Environmental impact assessment on the porous stone masonries of the Rethymnon Fortress

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Abstract

The weathering of monuments, considered as interaction between building materials and environmental factors, presents specific interest in the case of the marine environment in the mild climatic conditions of the Mediterranean.

An extended monument, like the Fortress of Rethymnon could well serve as an example. It is constructed by a susceptible to salt decay biocalcareous porous stone and suffers mainly from salt crystallization and hard carbonate crust formation.

The research program develops on various masonry surfaces, as far as position and exposure orientation to various environmental factors are concerned mainly regarding humidity sources like groundwater's capillary rise and marine salt spray. Stone specimens from various positions along the Fortress, characteristic of the various decay patterns, underwent mineralogical and microstructural examination.

Digital image processing is performed on characteristic surface images from the Fortifications, acquired from photograms and restituted in false colors, in order to assess and evaluate the environmental impact to the masonries according to the physicochemical criteria employed for the weathering classification (microstructure, texture and composition).

Digital image processing is proved to be a reliable automatic mapping method for environmental impact assessment on extended masonry surfaces, when the conversion of the varying surface energy contents renders and distinguishes the microstructural and textural characteristics of weathered stones. Hence, a sound basis for interdisciplinary scientific conservation planning is provided.

Introduction

Several mapping techniques are recently applied to serve conservation needs. Photogrammetrical surveys provide a general representation, of the geometric architectural and structural characteristics (Cundari), while specific mapping techniques of lithotypes and of weathering forms are developing nowadays. In particular, the ultrasonic measurements permit the monitoring of the structural damages and the distinguishing and evaluation of the various zones of the monuments in respect with the weathering resistance (Mamillan). In combination with the microstructural analyses (Fitzner), it is capable of investigating and recording the various weathering patterns present on the stone surfaces. Finally, with this method, the lithotypes and the weathering forms can be identified (Zezza through the
attribution of different information to different colors, on simple photograms. In this way, a fast, automatic and detailed recording of information can be done. Thus, the classification of the weathering patterns consist a key element in the weathering mapping. In order to establish the forms of the process of the stone decay, the light reflected and diffused by the surface is exploited; the real surface image is acquired from photograms. The basic principal of the method is that the irregularity of the damaged stone surface corresponds to different levels of light returned from different parts. The quality of the image must be such, that the chromatic variations and the material characteristics of the stone can be distinguished.

The process of conversion from pictorial image to digital image consists, in the first place, in the sampling of the function \( f(x, y) \) according to a square dot matrix and successive quantification of spatial samples codified in binary system. The individual spatial samples (pixels) are represented by a whole value (\( L_g \)) which indicates the level of luminosity relative to an appropriate scale.

The numerical extension of this scale depends on the number of bits (8 in the processing system used) which are used for the conversion of the \( L_g \) value associated with a particular pixel.

The equipment adopted in this research should also allows for the distinguishing of \( 2^8 = 256 \) levels of grey, so that each element making the image may assume any value between 0 (black) and 255 (white). The conversion of the pictorial image into digital form is carried out by means of a telecamera. Nevertheless it should be noted that such conversion processes produce a certain amount of errors which is related with the device characteristics.

The digital image is memorised and may be synthetically described by:

\[
f(x,y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} h(u,v,x,y) \cdot f(x,y) \, du \cdot dv
\]

where:

- \( u, v \) the spatial coordinates of the real image, \( h(u,v,x,y) \) a function that hinder the distortions produced by the conversion device in the process of producing the image.
- Using suitable processing, knowledge of the \( (u,v,x,y) \) function, which can be defined as an impulsive response of the filming system, allows for distortion to be reduced.

The results so far, show that we can obtain images in false colors which with particular reference to the nature of the stone, can be the first step of the distinguishing of the surface texture, the structure and the chemico-mineralogical lithologic composition of the rocks under review (Moropoulou).

However, in view of the fact that the theoretical basis of the investigation lies in the level of restitution of light energy from the surfaces exposed, an initial analysis of the image must aim to establish the characteristic chromatic variations of the texture and the material of the stone under study.

In the present work the following are performed:

- digital image processing, concerning characteristic surface images from the Fortifications of the Venetian Fortress of Rethymnon as an example, acquired from photography and restituted in false colors.
- the assessment and evaluation of the efficiency and reliability of the mapping method according to the physicochemical criteria employed for the lithotypes and weathering classification (microstructure and composition).
Investigation Procedures and Materials

The working method developed combines picture processing with the weathering investigation at site and in the laboratory. In the first working step characteristic general views and details concerning lithology and weathering are documented by photograms. The selection of the specific architectural surfaces to be documented and investigated was made during the macroscopic in situ study of weathering and the classification of decay patterns.

