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Journal of Cultural Heritage 5 (2004) 119–127
Journal of Cultural Heritage
www.elsevier.com/locate/culher

Review

Applications of infrared thermography for the investigation of historic structures

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Received 22 January 2003; accepted 28 July 2003

Abstract

This paper contains an overview of infrared thermography and its applications relating to the investigation of historic structures. In particular, this state of the art, non-destructive technique was used for the assessment of various traditional–historical materials and structures after they had been conserved, restored or repaired using, depending on the case, different treatments. Non-destructive testing and evaluation was performed on the materials and structures in order to assess the physicochemical behaviour of conservation treatments such as stone cleaning, stone consolidation, repair mortars, as well as to disclose any substrate features, such as tesserae on plastered mosaic surfaces. Wherever necessary, the emissivity values of the investigated materials were taken into account, after their determination in the laboratory on representative samples. The outcome of this work provides strong evidence that infrared thermography is an effective technique for the evaluation of historic buildings and sites.

Keywords: Thermal imaging; Cleaning; Consolidation; Stone; Mortar; Marble; Conservation; Historic structure; Mosaic; Emissivity

1. Research aims

Although, the efficiency of infrared thermography as a non-destructive testing and evaluation (NDT & E) technique in the literature is well documented, in the investigation of historic structures, where a restoration or conservation treatment can cause irreversible damage to the structure, it is considered to be of most importance. Infrared thermography is a non-destructive investigation technique that can be widely used due to the outstanding advantages that it offers in a number of applications and specifically in the assessment of structural materials and techniques. In the present work, both infrared thermographic approaches, passive and active, were used, depending on the application, for the investigation of traditional–historical materials and structures. IR thermography was applied on restoration and traditional–historical materials and structures for the evaluation of conservation interventions (materials and techniques) concerning cleaning of architectural surfaces, consolidation interventions on porous stones, restoration of masonries by repair mortars, as well as the disclosure of tesserae on plastered mosaic surfaces. For this reason, diagnostic studies on historical sites and structures took place. Furthermore, in order to obtain useful information from the infrared thermographic surveys various properties (thermal, optical, physical) of the examined materials were taken into account. So, the main aim of this work was to consider whether thermography ought to be considered as an assessment tool for the preservation and protection of cultural heritage.

2. Experimental section

2.1. Introduction

There have been many examples of conservation interventions or restorations where the use of incompatible materials or treatments accelerated the damage to the authentic historic structure [1,2]. For this reason, the development and use of evaluation techniques for the appropriateness of a conservation treatment is essential. Infrared thermography has been

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doi:10.1016/j.culher.2003.07.002

Table 1
Thermo-physical-optical properties of various materials

Material	Density ($kg\ m^{-3}$)	Specific heat ($J\ kg^{-1}\ K^{-1}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Thermal diffusivity ($\times10^{-9}\ m^2\ s^{-1}$)	Thermal effusivity ($W\ s^{1/2}\ m^{-2}\ K^{-1}$)	Emissivity (at λ = 8–12 µm)
Limestone	2600	920	2.1	877.92	2241.25	0.93
Plaster	1440	800	0.5	434.03	758.95	0.91
White marble	2695	870	3.14	1339.22	2713.33	0.95
Grey marble	2650	870	6.7	2906.09	3930.25	0.94
Cement mortar	3100	840	0.85	326.42	1487.75	0.86
Concrete	2400	1008	1.65	682.04	1997.92	0.94
Red brick	2025	800	0.6	370.37	985.90	0.90
Air	1.16	1007	0.026	22 257.98	5.51	–
Water	1000	4193	0.586	139.76	1567.51	0.96

applied for more than 25 years in buildings and historic structures monitoring [3]. Although this technique has the potential to deliver first class results as far as detection and measurement of damage in a material is concerned, the interpretation of a thermographic survey can be quite complicated. During an infrared thermographic investigation of a material or a structure, there are various physical properties that need to be considered. An understanding of the history of the investigated material(s) is also necessary for the best possible result. All these properties–characteristics are listed below:

- Thermal properties: conductivity, diffusivity, effusivity, specific heat.
- Spectral properties: emissivity, absorption, reflection, transmission.
- Other properties–characteristics: porosity, volumetric mass, physiological water content.

