المجلة الأردنية للتاريخ والآثار

Volume **VI**, No.**1**, 2012

Physical and Mechanical Properties of Historic Building Materials: Towards Documentation and Conservation of Qusayr Amra in Jordan

Fadi Abedallah Bala'awi[1*] , Firas Mohamad Alawneh[1,] Yahya Sulieman Alshawabkeh[1] and Naif Adel Hadad[1]

Abstract

The current study investigates the chemical and physical properties of the stone building material used in Qusayr Amra, one of the UNESCO World Heritage Sites in Jordan. The chemical weathering impact of salt crystallization on these stones was evaluated with the goal of improving conservation efforts. Thermodynamic data from the tested samples using Runsalt software showed that Halite, Sylvite and Calcium Nitrate were the main potential soluble salts. High resolution 3D models and scans were produced using laser scanning in order to provide reference data and improve monitoring of the changes that affect the building. The results of this research point to the possibility of reducing the problems in the building by changing the current environmental conditions around the building and thus mitigating the major deterioration factor in this site due to the crystallization and distribution of salt.

Keywords: Qusayr Amra, Building conservation, Thermodynamics of salt, 3D modeling.

Introduction

Many Umayyad palaces in Jordan have suffered serious damage and deterioration due to such natural and environmental factors as earthquakes, structural deterioration, weathering, bio-deterioration and other such factors. Considerable decay is evident in many predominantly limestone Umayyad palaces, especially in aggressive polluted environments (Elgohary 2008). The Umayyad palaces in Jordan have become vulnerable because of the rapidity of deterioration processes resulting from many factors such as pollution, modern use,

[1]Queen Rania's Institute of Tourism and Heritage, The Hashemite University.
Received on 2/6/2011 and Accepted for Publication on 15/12/2011.

lack of maintenance of vulnerable materials or inappropriate conservation methods.

Knowledge of the physical and mechanical properties of the building stone material of Qusayr Amra (Amra palace) in Jordan allows an integrated vision of the expected damage and loss to the palace's structural properties, and of their mitigation, thus providing a useful tool for designing a more effective conservation plan. However, a higher priority shall be put on the evaluation of risks concerning the physical structure of the stone of the palace in relation to its physical and mechanical properties**.** This will help to produce a system of regular and permanent maintenance to ensure the proper preservation and conservation of this monument. For that a 3D model will be constructed for better monitoring stone deterioration and decay. Data have been collected in the framework of a project aimed at the generation of a 3D documentation system of the desert palaces in Jordan using photogrammetry, a laser scanner and a GIS system.

Figure 1. General view of Qusayr Amra

Significance Qusayr 'Amra

Qusayr 'Amra (705–715), an Umayyad bath complex Located east of 'Amman, was part of the Umayyad settlement policy in the region between the cities of Amman and Azraq. The bathhouse in Qusayr ’Amra was the centre of a larger complex of buildings. It is composed of three long halls with vaulted ceilings resting on transverse arches: the audience hall, the baths and the hydraulic system (Al-Asad *etl* 2000, Creswell 1989, Hillenbrand 2000 and Ettinghausen 1987). The audience hall is rectangular in shape with a throne alcove in the middle of the south side. The bath complex comprises 3 rooms, corresponding to the In terms of preservation status, Amra is the best preserved among the Umayyad desert palaces. It was added to the UNESCO's World Heritage list in 1985, which has proven vital to some of the conservation and preservation efforts of this building complex (Bianchin *etl* 2007). Qusayr ’Amra, is the most outstanding Umayyad palace and it is famous for its wall and ceiling frescoes. Those exquisite paintings are characterized by a rich iconographic repertoire that consist a major component of the Umayyad cultural heritage and an invaluable source of historical, artistic and technical information.The most notable feature of Qusayr ‘Amra, one that has fascinated scholars and travelers since the end of the nineteenth century, is the frescoed interior of the bath complex. Indeed, these four hundred-and-fifty square meters of painted walls are among the most extensive and complete decorative programs to survive from the ancient world in Jordan. The extensive Fresco paintings of Qusayr Amra depict a seemingly disparate collection of subjects, hunting and bathing scenes, athletic activity, mythological images, dancing girls, acrobats and wrestlers, musicians, royal portraits, astronomical representations, as well as craftsmen at work . It has been suggested that such scenes depict the pastimes of members of the ruling elite as a way of indicating their royal status. According to the Arabian and Greek captions, one famous fresco in the Bath / palace depicts the enthroned caliph being paid homage by six contemporary rulers, among which Basileus (the king) of Byzantium. That scene, in particular, emphasizes the self-esteem felt by Umayyad rulers, after their decade-long conquest of lands from Spain to the Hindu Kush. They were a kind of secular self-celebration of success and wealth (al-Shar'a 2009 and Haddad 2009). As a whole the frescoes in Qusayr ’Amra generate the impression that the new rulers adopted the lifestyle and tastes, as well as the desire for power, from their Byzantine predecessors [10-12].

