INFRARED THERMOGRAFIC INVESTIGATION OF BASILICA DELLA SALUTE FLOOR

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Abstract. *The infrared thermography applied to cultural and monumental goods diagnostic is one of more consolidated non-invasive techniques used actually. Its popularity is mainly due to its capacity to indentify non visible faults, humidity and others normal occurrences in works of art. In this work the experimental results obtained through the infrared thermography implementation on samples of the Basilica della Salute (Venice – Italy) floor are presented. The experimental procedures have been carried out using active thermography where the artificial heating has been obtained through the use of tungsten lamps. The thermal analysis allowed to identify restoration operations due to materials used which have different origin of the base material and, consequently, different thermal diffusivity and emissivity. The influence of the superficial color over the results is also discussed.*

Keywords*: Infrared thermography, active method, emissivity, thermal diffusivity, Basilica della Salute of Venice*

1. INTRODUCTION

The infrared thermography, applied to cultural and monumental goods diagnostic is one of more consolidated non-invasive and non-destructive techniques. It have been used as tool to acquire data during maintenances and restores programs, having the advantage to present physical principles perfectly known and a great amount of references in literature.

Very versatile, the infrared thermography can be used with a scientific objective, based on rigorous analysis methods and acquired data procedures; otherwise can be used qualitatively, supplying information directly in situ, during the date acquire phase.

This work presents the results supplied by active infrared thermography when applied over some floor samples of the Basilica di Santa Maria della Salute, situated in Venice (Italy). The floor, constituted by diverse types of marble, had been passed to diverse non registered interventions of restore. During these interventions have been used materials similar to the original, selected in order to minimize the visual effects of the restore.

From the analysis of the corrected emissivity of materials used during the restore and from the effects of thermal diffusivity in these materials, was possible, using thermographic tests, identifying the aforesaid restoration processes. Normally, just destructive techniques, based in physical-chemical analysis, could be identifying these pathologies. By other hand, the detail photo was not also able to estimate the problematic presents on the floor under examination. Others techniques, like the ultraviolet photography, could be implemented but, once more, the low contrast of the details obtained with its results have been a problem.

2. THE BASILICA DELLA SALUTE OF VENICE

The Basilica di Santa Maria della Salute is located at the end of Grand Canal on the lagoon of Venice, on the opposite side of Piazza San Marco, on the isle of Giudecca. It is an evident point of reference in Venice scenery for its immaculate white colour and the classical Renaissance style, which makes it stand out among other buildings.

It had been built starting from the 1631, following the project by Baldassarre Longhena, as thanksgiving act by the whole city of Venice who, hit by a lethal epidemic of plague of 1630, made the promise to Virgin Mary to build a new and magnificent church to get her help against the ill.

Venice kept the promise and built a wonderful and majestic church: on the octagonal basis it raises an imposing dome in Venetian style, followed by a smaller dome over presbytery, on whose sides there are the twin bell towers. Around the major dome there are the characteristic concentric marble volutes. Inside the church a precious floor with polychrome marbles and paintings by Tiziano and Tintoretto. The Figure 1 shows some views of the Basilica.

Figure 1. Views of the Basilica of Santa Maria della Salute

The floor of the Basilica della Salute is realized with several series of various color and shape marble elements. As shown in Fig. 2, when seen from the dome, the disposal of the polygons tablets of polychromatic marble makes that the floor seem to be observed through a kaleidoscope. The colors of the marble used were, beyond the white and the black, the gray and some tonalities of red. Polygons of gray-white and the red-brown marble were used too.

Figure 2. The floor with polychrome marbles

In the course of the centuries, some parts of the floor have been deteriorated presenting points of erosion and chippings. These occurrences are related to the presence of humidity from the structures on which the Basilica rests. In truth, its structure, like all the rest of the Venice historical center, is constructed directly on the sea. Therefore the elements of foundation and the superstructures are always in contact with the water provoking moisture problems.

