Early detection of biofilm development on stone monuments thanks to pulsed IRT and SVD

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ABSTRAT

IRT has been used as a first investigation in laboratory to detect pioneer biofilms which help the biological fouling of stone monuments. Biological development is often removed because of the unsightly aspect and it favours stone deterioration with mineral dissolution by production of organic acids, salting induces physical damage which helps to the development of macroscopic vegetation. Biological deterioration leads to the degradation of stone monuments and to the irretrievable loss of artefacts for our Cultural Heritage. Two limestones, Courville and Savonnieres stones used in major buildings in eastern France and the surroundings of Paris have been investigated. On first, stone samples have been exposed in outdoor test to favour the natural colonisation of first micro-organisms. They have been collected after six months exposure and compared to three non-colonised stones throughout IRT measurements of stone surfaces pulsed by a flux of photons. First results on Courville stone, showed Look Up Table (LUT) was important to emphasize slight variations of static images between stones with biofilm and control stones without it. Moreover, mathematical post-processing as SVD, usually applied to decrease thermal artefacts at the surface of a work of art and to improve detection of flaws inside it, here was to detect biofilms as surface artefacts thanks to the first EOFs. Savonnieres stone, which has different intrinsic properties than Courville stone showed static images can induced artefact associated to experimental conditions which was avoided thanks to SVD post-processing.

Keywords: Infrared thermography, biofilm, stone monument, post-processing, SVD

1. INTRODUCTION

Natural stones have been used throughout ages to raise buildings, monuments and sculptures that now belong to our Cultural Heritage. Historical and cultural significance of many monuments calls to a strong attention to their safeguarding and to avoid their degradation[1]. Stone deterioration is the consequence of many factors combining environmental factors as climatic conditions (temperature, humidity, freeze-thaw), micro-organisms development and anthropic activities (atmospheric black carbon, dust, particular matter) that lead to soiling, weathering and irreversible decay[2–5].

Life on stones as microbial communities colonized substrates freshly exposed to the atmosphere where climatic conditions as sunlight ,temperature and water availability are the key factors to the micro-organisms development[6,7]. It causes on first an unsightly effect by a fouling and a change of stone colour [8,9]. Over time, biofilm induces undesired change of stone properties by a biochemical action as dissolution with the production of organic acids by the cell metabolism, salting and a mechanical action by the growth of vegetation that induce physical damage[10–12]. At the final state, the weakness of materials leads to their breakdown and an immense financial damage for community in charge of heritage restoration.

In this respect, the early detection of biofilm can be helpful for a preventive action which can be quicker and cheaper than a restoration work. Colour measurement is currently used as a NDT which assesses the biodeterioration of the stone through its colour change[13–15] but the tracking of pioneer micro-organisms on stones is not always easy by this method as colour stone may change with humidity degree and many stones especially limestones get patina over time. Because of the great expertise of IRT in Cultural Heritage for many years [16–19], this NDT was tested to track the pioneer natural biofilm on building stones. Such microbial communities are often organised in biofilms to live in drastic conditions by producing extracellular polymeric substances (EPS) that keep water for long periods, maintain the viability of the cells and help access to water vapour in the atmosphere [20,21]. Biofilms colonise every substrate in every environment but the development time varies mostly with the substrate properties, climatic conditions and exposure. For that reason, two limestones with different composition and intrinsic properties have been investigated. Both substrates provide a good environment for the development of biofilms as Courville and Savonnieres stones which are renowned for their use in many buildings and monuments in France and Western Europe. Stone samples have been exposed in an outdoor in Reims city for a natural biofouling test. They have been collected after six months of exposure to be tested in laboratory through a pulsed IRT experiment. Thermograms of stones with biofilm have been compared to those of control stones and analysed on first on Courville stones. The best Look Up Table which reflected this comparison has been selected. Considering SVD decomposition has already proved its significant performance in the thermography of works of art [22,23], the principle and an example of flaws detection have been displayed on first. Then this post-processing has been applied on our experiment, on thermograms after excitation in order to lay emphasis on the early detection of biofilm at the stone surface. Finally, Savonnieres stone has been studied to confirm results or to refine them.