Methodology

Typically, masonry structures have problems and damage associated with one or more of the following: foundation displacement – also known as settling – over time, the penetration of water into structural walls, shoddy construction and poor materials, stresses on the masonry walls due to fluctuations in temperature and ageing of mortar in masonry joints. A successful working schedule should include scientific tools to prevent the harmful effects on the main building material of Qusayr Amra, based on scientific diagnosis, and through the use of several methods and analytical techniques to define the physical and mechanical properties, which will assist in understanding the nature and status of deterioration.

In order to select the best method of treatment, several tests were performed on the main stone structural material. A series of experiments were conducted and studied with petrographic methods. These analytical methods, techniques and experimental studies consist of an evaluation of the porosity of the limestone, an open porosity test, a water absorption test, X-Ray fluorescence (XRF), a wetting and drying test and an examination of the soluble salt content. A 3D laser scanning system GS100, manufactured by Mensi S.A., France was used, shown in Figure 6. Different high-resolution images of the damaged areas were collected using a Canon 400D portable calibrated camera, which provides a resolution of 3888x2592 pixels with a focal length of 20 mm. These images were taken at different times (25/11/2008 and 31/8/2009), depicted in Figure 5, and were used to generate a true orthophoto. The 3D model of Qusayr Amra and the wall under study are depicted in Figure 7. The model has an average resolution of two cm.

The following is a brief description of the sampling methods and testing procedures for each of the analytical methods listed above.

Open Porosity Test: Porous materials are more susceptible to weathering agents than non-porous ones, and the pore space affects the pathways of the solutions and their interaction with surrounding materials and with the surrounding microclimate. The tested samples were analyzed using the following procedures:

1. Three samples were randomly chosen and labeled.

2. The samples were dried in the oven at 105° C until a constant weight was

reached.

3. The samples were allowed to cool in dry air in a desiccator.

4. The dry weight of each sample was recorded (W_d).

5. The dimensions of each sample were measured in centimetres.

6. The volume of each sample was calculated.

7. The samples were put in a desiccator and then immersed in distilled water.

8. The desiccator was closed, a vacuum pump connected to the lid was switched on and the samples were kept in the water for two hours.

9. The samples were then taken out of the desiccator using a wet cloth and weighed again. The saturated weight of each sample was recorded (W_s).

10. The weight of water in each sample was then calculated by subtracting the dry weight from the saturated weight.

$W_W = W_s - W_d$

11. The volume of water in each sample was calculated as follows:

V_w = weight/density

Since water density equals 1g/cm³, the water volume equals the water weight.

12. The porosity of each sample was calculated by dividing the volume of water in each sample by its original volume and multiplying by 100%.