Restorations have been done during the years, but just a few have been documented. The restorations have been done in form to reproduce, of faithful form, the original floor. Restore mortar have been used to connect the fragments of cleavage marble and to rebuilt the empty created, in order to be able to seem marble. The mortar of restoration has probably been create using, beyond the mortar, marble dust and some metallic element, often used by the restorers in the beginning of the century XX.

The thermographic tests had been applied over samples of the floor situated in front of the greater altar. The objective of the tests was to identify the interventions of restore and, more specifically, to discriminate the restoration mortar from original marbles. The samples, similar between them for geometric composition, are constituted by a series of floor portion in which are presents the typologies of marbles used for the entire floor. The planimetry of the church is presented in Fig. 3, where the positions of the samples analyzed during the tests are underlined.

3. TERMOGRAPHY INVESTIGATION

In point of view of the thermal stimulation, thermography can be classified in active and passive (Maldague, 2000). In the passive thermography natural contour conditions are used in the analysis a time that no artificial thermal stimulation is used. In this case, it must exists a natural temperature difference between the object under study and the environment where it's inserted (Tavares and Andrade, 2003).

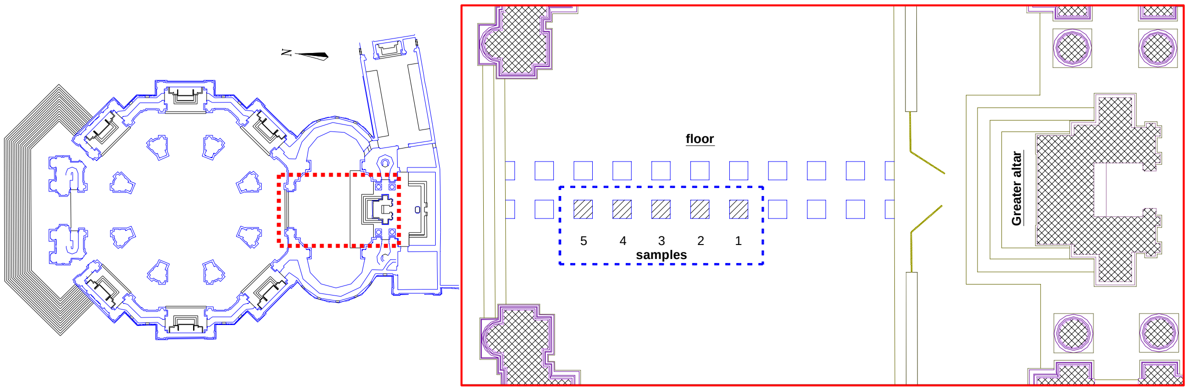

Figure 3. Planimetry of the church and test samples

In the active thermography, some thermal stimulation methodologies can be used each one with characteristics and proper limitations (Maldague, 2000, Carlomagno and Meola, 2001). The choice about the kind of thermal stimulate depends not only of the testing surface characteristics, but the type of information required.

The more used stimulation techniques are the pulsed thermography, the modulated (or "lock-in") thermography and the pulse phase thermography.

The pulsed thermography, PT, used in this work, is the most traditional of them consisting in the stimulation through energy pulses. The study normally is done during the cooling of the sample by the analysis of the temperature decay curve (Maldague, 2000). The thermal energy is supplied to material in form of squared pulse, that extend as heat waves, from the material surface for its interior, subordinate to the Fourier diffusion equation (Maldague and Marinetti, 2002). This propagation and the loss by radiation and convection generate fast change of the material superficial temperature. It is caught and registered by thermal camera (Maldague and Marinetti, 2002). The phenomenon evolution can be remarked by the acquisition of an images sequence that processed supplying information about the structure including possible fails, its dimensions, depth, thermal resistance and material characteristics (Carlomagno and Meola, 2002).

Details about the PT and about the modulated and pulse phase thermography can be found in Tavares (2006).