All of the above mentioned features are very important in order to understand the outcome of a thermographic survey. For instance, a material with voids or pores, decreases its thermal conductivity and density, its thermal diffusivity is altered and so the conduction of heat transfer within the material is affected [4]. This can be realised when considering the following equation:

$$a = \frac{k}{\rho C_p} \tag{1}$$

where a is the thermal diffusivity ($m^2\ s^{-1}$), k is the thermal conductivity ($W\ m^{-1}\ K^{-1}$), ρ is the density ($kg\ m^{-3}$) and C_p is the specific heat capacity ($J\ kg^{-1}\ K^{-1}$).

Another example is when the investigated material presents moisture. In such cases, the optical properties are altered, the density, specific heat capacity and thermal conductivity are also affected and so any temperature changes are much slower in a moist area [5]. In other words, the energy required to raise the temperature of a moist area would be much greater than an area that is unaffected by water. This can be understood from the following equation:

$$Q = mC_p \Delta T \tag{2}$$

where Q is the absorbed energy (J), m is the mass (kg), C_p is the specific heat capacity ($J\ kg^{-1}\ K^{-1}$) and ΔT is the change in temperature (K).

Another consideration when an infrared thermographic survey is to be completed is the thermal effusivity values of the materials to be tested. Materials with low effusivity values will increase the temperature rapidly, since

$$T_{(t)} = \frac{Q}{e\sqrt{\pi t}} \tag{3}$$

where Q is the input energy (J) and e is the thermal effusivity ($W\ s^{1/2}\ m^{-2}\ K^{-1}$), which can be calculated by

$$e = \sqrt{k\rho C_p} \tag{4}$$

In order to investigate a material or a structure with infrared thermographic means, there are two approaches that can be used, passive and active. In the passive approach, commonly used for civil engineering structures inspection, the material under investigation is usually examined in terms of qualitative means (detection of an anomaly or possible defect, void, etc). On the other hand, since in the active approach an excitation source, such as heating or cooling systems, is used, it is also possible to attain quantitative results. This is mainly because the heating or cooling features of the excitation source are specified in time and amplitude. Nonetheless, when a material is heated, the thermal waves penetrate the material's surface. These waves are generally of various amplitudes and frequencies and are launched into the specimen, in a transient mode. The thermal diffusion length is expressed by

$$\mu = \sqrt{\frac{\alpha}{\pi f}} \tag{5}$$

where f is the frequency (Hz).

So, since the thermal diffusion length is inversely proportional to the frequency, then at high frequencies there will be a near to surface analysis, whilst at low frequencies the thermal waves will propagate deeper, but also slowly, since the speed is given by

$$V = \sqrt{4\pi f \alpha} \tag{6}$$

A table of thermo-physical-optical properties mostly of various structural-building materials obtained from the literature [6,7] is presented (Table 1).

2.2. Infrared thermography

Infrared thermography was applied on various materials and structures in order to assess, physico-chemically, conservation treatments such as stone cleaning, stone consolidation, and repair mortars, as well as to disclose the original mosaic–tesserae beneath plastered mosaic surfaces. In the first three cases, the passive approach was used, whilst in the plastered mosaics examination, active thermography (using heating lamps) was employed. Whenever necessary, the emissivity values of the investigated materials were taken into account, after their determination in the laboratory on representative samples [3,8,9].

Infrared thermography measures the thermal radiation coming from the material under investigation and renders the image of the surface area in colours or in grey scale, in relation to a temperature scale. The thermographic system used consists of an IR detector (TVS 2000 Mk II LW) and a processor (AVIO Thermal Video System). The IR detector is constructed of mercury–cadmium-telluride that gives a spectral response between 8 and 12 µm, with a scan speed of 15 frames per s.