$P = (V_w/V) \times 100\ \%$

Petrography Test: All thin-sections were prepared without using water in order to minimize the loss of salt crystals. The preparation procedure can be summarized as follows:

1. Samples were cut and trimmed with a 150 mm diameter diamond saw.

2. Samples were vacuum impregnated for porosity with blue dye Stuers 'Epofix' epoxy resin.

3. Samples were lapped flat with 230 grit silicon carbide powder mixed with kerosene on a glass plate.

4. Samples were lapped with 600 grit silicon carbide mixed with kerosene on a glass plate.

5. Samples were washed in kerosene and dried.

6. Samples were glued with 'EpoTek 301' epoxy resin to round/ashed 75mm x 26mm glass slides and left under a spring press at 70º C for 1 hour.

7. Sections were trimmed to 0.3 mm thickness using a Buhler ‘Petro Trim’ diamond saw/grinding wheel.

8. Sections were lapped to 30 micron thickness on Logitech ‘LP30’ using 600 grit silicon arbide/kerosene slurry.

9. Cover slips were mounted to some of the thin sections with Canada Balsam.

Samples were examined using a Leica DM LP Polarised Light Microscope and using magnifications of 40x and 100x. A digital camera attached to the microscope was used to record the features of the tested samples.

X-Ray Fluorescence (XRF) Test: A SPECTRO X-LAP 2000 at the Institute of Archaeology, University College London with menu-based X-LAP Pro software was used to determine the main elements in the laboratory test specimens. An 8 g portion of each sample was crushed to powder and pressed with a binding material to produce a 32 mm diameter pellet. Each sample measurement was repeated three times.

Water Absorption Test: Various testing methods were applied by different standard tests such as RILEM, ASTM and ISRM to measure water absorption. Specifically, the American Society of Testing and Materials procedure (ASTM C 642-97) was used (Annual Book of ASTM Standards 2004: Volume 04.02, 334-335). In this procedure the water absorption of the laboratory-tested stone after immersion and also after immersion and boiling was determined.

Results and Discussion

Petrography: Petrographic examination is an essential analytical method for evaluating the durability of stone materials (Robertson 1982). It identifies the mineral composition, homogeneity, pore space types and percentages and bedding planes of the sample (Bala'awi 2006). All those properties have a direct effect on the process of salt crystallisation (Nicholson 2001 and Ordóňez *et al.* 1997).

It was found that the stone used at Qusayr Amra is fine to medium-grained, homogeneous, buff-coloured oolitic limestone. The ooliths comprise approximately 60-70% of the rock, range in size from 200 to 600 µm and are cemented by sparite matrix. It was also found that the pore spaces (coloured with blue resin) are mainly very fine and difficult to distinguish and appear only within the ooliths rather than the cement (Figure 2).

Open Porosity Test: Three random samples of cubic shape were selected for this test. The first sample was selected from the lower part of building (1 m from the ground level), while the second sample were taken from the middle part (3 m from the ground level) and the last sample were taken from the upper part of the building (around 5 m from the ground level). Generally, all tested specimens showed very similar percentages of total open porosity with an overall average around 22%. See Table 1.

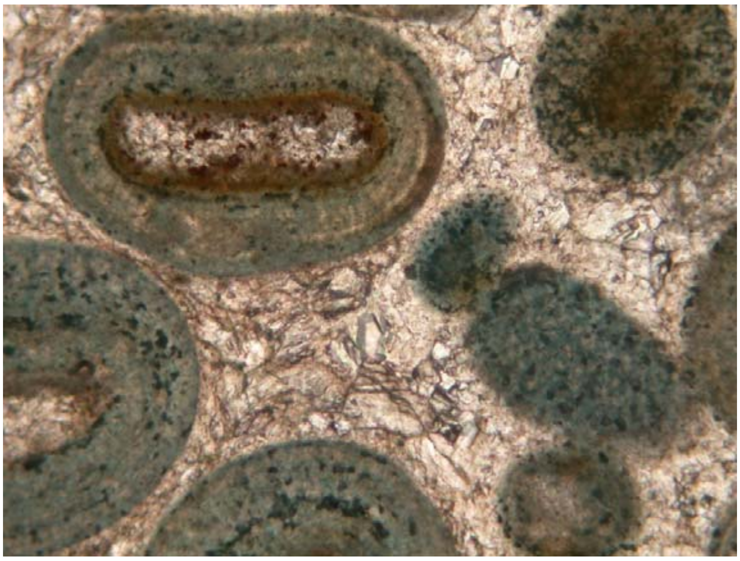


Figure 2. Thin section showing the oolitic limestone ,Field of view: 2.5 mm. Magnification: 100x. (ppl)