2. SINGULAR VALUE DECOMPOSITION (SVD)

2.1 Principle

The analysis of structures with a pulsed thermal excitation can be limited to the detection of internal structural anomalies as an artefact of a remote technique. Alternative basis functions provide interesting means to decompose thermal response data. A singular value decomposition makes a set of orthogonal statistical modes by the strongest projection of data [24]. This treatment builds the best empirical model of the experimentation. SVD is a useful tool for signal treatment since it needn't calculate the sum of trigonometric or exponential functions as the traditional Fourier or Laplace transforms. The approach is to specify a SVD of a defined data matrix resulting from the photothermal experiment. The matrix includes M lines and N columns (M > N) as M parameter is a thermogram pixels number and N parameter is the thermogram number. The resultant matrix consists of gathering in every column the thermogram pixels values. Then SVD is applied according to the following formula:

$$X = U \,.\, \Sigma \,.\, V^T \qquad (1)$$

U is an M x N matrix; Σ is an N x N diagonal matrix with positive or zero elements representing the singular values of matrix X; V^T is the transpose of N x N matrix. Data matrix X is designed with time variations as column-wise and spatial variations as row-wise. The columns of matrix U includes the set of EOF (Empirical Orthogonal Function) which describes spatial variations of data. Indeed, columns represent the directions of the greater space energetics variation of the experiment. They are orthogonal to each other and represent the axis of the orthogonal empirical base. They are arranged with the decreasing of the energetics importance. Accordingly, the first column of the U matrix is named EOF1, it is the most energetics direction of the experimentation empirical base. Then, the second column of the matrix U is named EOF2 and is the orthogonal direction, with an energetics perspective just lower than the previous one. That carries on to the EOF_m column. Σ is a rectangular and diagonal matrix with M lines and N columns. The whole of the diagonal values coincides with the representativeness of the previous "Empirical Orthogonal Function". The first value Σ_1 of the matrix Σ is the energetics representativeness of the EOF1. In the same way the second value Σ_2 ($\Sigma_2 < \Sigma_1$) is the energetics representativeness of the EOF2 and the calculation goes up to Σ_m. V is a square matrix with N lines and N columns. Each column is orthogonal to the others. The columns represent the directions of greater temporal energetics variation of the experiment. It moves away from the physical representation of the experimentation.

2.2 Application to improve the flaws detection

Simulations of flaws detection in mural paintings were carried out with pulsed IRT in the aim at testing the effectiveness of the SVD decomposition [23]. For this purpose, an experiment was set up with six flaws as air strips hidden inside a plaster block and spread at 2 mm of each other and at different depth. The pulsed IRT consisted in heating the sample for 2 seconds thanks to flash lamps corresponding to a deposited power of 1500 W. The excitation flux was 1,5 times higher in the lower part than in the upper part in the aim at simulating a variation of absorptivity of the substrate between the both sides. After the heating excitation, the temperature rose that was detected by IRT recording for 200 seconds.

SVD analysis has been carried out to focus on flaws detection. Post processed images as EOF0 and EOF1 displayed a difference between the lower and upper side that meant very first EOFs were sensitive to the heterogeneity of the energy deposit but the next EOFs from EOF2 were less dependent. Finally, EOF5 showed no variation depending on the energy flux and it detected only flaws in the substrate (figure 1). Accordingly, first EOFs detected variations at the surface of the substrate whereas next EOFs were more appropriated to highlight variations of energy associated to flaws inside the substrate.

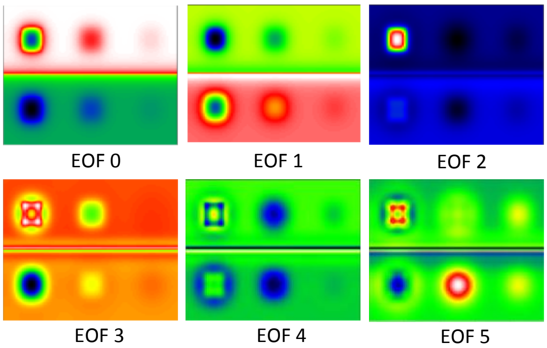

Figure 1. The first 6 theoretical EOF obtained by SVD decomposition for the detection of flaws inside the substrate[23].

This theoretical study was a preliminary research to investigate the effectiveness of SVD on the basis of various applications of EOF. While the first EOFs are dedicated to photothermal variations at the surface of the material, rather than EOFs of higher levels allow to detect thermal variations in the thickness. Then, results were applied to a specific case as the detection of the biofilm on stone that induced artefacts at the surface of the substrate.