2.3. Conservation treatments and their evaluation

2.3.1. Surface cleaning

The cleaning of historic buildings and monuments results in considerable aesthetic and physicochemical changes to the applied surfaces. Buildings are cleaned both to improve and unify their appearance, as well as to support preservation and conservation. Nonetheless, there are strict conservation regulations as far as cleaning interventions to historical sites and buildings is concerned. Since cleaning treatments can cause irreversible damage to the surface (i.e. incorrect use of method), a thorough investigation must be undertaken in order to decide whether cleaning should be performed and, if so, the features of how this has to be carried out.

According to British Standard 8221-1:2000 [10], buildings are cleaned either to enhance their appearance or to assist maintenance and/or conservation.

Reasons for wanting to enhance appearance include:

- Removal of disfigurements (e.g. stains, graffiti).
- Revealing the nature, colour or details of a building.
- Unification of the appearance of a building that has been altered, extended, repaired.

Reasons for cleaning a building prior to maintenance and/or conservation include:

- Removal of harmful or undesirable deposits or applied materials from the fabric in order to arrest decay.
- Exposure of hidden defects, where surfaces are very densely soiled, in order to establish the extent and nature of repairs required.
- Preparation of a surface for additional treatments.
- To fulfil the terms of a charter that requires periodic cleaning of a building.

A wide range of cleaning techniques is available, ranging from those that are intended for use on large facades to those that are intended for meticulous use on finely carved and delicate sculpture [11]. Each case where surface cleaning is applied can require a different approach or modifications to the selected system. Since all cleaning systems can be used correctly or incorrectly, deficient cleaning should not be liable on poor application alone, as it is often the result of incorrect selection of a process [12]. The efficiency of a cleaning technique is commonly assessed subjectively; nonetheless objective procedures have been described [13].

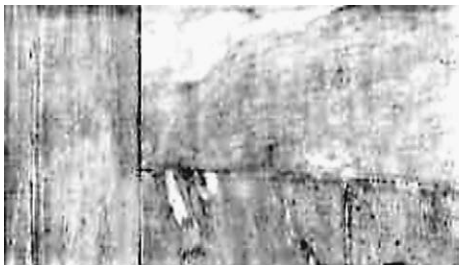

Fig. 1. White Pentelic marble surface at the Bank of Greece historic building in Athens.

The launch of new and more efficient cleaning techniques after 1945 was mainly the product of closer collaboration between conservators and scientists. Particularly, in the field of stone and plaster, since surfaces commonly show severe damage from chemical transformation caused by external deposits or internal transport of acidic or basic salts, a wide range of cleaning products and methods have been tested [14].

Considering that in most cases, taking samples from historical buildings for investigation is restricted or even prohibited, the development and use of NDT & E techniques for the extraction of safe conclusions is important.

In this work, infrared thermography was used with the intention of investigating the efficiency of specific cleaning treatments on certain architectural surfaces of different materials and decay patterns at the Bank of Greece historic building in Athens. The cleaning methods applied on the architectural surfaces were either distilled water with controlled pressure or sepiolite poultices. In Fig. 1, a white Pentelic marble surface, a metamorphic limestone consisting almost

Fig. 2. Kapandriti's stone surface at the Bank of Greece historic building in Athens.

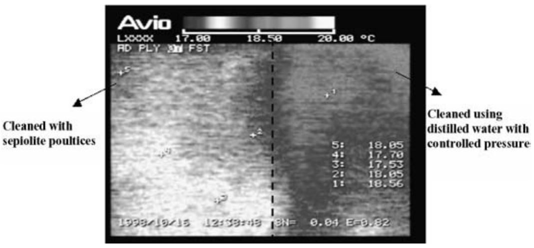

Fig. 3. Thermal image of White Pentelic marble surface.

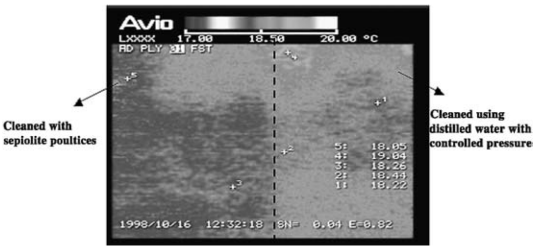

Fig. 4. Thermal image of Kapandriti's stone surface.

exclusively of calcite grains and quarried from mountain Penteli in Athens, is shown; whilst in Fig. 2 the investigated porous stone surface (Kapandriti's stone), consisting mainly of calcite minerals and quarried from the Kapandriti area in Attica, is presented [15].