The results of the open porosity test showed a high percentage of open porosity ratios within the building stone materials, which as a consequence could result in a building highly susceptible to weathering agents, especially salt damage and air pollution. The following sections will discuss the salt damage decay agent in more detail.

Table 1. Results of the Open Porosity Test ((LQA1, LQA2 and LQA3) of the limestone of Qusayr Amra

Sample Code	Open Porosity %%
LQA1	22.4
LQA2	21.9
LQA3	21.5

Water Absorption Test: The test results have shown that the limestone of Qusayr Amra had a relatively high water absorption capacity (see Table 2). The differences between the water absorption capacity after immersion and after immersion and boiling have highly supported the nature of the fine porous system. These types of materials are more susceptible to salt damage.

Table 2. Results of the Water Absorption Test ((LQA4, LQA5 and LQA6) of the limestone of Qusayr Amra

Sample Code	WAC after Immersion	WAC after Immersion and Boiling
LQA4	9.33	9.99
LQA5	10.43	11.21
LQA6	9.31	10.82

X-Ray Fluorescence (XRF) Test: A SPECTRO X-LAP 2000 at the Institute of Archaeology, University College London, with menu-based X-LAP Pro software was used to determine the main elements in the laboratory test specimens. An 8 g portion of each sample was crushed to powder and pressed with a binding material to produce a 32 mm diameter pellet. Each sample measurement was repeated three times. The test results indicate that calcium is the main component, with silicon as a minor component (approximately 2%) and traces of aluminum (less than 0.5%). See Table 3.

Wetting and Drying Test: Studies of the wetting of walls show that there is appreciable non-uniformity of wetting and confirm what is often noticed when buildings are wetted by rain: that much more intense wetting usually occurs near the top of walls than at lower levels. Differences in wetting are attributable to the wind-flow patterns over the wall surface, which direct the paths of the falling raindrops (Ritchie 1976).

Table 3. The original distribution of the elements in the tested samples (expressed as oxides, %)

Sample Code	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	P_2O_5 %	SO_3 %
LQA7	0.11	0.41	0.49	2.21	0.09	0.00
LQA7_1	0.13	0.49	0.32	2.41	0.03	0.00
LQA7_2	0.08	0.44	0.45	2.22	0.02	0.00
Sample Code	Cl %	K_2O %	CaO %	TiO_2 %	MnO %	Fe_2O_3 %
LQA7	0.01	0.08	62.27	0.06	0.10	0.02
LQA7_1	0.04	0.09	59.68	0.00	0.06	0.04
LQA7_2	0.03	0.01	60.11	0.02	0.07	0.00

The degree of rain-wetting, however, should be expected to depend on two factors: (1) The amount of rainfall, which varies per year and (2) The force of the wind, which not only blows the rain onto a wall but applies a pressure to the wall surface forcing the rain into the pores and openings of the masonry.

The rain that falls on the masonry walls of Qusayr Amra has three possible paths of penetration: through the body of the unit; through the body of the mortar; and through openings between the unit and the mortar. However, the amount of water that penetrates the mortar does not contribute significantly to a leakage problem. Staining and efflorescence on masonry walls reflect the patterns of the wetting and the manner in which water runs over and off the wall surface. The water flow patterns may also produce stains and streaks by eroding the masonry material, the resulting differences in texture and color giving an appearance of vertical streaks on the wall surface.