The thermal camera used in this study was the Avio Neo Thermo serie TVS-600. The thermal excitement has been obtained by using lamps installed on a panel purposely realized.

3.1. Thermal excitement

The lamps used for the thermal excitement are produced by Osram (Ultravitalux® model) with power equal to 300W. This is a high pressure lamp, constituted from a filament of tungsten and special glass that has the advantage to generate a spectrum of emission with the complete range of the typical solar irradiation. The special treatment of the bulb glass makes that the floodlight emitted has been, mostly, UVA and UVB radiations, presents in the solar light.

The irradiant flow for each lamp has the format seems a bell: more emphasized to the center and decreases to the edges. In order to obtain a uniform flow, the single flows of the lamps must be overlapped in way that the sum of the flows generates a unique constant flow. From this problem, have been definite the number of lamps and its position in the panel, built in order to provide a homogenous energy. The panel, of 1 meter of side, is shown in Fig. 4a. As can be also in Fig. 4b, the panel is able to produce a maximum flow of $1kW/m^2$, with about 5% of uniformity, placing the surface to a distance of 500 mm from the bulb of the lamp.

Although the surface irradiated from the described simulator has been of $1m^2$, the flow can be considered uniform just in the area enclosed between the edge lamps (the area of 750 mm x 750 mm). This situation has been verified in laboratory with radiometer measures. Beyond this limit, the contours conductions makes that the borders have been first cooled and the heat have been dispersed.

3.2. Measure procedure

In this work, the data acquisition has been done during the cooling period of the sample through the register of an images series taken in equal time intervals. The duration of the heating time have been determinate by means previous tests, carried out in situ. The objective of these tests was to verify the optimal heating time that better placed in evidence the pathologies existing in the floor. Therefore, the heating time has been fixed in, approximately, 5 minutes. The images sequence acquisition has been carried out until the thermal image did not supply significant information. The distance between the sample and the thermal camera had been kept equal to 1,80 m. The temperature of the floor before the thermal excitement was of 7°C. After the heating, its average temperature arrived to 16°C. An increment of approximately 10°C is not a problem to the marble integrity.

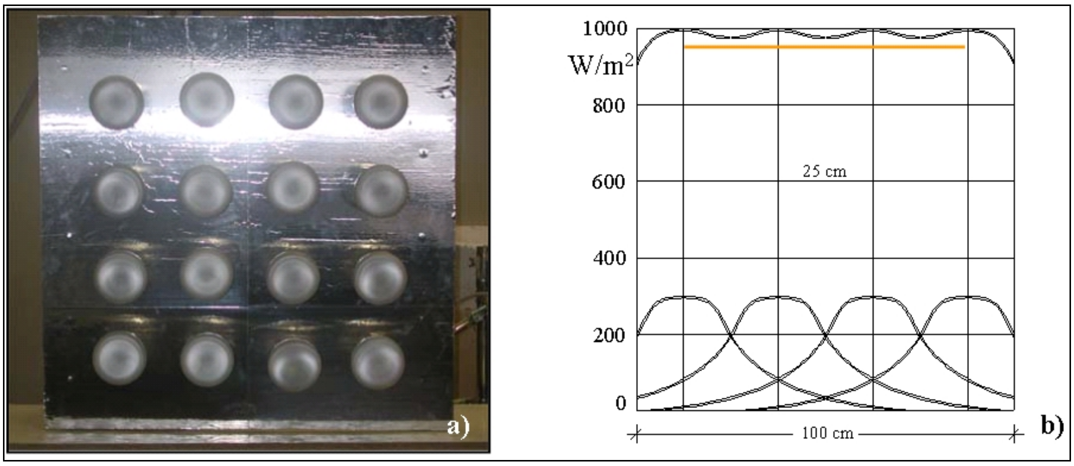

Figure 4. a) Lamps panel; b) Radiation obtained from the radiant panel

The heating system has been placed horizontally and in parallel with the floor. After the period of heating, the lamps panel has been moved and started the data acquisition. The bench can be seen in Fig. 5.