From the obtained thermal images, it can be observed that the architectural surfaces, either of marble or of porous stone, where cleaning was applied with the use of sepiolite poultices, on the left part of thermal images from Figs. 3 and 4, there are traces of moisture deposits (indicated with low temperatures on the thermal images) when compared to the right part of the thermal images, where cleaning was accomplished using distilled water with controlled pressure. Since the specific heat of water is approximately five times greater than marble or porous stone, this would mean that any changes in temperature would be much slower in an area contaminated by water. So, the affected by water areas present lower temperatures and thus can be detected by thermography.

Since there were traces of sepiolite on the cleaned marble and porous stone surfaces, the sepiolite poultices should be applied using Japanese paper between the poultice and the architectural surface. The sepiolite poultices should be covered with polyethylene film in order to avoid rapid evaporation of water at low relative humidity environments and relatively high temperatures that lead to the hardening of the sepiolite on the stone surfaces. The performance of the hardened sepiolite on the stone surfaces increases the specific surface area of the exposed surface and acts as a good allocation site for suspended particles and pollutants.

2.3.2. Consolidation of stone

The application of a consolidation material aims to restore the cohesion of a weathered stone. A consolidation material should fulfil specific requirements that deal with the change in the porous structure of the stone, the impact in moisture transfer, as well as compatibility with the authentic structure.

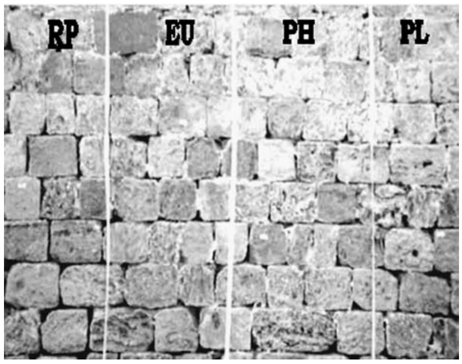

Fig. 5. Consolidated masonry under investigation in the Medieval City of Rhodes (southeast orientated).

Stone consolidation is quite a risky conservation intervention. Nonetheless, it is a necessary intervention since stones decay and loose cohesion in the exposed surfaces down to a certain depth [16]. Many consolidation materials form a film on the surface of the stone that obstructs the conventional transport of water–moisture via the capillary systems within the stone(s). However, the evaporation of water should also be usually considered, especially in cases where intense environmental conditions are present (i.e. high winds, elevated temperatures) as it accelerates its evaporation rate leading to the formation of salt efflorescence and crystallisation; thus accelerating damage for the structure.

A consolidant must be hydrophilic allowing the water to pass through the treated layer of the stone. It must also have the ability to penetrate the stone (i.e. low viscosity), as well as not to present or cause any colour alterations to the stone.

There are various application techniques for stone consolidation. Commonly, they are applied to the surface of the stone by brush, spray, pipette, or by immersion, and are drawn into the stone by capillarity [11].

In this work, infrared thermography was used in the investigation of consolidated porous stone masonries. Ginell [17] showed that due to the difference between the thermal diffusivities of consolidated and untreated stones, thermography is capable of imaging large areas and displaying qualitative dissimilarities in penetration depth, emerging as surface temperature variations on the obtained thermal images. It has also been seen that simulating work in the laboratory [18] can be important in order to make proper interpretation as far as a consolidation treatment is concerned.

In Figs. 5 and 6, photographs of masonry within the Medieval City of Rhodes in Greece, comprised of large consolidated stone blocks, are presented. The masonry is orientated southeast and south, respectively. The consolidation interventions on both masonries were performed in 1997. The consolidation materials used were silicon-based materials since they present good compatibility with the stone, chemical stability owing to the Si–O–Si bond, preventing discoloration. Furthermore, due to the low viscosity of these products they provide deep penetration into the stone. The capillary system of the stone in combination with the low viscosity of the solutions used, facilitated the application of spraying; the products are presented in Table 2.