Sampling at the monument and investigations, focused on microstructure and composition analysis, comprise the study of weathering. The weathering data can be obtained by direct measurements, as X-ray diffraction analysis (by a Siemens D-500 X-Ray Diffractometer aided by a Diffract - EVA quality analysis software) as well as optical and electron microscopy combined with maps of X-Ray chemical microanalysis (by SEM Jeol, electron probe X-Ray microanalyser, SuperProbe 733 and Infra Red Spectroscope BioRad FTS 40) and indirect measurements, as mercury porosimetry (by Carlo Erba 4000 mercury porosimeter). The various structural and textural investigations and especially the porosity characteristics and their modification due to weathering are employed to judge mapping reliability.

In a final working step, the monuments' surface images are being analyzed by digital image processing and this interpretation in false color systems that sound to render materials' state information is attempted.

In situ study - Macroscopic investigation of the decay patterns

The macroscopic in situ investigation revealed the coexistence of various decay patterns on the walls of the Fortress. The main weathering phenomena are present in the following forms:

1) Salt efflorescences due to the capillary rise effect on the masonry and the salt spray. The measurements of the permanent humidity in the walls of the Fortress has shown low values (Sample 1). This is macroscopically confirmed, not only on the building stones but also on the mortars and plasters. On the contrary, serious problems were identified in those buildings where recent restoration work has been performed and in particular, where cement has been used (buildings in the historical center and Sultan Ibrahim Mosque).

2) Hard carbonate crust. On the walls of North or South orientation, due to their low sun exposure and good protection from strong winds, the evaporation phenomenon is quite mild, and thus the formation of carbonate crusts is preferred. In the North side of the Sta. Maria Bastion (fig. 1) (Sample 3) and in the South side of St Paul, a combination of white and grey biological crusts can be observed on the middle and lower parts. On the upper layers, that is on the crenelates (ph. 2a) white carbonate crusts attributed to water condensates are mainly observed. The later coexist with plasters remnants.

3) In the same positions with the above orientation grey crusts can also be observed (Sample 3), attributed to biological weathering from algae and leachens, the growth of which is augmented by the relatively high permanent humidity. The action of the microbiological species (acid attack) in combination with the plants action (mechanical stresses) lead to the decay of the binding material (mortars and plasters) (Sample 6) and the stone.
4) In those walls (ph. 2b) where the sun exposure is intense and thus a greater evaporation is present, **salt decay problems** of different intensity are observed. The alveolar disease, ranges from grain disintegration and flakes detachment to cavities formation, which presents selective localized weathering in the honeycomb pattern (Sample 2) preferably when fossils are present (Sample 12). In particular, in the west side, where the conditions are more severe due to salt spray from the nearby sea, even compact stones suffer from intense salt decay and present characteristic sugar texture (Sample 23).

5) In some positions, where air turbulence is present either because of the orientation (East, Central Entrance), or because of usage (passage of transport vehicles) **selective localized weathering** depending on the texture and the layers of the stone is observed in parallel with the air flow and turbulences, according to the **stripped pattern**.

6) In the western and eastern walls, that are exposed to sun, intense **color change** of the surface of the building stones towards the red, can be observed under conditions of rapid evaporation. As such conditions suggest intense oxidation taking place at the interfaces within the stone pores and in particular at the outer surface (Sample 9). Possible chemical alteration during the oxidation and hydrolysis of Fe to lemonite dispersed in calcium-allumino-silicate phases should be further investigated.

7) The **weathering of the masonry mortars** is of particular interest, as they are observed frequently almost completely decayed (Samples 6-10). Recent, dispersed, almost random cement interventions can augment the weathering, because of the incompatibility of the materials and the excess of soluble salts supplied by the cement to the stone. The plasters which in other cases such as in the Central Eastern Gate appear to be rather strong, are dispersed and suggest either a general weathering phenomenon in the form of detachment or some localized interventions with plasters intended to save the deteriorated stones. A specific study is performed regarding the masonry mortars and plasters (Moropoulou).

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**Table 1: Classification of the decay phenomena**

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1   | a) Capillary rise effect  
     | b) Salt efflorescences  |
| 2   | Hard carbonate crust |
| 3   | Biological crust |
| 4   | Alveolar disease  
     | a) sugar textured decay  
     | b) selective localized corrosion (granular disintegration, flakes detachment, honeycomb corrosion)  
     | c) cavitation  |
| 5   | Stripped decay from air turbulences and winds due to position and traffic of vehicles |
| 6   | Color alteration |
| 7   | Deterioration of the joint mortars |
| 8   | Plasters' detachment |
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Sampling
The sampling was performed on the Fortress (Table 2) in order to:
- Identify the building stone,
- Study the weathering phenomena.