Figure 5. Thermografic bench

In the case in which ulterior measures have been executed on the same sample, the necessary time to the total cooling of the sample has been respected, before to carry out a new series of tests. This has been done to avoid that the new thermal measure presented errors due to presence of residual heat in the sample.

3.3. Emissivity choise and thermal diffusivity effect

The marble presents on the Basilica floor are different in the color but equal in that concern to their petrography: smooth and consumed in surface.

The superficial color of an object influences the amount of heat accumulated on it during the heating phase and the amount of energy emitted by it. This problematic is considered during the set up of the emissivity in the measurement system. By other hand, the knowledge of the material diffusivity is important once that this variable defines the speed of the superficial temperature decay.

Table 1 presents the indicative value to the emissivity for the marble and for others building materials (Holst, 2000).

The color effect is very common in thermal analysis applied to works of art diagnostics. This effect could be minimized during the image treatment and/or during in situ investigations. The procedure used in this work has been suggested in Tavares *et al.* (2006) and consists in adjust the emissivity in the thermal camera to indicate the same temperature obtained through contact technique of lesser uncertainty. The average emissivity to the whole surface obtained during the thermal camera calibration proceeding was equal to 0,93. Considering that the samples inquire have been constituted from several marble tonalities, whose surface is smooth but not polished, this emissivity value is coherent with the value attributed to the polished marble of color light gray at temperature of the 22°C and also to the generic marble. Although it is not feasible to apply such a procedure in situ, in laboratorial studies, tests can been carried out setting up the thermal camera with a average emissivity value and using an appropriate emissivity value for each pigment during the phase of image analysis (Tavares *et al.*, 2006).

Table 1. Total emissivity of some materials

MATERIAL	TEMPERATURE (°C)	Emissivity
Marble, white	38	0,95
Marble smooth, white	38	0,56
Marble polished gray	38	0,75
Marble polished light gray	22	0,93
Generic marble	0-100	0,93-0,94
Granite	21	0,45
Gypsum mortar	25	0,90
Plaster	30	0,91
Cement mortar	30	0,86
Lime mortar	38-260	0,90-0,92
Mortar poor in water	36	0,94
Lead	30	0,40
Oxidate lead	30	0,20-0,60

The thermal parameter more often used in order to characterize a material from the thermal point of view is its thermal conductivity. However, for measurements carried out in transient regime the parameter that better describes the thermal comportment of the material is its diffusivity (Bison *et al.*, 2004). Table 2 presents the conductivity and diffusivity values of the some materials contained in the investigated floor and of the some others reference materials (Holman, 2002).

Table 2. Thermal characteristics of some materials

MATERIAL	THERMAL CONDUCTIVITY [$W.m^{-1}. K$]	THERMAL DIFFUSIVITY [$m^2. s^{-1}$]
Generic marble	3	$12,6 \times 10^{-7}$
Marble High Value)	2,07	-
Marble (Low Value)	2,94	-
Marble (Halston)	2,80	-
Granite	1,7-4,0 (medium 3,0)	11×10^{-7}
Cement mortar	1,73	$9,1 \times 10^{-7}$
Cement plaster, sand aggregate	0,72	-
Lime-cement mortar	1,00	-
Gypsum plaster	0,48	$4,1 \times 10^{-7}$
Plaster	0,73	$6,2 \times 10^{-7}$
Lime mortar	0,65	
Lead	35	25×10^{-7}

Once that the diffusivity indicates the capacity of the material to dissipate energy, the presence of plaster (probably, with the presence of enclosed metal dust) on some areas of the floor changed the heat flow on that points. The lesser diffusivity becomes difficult the heat diffusion resulting in the register of greater superficial temperatures by the thermal camera. The difference in the thermal properties of the base material (marble) and of the material used in its restoration (plaster) made possible the identification of the restore points.