On the other hand, decay due to freezing is a serious consequence of the wetting of masonry. Experiments have shown that damage done to masonry materials by freezing depends in large measure on their moisture content when the materials are frozen (Ritchie 1976). The deterioration of masonry materials because of frost action is more rapid and intensive, therefore, in those wall areas where excessive wetting of masonry occurs at the top of a wall.

In our study, 15 cycles of wetting and drying were carried out on three limestone samples from Qusayr Amra. The Building Research Establishment (BRE) procedure for the wetting and drying test (Ross and Butlin 1989) was followed and each cycle was carried out. Based on the findings of the current test, shown in Table 4, it can be stated that the Qusayr Amra stone building materials are relatively sound and the minor loss could be related to the salt content of the building and not to rock main components.

Table 4. Results of wetting and drying of the limestone of Qusayr Amra

Sample Code	**Original Dry Weight (g)**	**Dry Weight 1^{st} cycle (g)**	**Dry Weight 2^{nd} cycle (g)**	**Dry Weight 3^{rd} cycle (g)**	**Dry Weight 4^{th} cycle (g)**	**Dry Weight 5^{th} cycle (g)**	**Dry Weight 6^{th} cycle (g)**	**Dry Weight 7^{th} cycle (g)**
LQA8	118.23	118.1	118.1	118.0	118.0	118.06	118.01	117.98
LQA9	123.99	123.9	123.8	123.8	123.8	123.84	123.80	123.78
LQA10	120.84	120.8	120.8	120.8	120.7	120.77	120.75	120.68
Dry Weight 8^{th} Cycle (g)	Dry Weight 9^{th} cycle (g)	Dry Weight 10^{th} cycle (g)	Dry Weight 11^{th} cycle (g)	Dry Weight 12^{h} cycle (g)	Dry Weight 13^{th} cycle (g)	Dry weight 14^{th} cycle (g)	Dry Weight 15^{th} cycle (g)	ΔM (mass loss or gain) after the drying-wetting test (%)
117.98	117.95	117.9	117.9	117.9	117.9	117.92	117.90	0.33-
123.77	123.75	123.7	123.6	123.6	123.6	123.65	123.63	0.36-
120.67	120.65	120.6	120.6	120.6	120.5	120.56	120.54	0.30-

Soluble Salt Content

Efflorescence is caused by the absorption of water by masonry materials. The water dissolves salts in the masonry, forming solutions that subsequently move to the surface where the water evaporates, depositing the salts. The salts may have originated within the masonry units or the mortar, but the latter is a particularly important source. Efflorescence frequently reflects the direction of wetting walls. Efflorescence also reflects differences in the amount of wetting received by a wall; it often appears at the top of the wall but not at the bottom (Ritchie 1976).

Formations of some salty hard-crusts on the Qusayr Amra stone surfaces and within stone pores create some aggressive internal pressures that finally lead to bleeding of stone aspects. The rate of chemical reaction between the stone surface and acid rain depends mainly on several catalytic metal ions (Penkett *et al.* 1979 and Flatt *et al*. 1995). Finally this salt penetrates into stone pore spaces and crystallizes there, leading to crystallization processes over years, and then breaks the stone surfaces. This phenomenon depends essentially on the amount of salt present, its nature and the number of dry-wet cycles (Binda and Baronio 1985).

The results are shown in Tables 4, 5 and 6. Marked decreases of CaO and MgO from fresh to weathered samples indicate high mobility of Ca and Mg elements. According to Moon and Jayawardane a lessening amount of CaO and MgO as well as FeO indicates loss of strength of the rocks. The weathered rocks have lower Na_2O compared to fresh rocks. This suggests that the Na is also mobile during weathering. Duzgoren-Aydin et al. (2002) reported that as the intensity of weathering increases, Ca, Na and K decrease. This may be due to the high absorption rate of the weathered rocks. These tuffs also have soft cement between the particles. The density of the fresh rocks is higher than that of weathered samples, indicating the higher durability of the fresh rocks.