Table 2: Sampling

<table>
<thead>
<tr>
<th>No</th>
<th>Building Material</th>
<th>Position</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Sta. Maria Bastion</td>
</tr>
</tbody>
</table>
| 1  | Stone             | Outer south wall at 1.70m height from ground level | a. Salt efflorescences  
b. Capillary rise effect |
| 2  | Stone             | North wall at 1.50m height | Alveolar disease  
a. Selective deterioration  
b. Cavitation |
| 3  | Stone             |          | Biological encrustation, algae and dead leachens.  
Intense permanent humidity |
| 6  | Stone and Mortar  |          | Deteriorated mortar |
| 9  | Stone with Plaster| At 1m height | Color alteration. Evidence of hydrolyzed ferrous oxides |
| 10 | Stone and mortar  | From same position as sample 9 | |
| 11 | Stone             |          | Hard stone with fossils - less decayed |
| 12 | Stone             | Left from sample 11 at 1m height | Alveolar disease. The stone contains fossils |
| 15 | Stone             | Central Eastern Gate - Corridor 1cm height to the left | Stripped pattern |
| 23 | Stone             | From the crenelates towards the sea. Western side of the wall | Calcareous limestone with severe sugar textured decay |
| 24 | Stone             | From the crenelates towards the sea. Western side of the wall | Calcareous limestone with severe sugar textured decay |
Results and Discussion

Study of weathering

From the results of the XRD analysis of the samples 1, 2, 11, 12, 23 and 24 (Table 3) is deduced that the building stone is almost exclusively calcitic, with a small percentage of quartz embedded and traces of plagioclases and aluminum-silicate compounds. Samples 1 and 2 show dolomite traces.

The sample 15 presents a high calcite and quartz percentage. Also measured, were a small dolomite and chlorite percentage as well as traces of plagioclases.

In all the weathered samples (2, 12, 23, 24) halite is traced.

Table 3. X-Ray diffraction results

<table>
<thead>
<tr>
<th>No</th>
<th>Cc</th>
<th>Qz</th>
<th>Dol</th>
<th>Gy</th>
<th>Pgs</th>
<th>A-Fsp</th>
<th>Mica</th>
<th>Chl.</th>
<th>CAH</th>
<th>CS</th>
<th>H</th>
<th>Ag</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>++++</td>
<td>++</td>
<td>Tr.</td>
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</tr>
<tr>
<td>6</td>
<td>++++</td>
<td>++</td>
<td>+</td>
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<td>tr.</td>
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<tr>
<td>11</td>
<td>++++</td>
<td>+</td>
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<td>tr.</td>
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<td>-</td>
<td>tr.</td>
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<tr>
<td>12</td>
<td>++++</td>
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<tr>
<td>15</td>
<td>++++</td>
<td>+++</td>
<td>+</td>
<td>tr.</td>
<td>-</td>
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<td>+</td>
<td>-</td>
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<td>tr.</td>
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<td>-</td>
</tr>
<tr>
<td>23</td>
<td>++++</td>
<td>++</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>tr.</td>
</tr>
<tr>
<td>24</td>
<td>++++</td>
<td>+</td>
<td>-</td>
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<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>tr.</td>
</tr>
</tbody>
</table>

Qz: Quartz: SiO₂ (5-0490),
Cc: Calcite: CaCO₃ (5-0586),
Pgs: Plagioclase: Ca-NaAl₂Si₃O₈ (9-465, 9-467),
A-Fsp. Sanidine (10-357), Mica: (K,Na)(Al,Mg,Fe)₂(Si₂Al)O₁₀(OH)₂ (7-42),
CSH: Calcium Silicate hydrate: 5Ca₂SiO₄·6H₂O (3-0248),
Gypsum CaSO₄·2H₂O (6-0046)
CAH: Calcium Aluminate hydrate: Ca₃Al₂O₆·8H₂O (2-0083),
Chlorite Mg-Mn-Fe-Al-Si-O-OH (12-242),
Dol: Dolomite CaMg(CO₃)₂,
Halite NaCl (5-628)
very abundant: ++++, abundant +: ++++, abundant -: +++, present: ++, small amount: + traces: tr.

