-7} \text{ m}^2/\text{s}$ for the natural marble and $5.60 \times 10^{-7} \text{ m}^2/\text{s}$ for the artificial one, highlighting a quicker propagation of the thermal wave in the natural sample.

The calculated SRI (the main parameter that describes the energy balance of a surface hit by solar radiation) of tested marbles resulted higher than 100, proving its high performance as reflective material for roof coverings. SRI values higher than 100 testify that the marble cooling capacity is better than the standard white surface [30]. Although the experimental measurements did not follow exactly the SRI standard conditions, the excellent behaviour of the tested marbles is confirmed by the measured surface temperatures (almost 39 - 41°C), values lower than the white standard surface temperature (44,7°C). This feature makes the marble suitable for cool roofs or coating of outdoor surfaces, where people can walk barefoot during the summer season, such as swimming pools or religious places (mosques and churches). The comparison of the SRI between the two typologies of marble indicates that the natural marble, when subjected to the same solar irradiation of the artificial one, reaches a slightly lower temperature. The comparative analysis of a theoretical model (Lumped Capacitance Method) and a finite volume method with experimental data showed encouraging results on the thermal transient assessment, with small differences mainly due to the simplifying hypotheses and to the uncertainty of the marble thermophysical properties measurements. Thus, the analytical and the numerical model could constitute an easy and quick tool to evaluate the transient and stationary response of materials subjected to solar irradiation.

6. References

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