Fig. 6. Consolidated masonry under investigation in the Medieval City of Rhodes (south orientated).

Thermal images were acquired 3, 15, 28 and 33 months after the consolidation treatment. The results from the first investigated masonry are presented in Fig. 7. Different temperatures at the same height of the stonework were noticed, due to the use of the various consolidants. Although the images were acquired at different times-seasons, it can be said that treatments with RP and EU present relatively higher temperatures when compared to the treatments with PH and PL. This is probably due to the fact that the first two treatments alter the respiration of the stones.

Table 2
Description of consolidants

Code name	Description of consolidant	Commercial name
RP	Ethyl silicate	Rhodorsil RC 70
EU	Acryl siliconic resin	ACS 2001
PH	Prehydrolysed ethyl silicate with amorphous silica	Silbond HT20
PL	Aqueous colloidal dispersion of silica particles	Ludox HS30

In the infrared images of the second investigated masonry (Fig. 8), treatments with ethyl silicate and acryl siliconic resin once more diminish the respiration of the stones, elevated temperatures, when compared to the other two treatments, PH and PL. In this case, the RP and EU treated areas seem to restrict the respiration of the stone, leading to higher temperatures.

It can thus be concluded that the different temperatures among the consolidated areas of the two examined masonries are due to the physicochemical variations that the consolidants present in comparison to the authentic stone. On the whole, RP and EU areas, obstruct the pores of the stone, whilst PH and PL treatments present physicochemical compatibility to the stone.

2.3.3. Restoration of mortars

The methodology for conservation and restoration of historic buildings and sites is an important issue. In cases where a new material is introduced for prospective restoration it must be compatible to the authentic materials to the degree that colour and appearance, as well as physical, chemical and mechanical characteristics are not distorted [19].

Binding mortars, which have the role to hold solid particles together in a coherent mass, are a mixture of inorganic binders, aggregates, water and sometimes additions and/or admixtures. Mortars consisting primarily of lime and sand have been used as a fundamental part of historic structures for many centuries. However, in the mid 19th century, the introductions of Portland cement and/or Roman cement, reduced the use of traditional lime mortar. This frequent use of cement binding mortars on historic structures has been causing compatibility problems to the authentic materials of a historic structure [20].

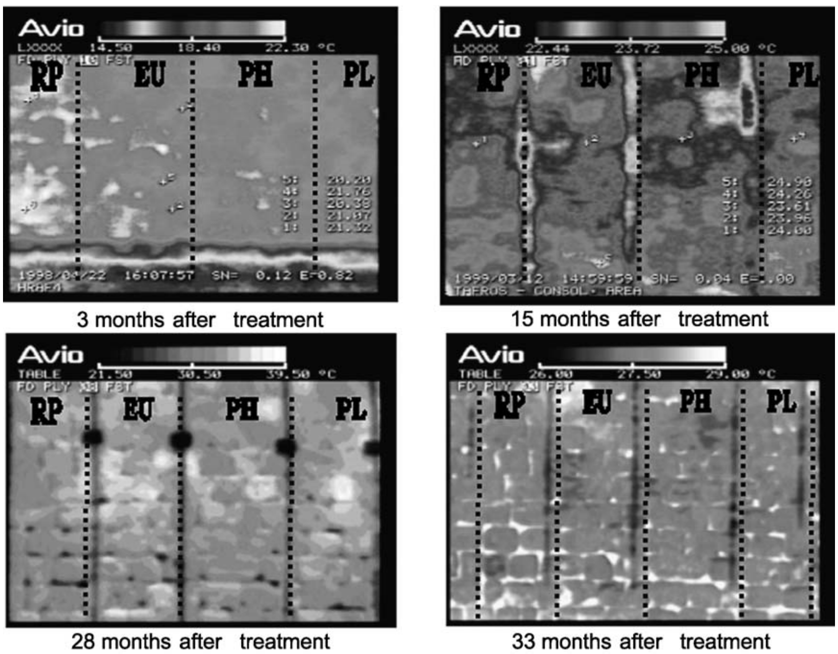

Fig. 7. Thermal images of southeast-orientated consolidated masonry.