From the observations at the optical microscope of the samples 1, 2, 3, 9, 11, 12, 13, 23, 24, it is deduced that the building stone is a biosparitic limestone with bioclastites, sparites, micrites and quartz (ph.1a). The bioclastites are presented in various sections, either in the form of rounded fossils fragments (corals) or as sharp edged fragments with radiolar remnants. The sparite is presented as binding cement, surrounding grains and is either finegrained or largegrained. The micrite is finecrystallised in the form of a thin film around the grains. The quartz seems to be homogeneous, microcrystallized and sharp shaped. No orientation was verified. In the sample 15 the stone is bioclastic limestone with the same ingredients and a smaller quantity of sparitic binding cement, and a greater percentage of quartz grains.
In the photos (1a,b,c,d) the various weathering phenomena are identified in the form of:
- granular disintegration (ph.1b - Sample 2), leaving large pores behind the external decayed surface,
- intensively oxidized crusts (ph.1c - Sample 3), where biodeterioration is combined with hard carbonate crust
- stone intensively oxidized at the external surface, where chromatic alteration is combined with severe alveolation (ph.1d - Sample 9).

Photo 1. Observations at the polar Microscope with // Nicols x 20.
a. Typical biosparitic porous limestone with fossils embedded - Sample 1.
b. Granular disintegration - Augmented porosity towards the external decayed surface - Sample 2
c. The lower part is porous stone with fossils while the upper one is intensively oxidized crust characterised of bideterioration along with hard carbonate crust - Sample 3.
d. At the external surface the disintegrated stone (Sample 9) is intensively oxidised.
Salts within the pores of the stone Sample 2.

NaCl crystals within the pores of the Samples 1,2 (ph.5a-b)

Salts within the pores of the stone Sample 2

Fe along with alteration products rich in silicates in the outer surface of Sample 9.

Gypsum crystals within the pores of the stone Samples 11, 12

Gypsum crystals within the pores of the stone (Sample 11)
The monument samples 1, 2, examined at Scanning Electron Microscope, were found disintegrated due to sodium chloride (photo 2a, Figure 1.1 -Samples 1) and gypsum (photo 2c, figure 1.3 - Samples 11) crystallization within the pores. A salt decay mechanism leading to alveolar disease as in the case of the porous stone masonries of the Medieval city of Rhodes is recognized (Theoulakis8). As salt sources should be identified the salt spray and groundwaters feeding the stone with salt solutions of or by direct attack or by capillary rise correspondingly. The significant presence of Fe along with alteration products rich in aluminium silicates is evidenced in the outer surface of the decayed stone (photo 2b, Figure 1.2 -Sample 9). Hence chemical alteration propounded by hydrolysis and oxidation comprises a specific "local" pattern of decay due to the composition of the stone.

The IR spectroscopy results confirm that the above mentioned observations, by the identification of gypsum, organic substances and products of chemical alteration - hydrolysis of Al- Si compounds in the monument samples. The porosimetric data (Table 5) show a porous tone with a pore size distribution presenting an analogy of large amount of small pores coexisting with a large amount of large pores. In agreement with the criterion for stone susceptibility to salt decay (Moropoulou9) the building stone of Fortezza can be assessed as very susceptible.

Table 4: Infra Red - Results

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>++++ Cc + Q + Db OH + Al-Si S-O Gy</td>
</tr>
<tr>
<td>3</td>
<td>++++       - - - - + + +</td>
</tr>
<tr>
<td>6</td>
<td>++++       + - ++ + + -</td>
</tr>
<tr>
<td>9</td>
<td>++++       - - + tr. + -</td>
</tr>
<tr>
<td>10</td>
<td>++++       tr. tr. + tr. + +</td>
</tr>
<tr>
<td>11</td>
<td>++++       - - + tr. + +</td>
</tr>
<tr>
<td>12</td>
<td>++++       + + + tr. + +</td>
</tr>
<tr>
<td>15</td>
<td>++++       ++ tr. + - - -</td>
</tr>
<tr>
<td>23</td>
<td>++++       + tr. + - + -</td>
</tr>
<tr>
<td>24</td>
<td>++++       - - - - tr. -</td>
</tr>
</tbody>
</table>

Cc : Calcite, Q :Quartz, Do : Dolomite, OH : Hydrolisis products
Al-Si : Silico - Aluminate compounds, S-O : Organic compounds, Gy : Gypsum

Table 5: Microstructural Characteristics

<table>
<thead>
<tr>
<th>Sample No</th>
<th>P (mm^3/gr)</th>
<th>A (m2/gr)</th>
<th>γ (gr/m^3)</th>
<th>r (μm)</th>
<th>P (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No 2</td>
<td>146,39</td>
<td>0,89</td>
<td>2,26</td>
<td>375840</td>
<td>24,88</td>
</tr>
<tr>
<td>No 6</td>
<td>162,82</td>
<td>1,37</td>
<td>2,86</td>
<td>530880</td>
<td>31,75</td>
</tr>
</tbody>
</table>

Pv: Total cummulative volume, A: Specific surface area, γ : Bulk density, r : pore radius average, P : total porosity
Digital Image Processing Applications on the Fortezza of Rethymnon

The weathering of the characteristic masonry and corner tower (St. Paul) of Sta. Maria bastion is rendered in false colors (ph. 3a-b) by digital image processing, using two different color systems.