Table 5. The main cations in the tested samples of the limestone of Qusayr Amra

Sample code	Height (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Fe (ppm)	Al (ppm)
LQA11	5	20.42	13.89	2.19	3.58	4.69	0.79
LQA12	55	19.22	12.99	1.86	2.67	0.00	0.13
LQA13	105	16.45	12.30	1.69	1.55	0.00	0.12
LQA14	155	16.54	11.34	0.59	1.20	0.00	0.23
LQA15	205	16.00	11.73	0.65	1.99	0.00	0.40
LQA16	255	16.19	9.49	1.19	1.20	0.00	0.16
LQA17	305	17.11	8.99	0.86	1.11	0.00	0.16
LQA18	355	16.45	8.30	0.69	1.15	0.00	0.12
LQA19	405	15.54	7.34	0.59	1.13	0.00	0.17

Table 6. The main anions in the tested samples of the limestone of Qusayr Amra

F (ppm)	**Br** (ppm)	**Cl** (ppm)	**NO_3** (ppm)	**PO_4** (ppm)	**SO_4** (ppm)
2.23	0.00	12.60	10.33	18.22	6.21
2.02	0.00	11.40	10.24	18.10	6.11
2.21	0.00	11.33	10.63	18.47	6.13
1.99	0.00	10.98	9.87	18.00	7.08
1.87	0.00	10.02	9.88	17.89	5.99
1.88	0.00	9.36	6.35	17.54	5.27
1.78	0.00	8.12	7.36	15.34	5.24
1.69	0.00	7.59	6.30	15.64	5.20
1.20	0.00	7.50	5.97	14.28	5.17

Table 7. The total soluble salts in the tested samples of the limestone of Qusayr Amra

Sum of Cations and Anions (ppm)	**Soluble Salt Content in the Sample** (%)
82.72	0.41
78.67	0.39
75.83	0.38
74.55	0.37
66.75	0.33
64.29	0.32
61.44	0.31
57.69	0.29

Thermodynamic Consideration of the Soluble Salts ECOS program

Despite the fact that the analysis of cations and anions of samples collected from the sampling profile at different heights has revealed very useful information about the salt content and distribution at Qusayr Amra, understanding of the dynamics of these soluble salts was limited. In other words, the relationship between the content, types and distribution of soluble salts and the surrounding environmental conditions was not adequately explained. Therefore, a more specific study of the thermodynamic behaviour of the soluble salts in relation to the surrounding environmental conditions is needed.

The determination of the hydrothermal conditions that control the behavior of single salts is a straightforward process (Benavente 1993). Each single salt has its specific equilibrium relative humidity (ERH) at a certain temperature and remains in solution when the surrounding relative humidity is higher than this ERH, but crystallizes when the surrounding relative humidity is lower than this ERH.

Following these observations, it might be assumed that salt damage could be avoided in a very straightforward way by controlling the surrounding relative humidity and temperature. Unfortunately, the reality is more complicated, mainly because contamination with single salts in porous materials is rare (Price 2000), while predicting the behaviour of a salt mixture is much more complicated. Many models have been presented in an attempt to understand the behaviour of mixed salt solutions. Pitzer's thermodynamic model (1973) is one of the most widely accepted models, applied in many areas in the chemistry of the natural environment (Clegg and Whitfield 1991). Price and Brimblecombe (1994) used a new version of Pitzer's model, PITZ93 (Clegg 1993) to predict the behaviour of two salt solutions that are commonly found in cultural heritage monuments and objects (the sodium nitrate – sodium chloride solution and the calcium sulfate – sodium chloride solution). The study examined the interaction of the salts in these solutions and their effect on each other's solubility. See Figure 5 and 6. The study also determined the 'safe' levels of relative humidity, where salt damage in monuments or objects contaminated with these salts can be minimized.

The use of the Pitzer model in preventive conservation studies (Steiger and Dannecker 1995 and Steiger and Zeunet 1996) led to the creation of an expert chemical model (ECOS) for determining the environmental conditions needed to prevent salt damage in porous materials (Price 2000). The Runsalt program, which is a graphical user interface to the ECOS thermodynamic model, will be used to study the salt composition and behaviour of selected samples from Qusayr Amra.