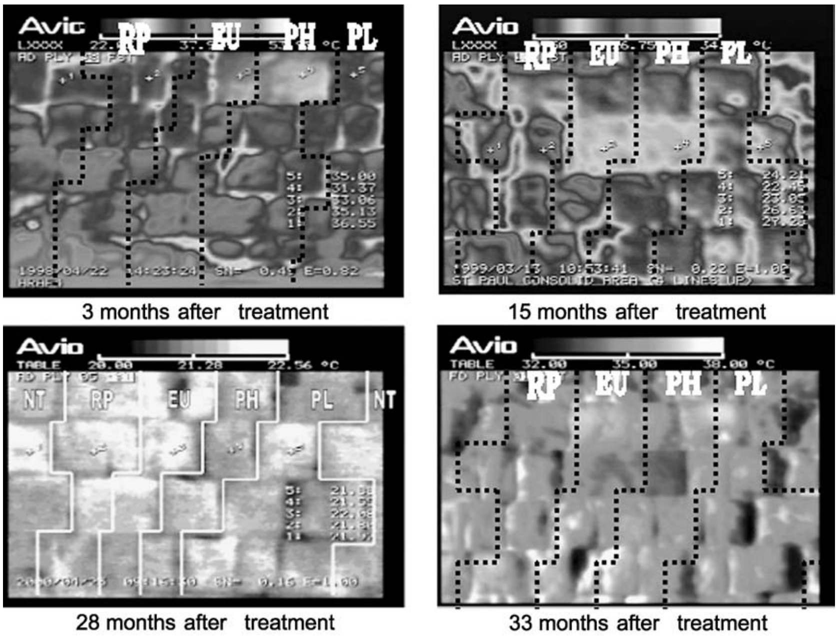

Fig. 8. Thermal images of south-orientated consolidated masonry.

So, in this work, a thermographic survey on the fortification masonry facing the National Stadium of Heraklion in Crete, as well as the western façade of one of the recent industrial monuments, the Tobacco Cutting Factory, situated in the centre of the historic Heraklion market nearby the seaboard provided evidence that cement mortars generate reinforced damage to the original materials of the historic structures. The two examined masonries are presented in Figs. 9 and 10.

From a previous work, where several masonry sandwich constructions consisting of two porous stones and between them a binding restoration mortar (lime or hydraulic lime or cement) were examined in the laboratory, it was proved that cement mortars present physicochemical incompatibility to materials such as limestones and lime mortars [21].

The obtained thermal images presented in Figs. 11 and 12 show a different behaviour of the joint mortar; cold building stones and hot joint mortars. This is because the old ones attain nearer temperatures to the stones, whilst cement mortars attain much higher temperatures, due to their impermeability to salt solutions [22].

Microstructural investigation that was carried out in a previous work [23] proved that cement mortars have different porosity values, as well as different pore size distributions, generating amorphous respiration among the porous materials within the examined masonry.

Fig. 9. Fortification masonry facing the National Stadium of Heraklion in Crete.

Fig. 10. Western facade of the Tobacco Cutting Factory in Heraklion, Crete.

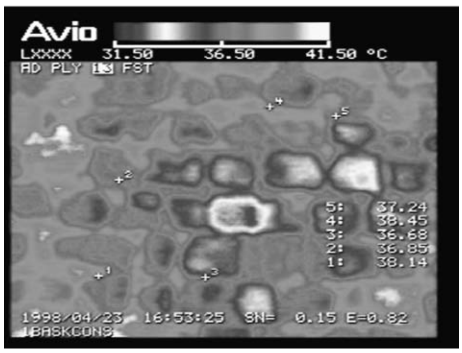

Fig. 11. Thermal image of masonry in the National Stadium of Heraklion.

Fig. 12. Thermal image of western facade from the Tobacco Cutting Factory.