White color restitutes the characteristic carbonate crusts, as well as the plasters remnants, whereas yellow or ivory render the alternated stone (ph. 3a-b respectively). The biological weathering is rendered with blue (ph.3a) or brown-yellow (ph.3b), while orange (ph.3a) or blue (ph.3b) restitute the selective localized weathering, as well as the deterioration of the joint mortars. Both images render and discern the various weathering patterns and record their characteristic distribution.

The second color system applied in the detail comprising of the crenelates above the Central Eastern Gate (ph.4a) restitutes the hard carbonate crusts in white the altered stone in ivory, the biological weathering in brown-yellow and the selective localized stone and joint mortars deterioration in blue. The combination of carbonate and biological crusts seems to prevail in the upper parts of the walls, rendered qualitatively by combination of white-ivory-yellow colors. Another color system restitutes the distribution of the weathering patterns around the Central Gate (ph.4b).

Photo 3. Sta Maria Bastion
a-b General Mapping by Digital Image Processing in two colour systems - Salt efflorescences, hard carbonate crust and alveolar disease are distinguished.
Photo 4. Central Eastern Gate. Weathering mapping by Digital Image Processing in two colour systems. 

a. Detailed mapping of the crenelates: hard carbonate crust from condensates is prominent.

b. General mapping: hard carbonate crust is distinguished from alveolar disease.
Photo 5 a,b. Detailed mapping of the crenelates. The quantitative assessment of the decay patterns is feasible.

It is of course difficult to discern the carbonate from the biological crust rendered by ivory yellow-orange-brown tones. On the contrary, a detailed mapping succeeds to discern these weathering patterns at the upper parts of the walls. In ph.5b yellow reconstitutes the remnants of the plasters, that are selectively and localized deteriorated (orange to blue), whereas the crusts due to condensation are rendered by white and the biological crusts with violet-brown-dark maroon.
Another system in ph.5a succeeds to discern the biological (green) and the physicochemical weathering (yellow to brown). The prevailing of the biological crust can be estimated quantitatively as more than 42%.

Conclusions

The building stone is a biosparitic limestone with bioclasterites, sparites, micrites and quartz very porous and susceptible to salt decay. A salt decay mechanism leading to alveolar disease is recognized due to the salt spray and groundwaters feeding the stone with salt solutions or by direct attack or by capillary rise along with chemical alteration developed by hydrolysis and oxidation comprises a specific "local" pattern of decay due to the composition of the stone.

The digital image processing of architectural surfaces acquired from photograms, rendering in false colors the different levels of light reflected and diffused by the real surface was found to be rather consistent with physico-chemical criteria of stone susceptibility and weathering classification. As may be concluded from the results of the working method developed in combination with investigations at site and in the Laboratory:

The prevailing weathering profiles of the alveolar disease, characterized by the way that they reflect the light are discernible by false colors towards black in the sequence of higher damage levels. This is in contrast to the hard crust formation, that due to its coherent micro-crystalline calcite surface exposed to the light, attains reflection towards the lightest shades of grey and is distinguished by false colors towards yellow, hindering however a potential advanced damage level due to the internal relaxation zone that it develops. The digital image processing results show the characteristic distribution pattern of the weathering forms. By general mapping various areas of the masonry can be compared with one another and evaluated as regards to their orientation. Taking into consideration the selection criteria of the exposed surfaces, the exact localized occurrence of different weathering forms gives information concerning causes of damage determined by the monument and its environment.

The several lithotypes used and the occurring damages could be localized exactly and their extent could be determined qualitatively (color) and even quantitatively (surface / color) when a reliable correlation among weathering forms and damage levels is presumed. Thus a sound basis for conservation planning (Moropolou) could be provided by lithotype and weathering mapping.

Concerning the conservation of Fortezza, such a planning has to take into consideration environmental management (Moropolou) and rehabilitation (Moropolou) criteria in order to act as European pilot project for local development based on the preservation of architectural heritage.

Acknowledgments

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References