3. DETECTION OF BIOFILMS ON STONE BY IRT

3.1 Substrates

Two natural stones have been selected for their use in many buildings in Eastern France, for construction before the first World War, after it for rebuilding the country and now for restoration works. Courville stone is one of the stones the most employed from antiquity to nowadays in major buildings and monuments like Gothic cathedrals in many French regions around Paris. It is dated from Lutetian age (45 My – tertiary era). It comes from quarries in Rheims surroundings located at 100 km to the East of Paris. Courville stone is a clear yellow limestone with coarse white shells and foraminifera [25] (Figure 2a). It is a microporous stone with a porosity between at 23,4 % and a good connection between pores (C_1 = 45,7 $g.m^{-2}.s^{-1/2}$) (Table 1). The last building stone quarry which is now closed from 2005 was at Courville village and provided the stone for the restoration of Rheims cathedral.
Savonnieres stone is a famous commercial stone which made buildings and monuments in eastern France and all over western part of Europe. It is a clear grey limestone with oolites as major components and bivalvia shell fossils which are surrounded by fibrous to bladed spar cements (Figure 2b). This stone has a macroporosity with the dissolution of nucleus of oolites and an intergranular porosity with smaller pores. The water porosity is around 40,4 % and is well connected (C_1 = 8,1 $g.m^{-2}.s^{-1/2}$) (Table 1).

Table 1. Description and petrophysical characteristics of Courville and Savonnieres stones.

Stone name	Courville	Savonnieres
Classification (Dunham)	Packstone	Grainstone
Water porosity (%)	23,4 ± 1,5	40,4 ± 2,0
Water absorption coefficient C1 ($g.m^{-2}.s^{-1/2}$)	45,7 ± 11,4	38,1 ± 4,4
Saturation (%)	85,6 ± 7,5	36,0 ± 3,8

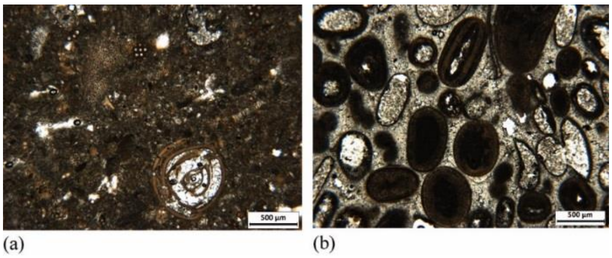

Figure 2. Photos of Courville stone (a) and Savonnières stone (b) in optical microscopy in natural polarized light.

3.2 Outdoor biofouling test

The test consisted of a natural biofouling of stone samples in the goal to develop micro-organisms on stone over time. Small samples (dimensions: 2 x 2 x 1 cm) have been settled on a galvanized steel platform, 1 m above the ground and 20° tilted to the SW to limit the stagnation of water and maximize sunshine. It located in outdoor, in the garden of Sacré Coeur secondary school in Rheims city (figure 3). Before setting up the stone samples on the platform, they were sterilized to kill bacteria still developed on the stone surface to start a new natural seeding from the beginning of the test. The experiment started in November 2016 and the first samples have been removed at six months of ageing and they were conditioned at room temperature and humidity in parallel to control samples in order to be investigated in IRT.

Figure 3. Platform of the biofouling test with samples of different limestones exposured in outdoor. Smaller ones on the left side were collected for IRT testing.

3.3 IRT procedure

Infrared thermography is a useful technique extensively applied to many fields including Cultural Heritage during the last two decades[26]. It provides an analysis of surface and subsurface structure and detect artefacts of heat diffusion in many materials as painting, stone, wood, etc. Deterioration processes change the thermal parameters of the material, IRT can reveal inhomogeneities and artefacts of the surface and the subsurface structure.

In that regard, the NDT was investigated to detect early biofilms on stone with pulsed IRT. This technique assesses the thermal response of the sample when a flux of photons, emitted by a short ring flash, excites it for 5 ms. Here the device is 20 cm diameter and the power of excitation was 3000 J (figure 4).

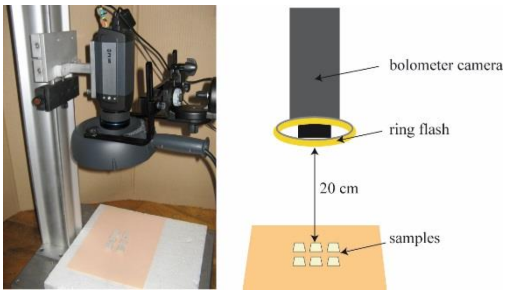

Figure 4. Device of the laboratory test, IRT is stimulated by a ring flash on stone surfaces. Temperature variations are recorded by a bolometer camera (FLIR SC655).