4. RESULTS

In Figure 6 are shown three thermal images of the sample 1. The times indicated refer to the period which elapsed after the thermal source has been removed. The same thermal scale has been used for the three thermal images.

The thermal image obtained in the initial instant evidenced clearly the presence of diverse materials in sample 1. With passing of the time and the cooling of the sample the thermal contrast is reduced and a more uniform distribution of the temperature is registered. In fact, for pulsed thermography, the thermal image analysis normally is carried out in the moment of the maximum thermal contrast, when the pathologies have been more visible. In others words, the best time for observation is when the temperatures registered by the measurement system are strongly affected by the thermal diffusion and by convection heat losses through the surface. In the image, the influence of these phenomena is represented exactly by the thermal contrast (Tavares *et al.*, 2006).

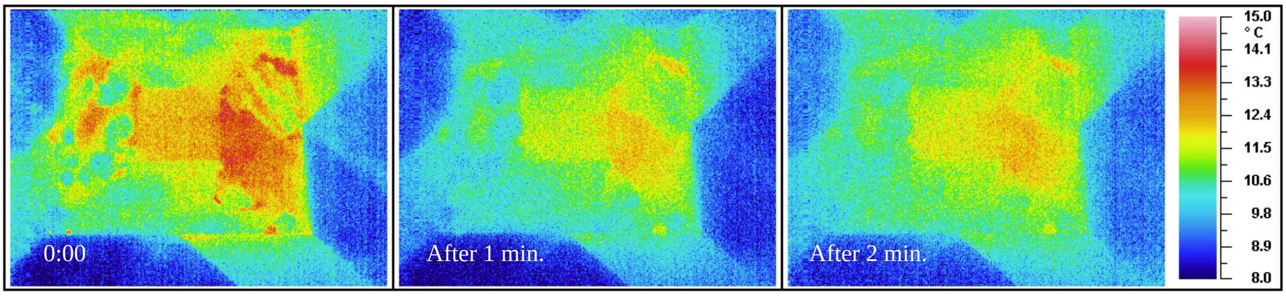

Figure 6. Thermal images of the sample 1

In Figure 7, the temperature field obtained in initial moment of the cooling processes is shown. For a best analysis comprehension, it is also presented a photo of the sample 1.