The two results for cations and anions from the sampling points 5, 105, 205 and 405 cm were chosen to evaluate the thermodynamic of the soluble salts at Qusayr Amra. The selection of these sampling points was based on the fact that they represent different heights and could reveal a good indication of soluble salt behaviour at the monument.

The Runsalt program requires the input of three types of data: cation and anion content with the average of one environmental parameter (temperature or relative humidity) and the range of fluctuation of the other parameter (temperature or relative humidity). The literature review of the Runsalt applications showed that temperature did not significantly affect the behavior of the salt solution, while relative humidity had the greatest impact. Therefore, the current research used Runsalt with the average temperature of each sampling period as the fixed parameter and with the entire available range of relative humidity (15-98%). The overall temperature for the first fieldwork visit was 30º C.

The thermodynamic data from the tested samples showed that Halite (NaCl), Sylvite (KCl) and Calcium Nitrate ($Ca(NO_3)_2$) were the main potential soluble salts. The data also showed that dangerous relative humidity ranges are mainly between 22-32%, while the safest relative humidity ranges are mainly above 65% (see Table 7). However, the relatively stable relative humidity ranges are mainly between 32-63%. By comparing these data with the environmental conditions in August 2010 (samples were taken on 1 August 2010), it can be concluded that the relative humidity at the site ranged between 10-85% with an average of 45% but rarely below 30%. Therefore the main concern at the site is to avoid the most dangerous ranges of soluble salt, which are between 22-32%. A simple natural shelter (Tress Shelter) could be used to avoid these dangerous ranges.

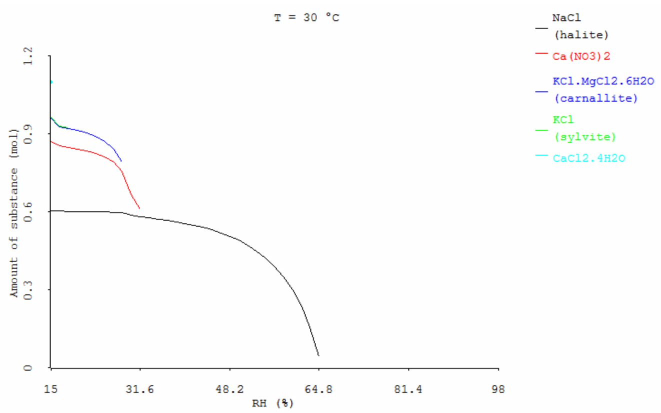


Figure 3. Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). Sampling number (LQA11). August 2010. (After the removal of Gypsum)