Six stone samples were investigated with 2 x 2 x 1 cm dimension (figure 5). Three upper samples were sterile stones non-exposed in outdoor and three lower ones were exposed in outdoor for six months then collected for testing. The temperature provided by the flash is considered uniform on the samples area and the heat diffusion takes place along an orthogonal direction at 20 cm to the samples. After the sharp rise, the temperature decreased with time due to the diffusion into the samples. The temperature variations were recorded by a bolometer camera (FLIR SC655) during 5 seconds and the acquisition frequency was equal to 50 Hertz.

Figure 5. Samples testing in pulsed IRT. The upper samples are control stones without biological colonisation, the lower ones are colonised at 6 months of exposure for Courville stones (a) and Savonnieres stones (b). Photos in natural light.

4. RESULTS

Recorded thermograms have been analysed thanks to IR Explorer software before the light excitation. The Look Up Table (LUT) basically used has been compared to others to define the best LUT which reflected variations of thermal signals for the detection of biofilm on stone surface. Fire LUT which was used by default by the software, displayed a weak colour variation between triplicate stones with biofilm which were darker (23,4-23,5°C) thus colder than controls (23,8°C) (Figure 6a). Numerous LUT have been tested with the same image to attempt to improve variations between samples. LUT named Hue ramp 08 seemed visually the best one to highlight slight variations of temperature as stones with biofilm in the bottom side were grey whereas controls in the upper side were green (Figure 6b).

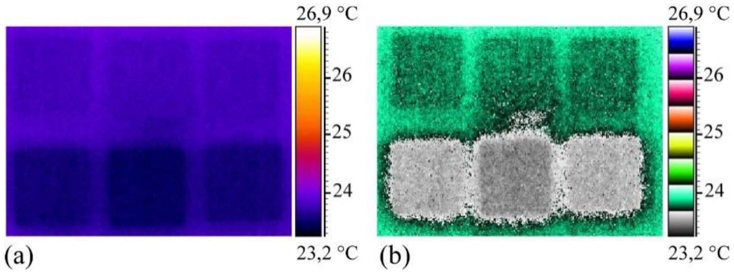

Figure 6. IRT images of Courville stones before the flash stimulation, upper samples are control and lower samples stones are colonised stones by biofilm in LUT fire (a) and in LUT hue ramps 08 (b).

Nevertheless, in Fire LUT after 20 milliseconds of flash excitation, all samples of the both batches showed the same temperature at 23,5°C thus they did not show colour variations anymore (Figure 7a) and in Hue ramp 08 LUT, very slight variations were perceptible between samples with biofilm which were darker grey and control which were grey (Figure 7b). Therefore, detection of biofilm was not detected by basic thermal recording after a flash excitation.

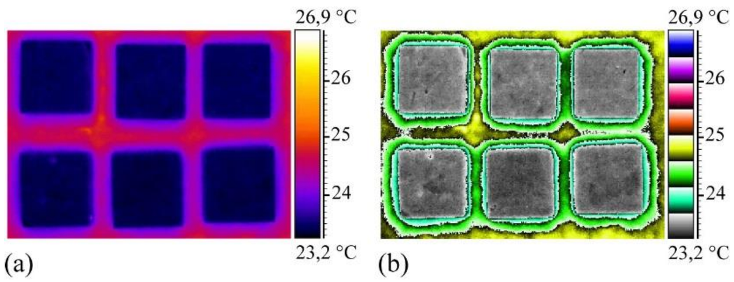

Figure 7. IRT images of Courville stones after the flash stimulation, upper samples are control and lower samples stones are colonised stones by biofilm in LUT fire (a) and in LUT hue ramps 08 (b).

Post-processing as SVD decomposition has been applied on the recorded thermogram from the flash time where the temperature was maximal to the cooling during 30 ms. The first two EOFs showed a net difference between triplicates with biofilm and controls (EOF0 and EOF1). Then in higher EOF from EOF2, no difference was detected anymore between the both batches (Figure 8). As describing previously by Mouhoubi (2014), the first EOFs were the most sensitive to photothermal variations in the most energetic direction when changes were located at the surface of an object as stone in our case. Therefore, SVD allowed to highlight more easily slight variations of energy than a static analysis in a row thermogram.