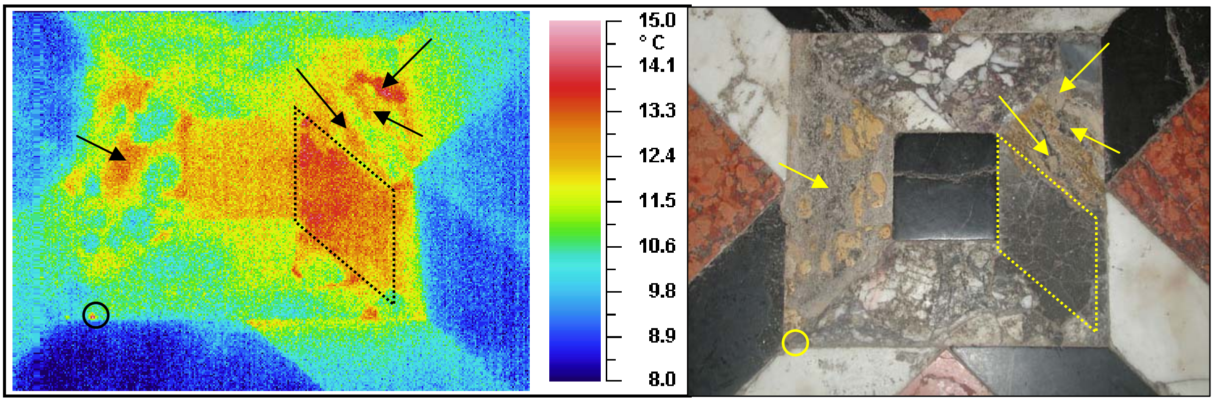

Figure 7. Thermal image and photo of the sample 1

How it can be noted, the temperature distribution in the surface of the sample 1 is much varied. In general form, the temperatures supplied by the thermal camera for the darker marbles – areas and points evidenced in Fig. 7 – have superior values regarding the values registered to the white marble. If the marble was the only material present on floor the color would be the only variable capable to provoke an increment of the temperature registered by the measurement system. This has been not verified once different temperatures have been registered for equal marble colors, what allows considering the presence of diverse origins materials. By other hand, the temperature differences between the areas with different colors (and not restored) are inside the measurement uncertainty of the thermal camera that is equal to ± 2ºC. Second Tavares *et al.* (2006) infrared thermography is capable of identifying and characterizing imperfections, only if, at least in a situation of recorded maximum thermal contrast, the differential of temperature existing between the damaged and perfect area will be greater than uncertainty of measurement on that same areas.

In Figure 8 has been shown some punctual temperatures of the thermal image and the temperature profile in a longitudinal portion of the sample section. The choice of the place within the thermographic image for analysis of the temperature profile has been made so that such profile presented spots coinciding with the diverse materials presents on the sample. The image corresponds to the moment of maximum thermal contrast.

In Figure 8 the relative temperatures to the points A, B and C, that oscillate around 10-11°C, are those ones attributable to elements in marble. The point A corresponds to the light brown marble, the B point to the square of black marble placed in the center of the sample, and the point C to the white marble. The highest level of temperature has been registered in the point C and the lowest in the point A. These differences of temperature are once more inside of the thermal camera uncertainty of measurement. So, the color effect is no significant.

If the average temperatures on the portions which contains marble are equal to 10,5°C, it can be estimated that the temperatures of the others three points (D, E and F), which present average values equal to 14°C, are attributed to the presence of a different material. This association is only possible due to the temperature difference between these points that are greater than the measurement uncertainty. The temperature differences between the several areas restored with mortar are, probably, due to the different kinds of mortar used or due to its thickness changeable. Another hypothesis to be evaluated is the presence of non visible detachments.

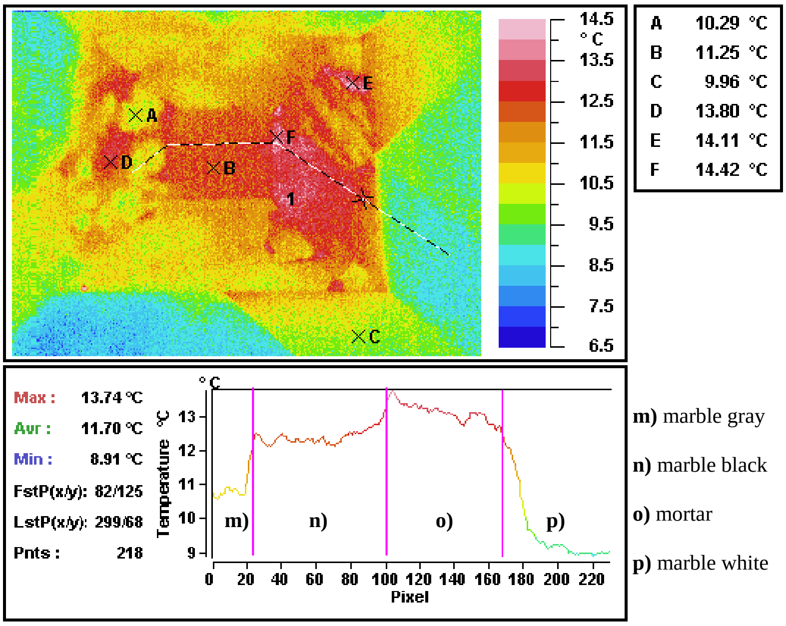

Figure 8. Punctual temperatures and profile temperature of sample 1

Figure 9a shows the thermographic image, in semi-transparency, superposed to the photographic image of the floor sample. This proceeding has permitted observing the correspondence between the areas of greater temperature, related to the presence of restoration mortar, and the real areas of the sample. The restored areas of the samples are evidenced by the dark line in Fig. 9b.