2.4. Examination of plastered mosaics

In view of the fact that destructive sectioning in mosaic conservation interventions is limited, the application of non-destructive techniques is considered to be important. There have been various works where the employment of non-destructive techniques provided substantial information attainment concerning materials examination. Principally, thermography has been utilised for applications such as moisture assessment in monuments [21,24] and detection of sub-surfaces [25].

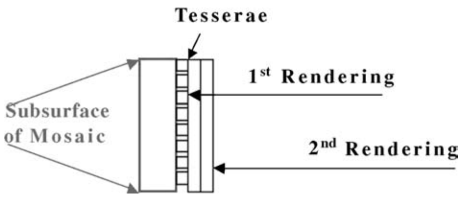

Fig. 13. Example of X-section of plastered mosaic panel.

Hagia Sophia in Istanbul is one of the unique monuments where different mosaic categories of invaluableness are presented. Nonetheless, major interventions in the past have caused aesthetic problems leading to some cases to severe damage of the mosaic. Such example is the intervention occurred in the early 1900s, under the General Directorate of Pious Foundations, mostly known as the "Vakif intervention". The plaster of this intervention was covered with an opaque yellow pigment in a glue medium. Stencil ornaments in pattern were applied on this yellow ground [26].

In a previous research work, various types of mosaics were investigated in the laboratory using infrared thermography, in order to reveal the mosaic–tesserae beneath the plastered surfaces [25].

Due to the different thermal diffusion that each layer renders (Fig. 13), infrared thermography was able to detect the different sub-surfaces on the plastered mosaics, presented with temperature variations on the surfaces. This was accomplished after employing the active thermographic approach, using an external heat source (infrared quartz tube heater) in order to uniformly heat the inspected panels.

So, in this work, a plastered mosaic surface (characteristic Vakif intervention surface) in the Hagia Sophia dome was investigated. The surface was situated between the 19th and the 20th rib at the northwest part of the dome, 16 m from the centre of the dome. Fig. 14 shows the examined surface.

A thermal image obtained from the investigation of this surface is shown in Fig. 15. The surface was heated by powerful optical lamps and during the cooling down process the presented thermal image was obtained. The image illustrates the existence of the coated mosaic, as well as the

Fig. 14. Investigated surface in the Hagia Sophia dome.

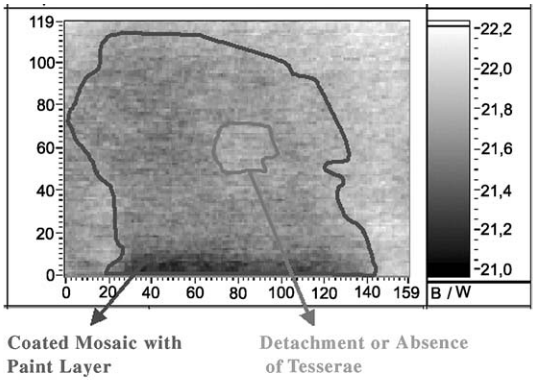

Fig. 15. Thermal image of plastered mosaic area (65–95 cm).

detached area within it. Whilst, darker grey areas—lower temperature values—represent the mosaic, the detached areas, behaving similar to a sub-surface defect, hold remarkably higher temperature values, due to the different thermal diffusion rate (thermal contrast).

3. Conclusions

The main objective of this paper was to present the effectiveness of infrared thermography as a NDT & E technique in the investigation of historic structures. From the diagnostic studies that were performed on the architectural surfaces of historic sites and buildings, it is deduced that infrared thermography as a result of recording thermal images of the surfaces under investigation provides significant information for the assessment of materials and techniques for the protection of cultural heritage. In particular, it can be used efficiently for the assessment of conservation materials and techniques on the subject of surface cleaning, stone consolidation, restoration of masonry by repair mortars, as well as to disclose any substrate features, such as tesserae on plastered mosaic surfaces. Conclusively, thermography ought to be considered as a valuable appraisal tool for the preservation and protection of cultural heritage.

Acknowledgements

are attributed to Professor M. Koui and Dr. P. Theoulakis for their valuable help during the infrared thermographic surveys, as well as to C. Williams for the final form of the manuscript.

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