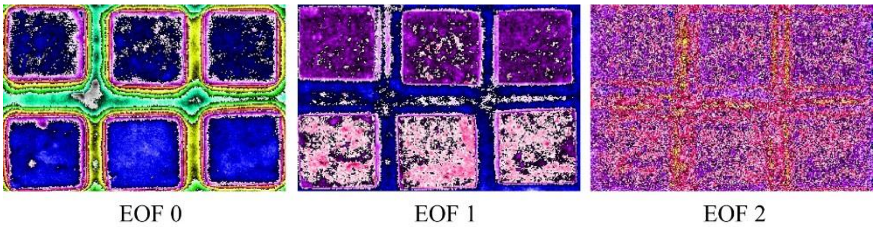

Figure 8. Images of SVD decomposition of Courville stones. Control stones are upper part) and stones with biofilm are lower part in LUT hue ramps 08 for EOF0, EOF 1 and EOF 2.

A second experiment has been carried out on Savonnieres stone which is a limestone with different intrinsic properties like texture and petrophysical parameters than Courville stone. Before the flash excitation, no variation has been recorded between control and stones with biofilm in LUT Fire (figure 9a) whereas more significate results have been displayed in LUT hue ramp 08. Two out of three samples with biofilm had a colder temperature (24,0°C) than controls (24,3°C) except for one sample with biofilm which displayed the same temperature than controls (figure 9b). Thus the analysis of the thermogram revealed a variation of energy between both batches of samples and between stones with biofilm for one of them. Such result displayed higher heterogeneities of the samples probably due to macropores of Savonnieres stones that could change the settlement of biofilm.

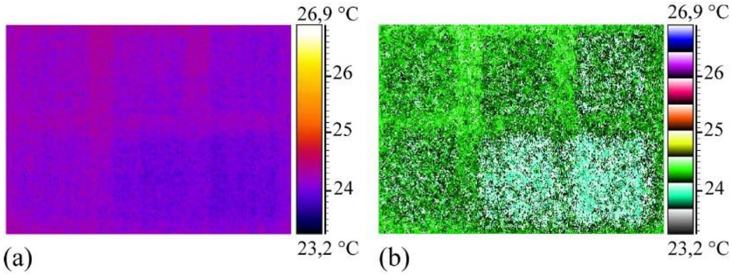

Figure 9. IRT images of Savonnieres stones after the flash stimulation, upper samples are control and lower samples stones are colonised stones by biofilm in LUT fire (a) and in LUT hue ramps 08 (b).

Nonetheless, SVD decomposition have been applied to validate this result (figure 10). EOFs didn't display the same variations than previously. The first EOF especially EOF1 revealed a homogeneity for each batch of stones showed by the same colour for controls and another one for all samples with biofilm. In consequence, variations between triplicates with biofilm noticed in the previous static analysis before the excitation, were an artefact due to the experimental conditions. SVD post-processing cleared the thermal signal of bias and highlighted a variation of energy between controls and stones with biofilm that could be induced by the development of biofilm at the stone surface.

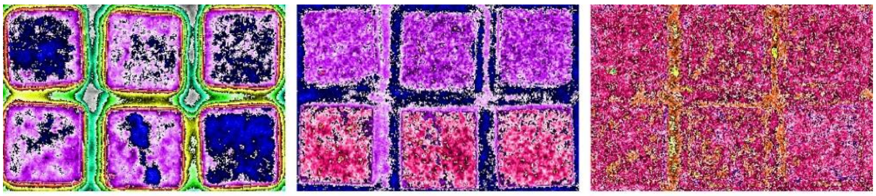

Figure 10. Images of SVD decomposition of Savonnieres stones. Control stones are upper part) and stones with biofilm are lower part in LUT hue ramps 08 for EOF0, EOF 1 and EOF 2.

5. CONCLUSION

In the context to limit the fouling of stone in the historical monuments by the biological development, the early detection of biofilms at the stone surface allows to react more rapidly and effectively face degradation. This experiment aimed at using a pulsed IRT as a NDT in laboratory on samples of two limestones called Courville and Savonnieres. Variations of energy of control stones have been compared to those of stones with natural biofilm developed for only six months in an outdoor test. As first results, thermograms of Courville stones before excitation so in passive IRT, displayed a variation of energy between both batches which have been clearly showed thanks to the LUT Hue ramp 08. That revealed IRT could detect an early biofilm at the stone surface. Moreover, the first EOFs of SVD post-processing corroborated the result and highlighted a net variation between stones without biofilm and stones with biofilm. Nonetheless, analysis of thermograms for Savonnieres stone show difference results than Courville that suggested static images passive IRT that suggested passive IRT was not reliable to detect biofilm in every stone. On the contrary, SVD post-processing in pulsed IRT still detected variations of energy of stones with biofilm compared to controls thus this treatment avoided artefact associated to experimental conditions. Consequently, SVD was a reliability and the usefulness analysis to highlight weak variations of energy for the detection of early biofilm.

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