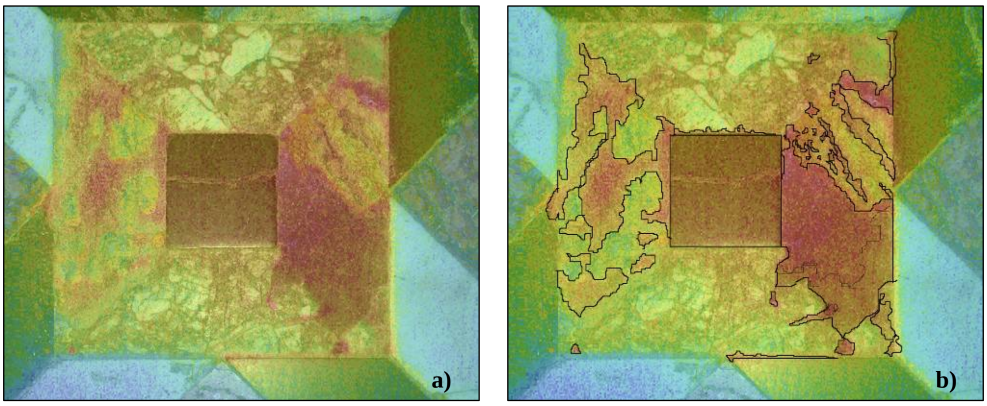

Figure 9. a) Superimposition termogram-photo of sample 1; b) Mortar of restoration evidenced

From the examination of the thermal images shown in the Fig. 6 to Fig.8 was not possible to recognize the visible horizontal crack in the black square of marble positioned in the center of the sample. The reason is in the fact that this fiction had had not restored. In this case, the marble results cracked and abraded.

In Figure 10 and Figure 11 are shown, respectably, the thermal images obtained to the samples 3 and 5. Once more the restoration areas appeared in the thermal images as sectors of superior temperature. The areas evidenced refer to sector of maximum temperature, probably related to the presence of a finer layer of mortar.

5. CONCLUSIONS

In this work, have been presented the results supplied by the active infrared thermography when applied over floor samples of the Basilica di Santa Maria della Salute, situated in Venice (Italy).

In the course of the centuries, some parts of the floor have been deteriorated presenting points of erosion and chippings.

Restorations have been done during the years, but just a few have been documented. Restore mortar have been used to connect the fragments of cleavage marble and to rebuilt the empty created, in order to be able to seem marble.

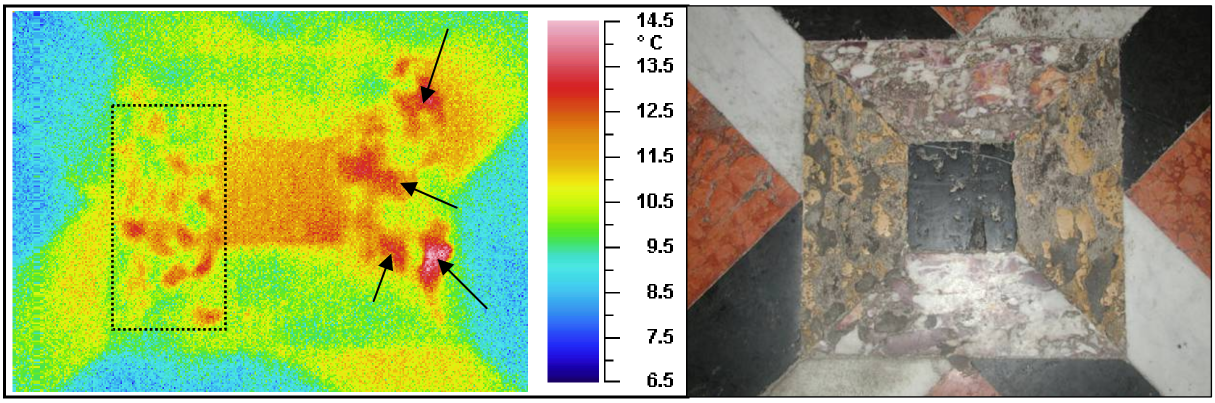

Figure 10. Thermogram and photo of sample 3

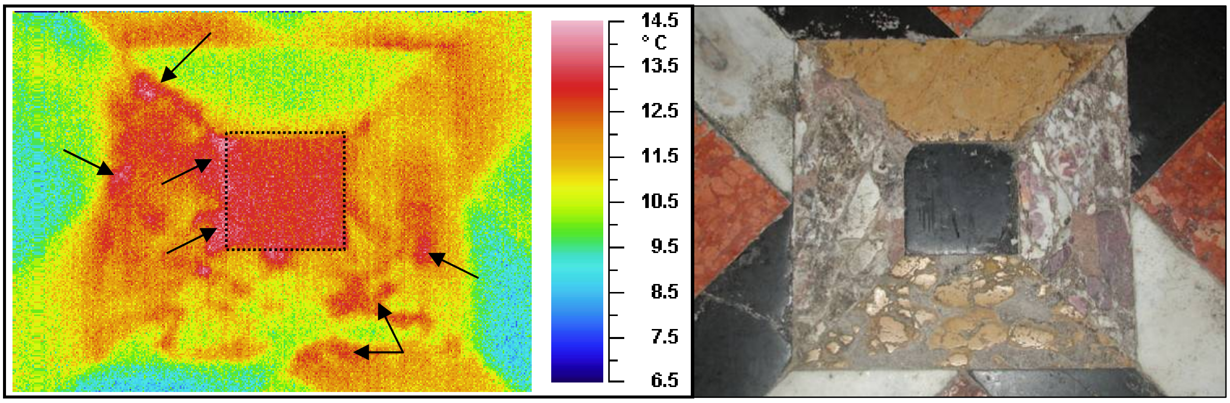

Figure 11. Thermogram and photo of sample 4

The objective of the tests was to identify the interventions of restore and, more specifically, to discriminate the restoration mortar from original marbles. The samples, similar between them for geometric composition, are constituted by a series of floor portion in which are presents the typologies of marbles used for the entire floor.

The thermal stimulation of the samples has been done using light flashes obtained by means 300 W lamps.

The data acquisition has been done during the cooling period of the sample through the register of an images series taken in equal time intervals. The procedure used to setting up the consists in adjust the emissivity in the thermal camera to indicate the same temperature obtained through contact technique of lesser uncertainty. The average emissivity to the whole surface obtained during the thermal camera calibration proceeding was used.

The temperature distribution in the surface of the sample 1, registered by the thermal camera, was much varied.

The color effect was no significant once the temperature differences obtained between the areas with different colors (and not restored) has been inferior to the measurement uncertainty of the thermal camera.

It was possible to recognize the restore areas in the samples. It was possible due to the temperature difference between the restored areas and the original areas that was greater than the measurement uncertainty. The temperature differences between the several areas restored with mortar are, probably, due to the different kinds of mortar used or due to its thickness changeable. Another hypothesis to be evaluated is the presence of non visible detachments.

It was not possible to recognize the visible horizontal crack in the black square of marble positioned in the center of the sample. The reason is in the fact that this fiction was not restored. In this case, the marble results cracked and abraded.

Similar results have been obtained when tested the sample 3 and 5.

A better characterization of the various types of mortar used in the sample could be carried out using some reference samples, for which it would be carried out through chemical analysis of the materials and the direct measure of the emissivity.

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