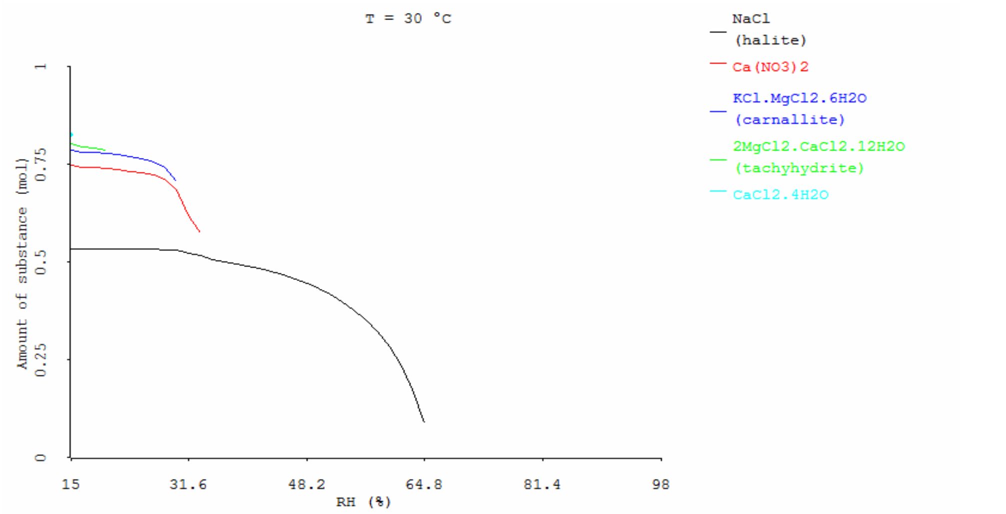


Figure 4. Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). Sampling number (LQA13). August 2010. (After the removal of Gypsum)

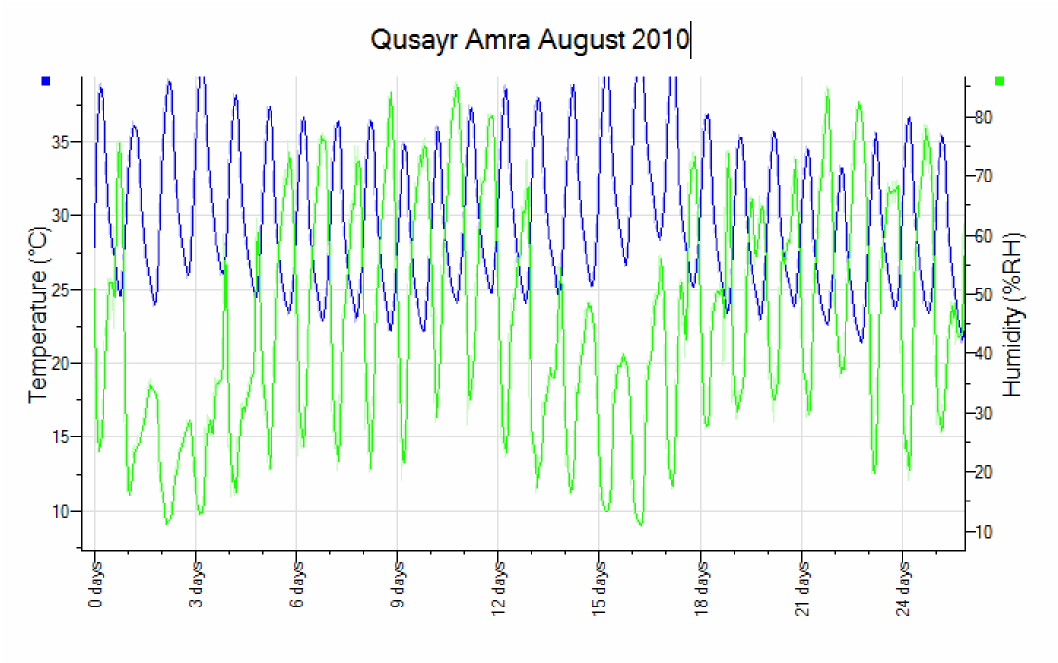


Figure 5. Relative humidity and temperature readings from the data logger. Location: Qusayr Amra. (Recorded period 1-30 August 2010).

Table 8. Dangerous relative humidity ranges, safe relative humidity ranges and relatively safe relative humidity ranges for the soluble salt content in the tested samples from Qusayr Amra.

Sample Number	Dangerous Relative Humidity Ranges (%)	Safe Relative Humidity Ranges (%)	Relatively Safe Relative Humidity Ranges (%)
LQA11	28.5-31 64-65	Above 65	15-17 32-63
LQA13	29-33 64-65	Above 65	15.5-19 34-63
LQA15	19.5-23.5 67-67.5	Above 67	24-67 15-19
LQA19	21.5-31.5 64-64.5	Above 65	32-64 15-22

In addition to the physical and chemical analysis, data about the spatial distribution and texture of the damage on the building surface are needed in order to provide reference data and guide the needed restoration and also for monitoring purposes. To achieve this goal data from laser scanning and digital imagery was combined. In this project, a laser scanner is used in order to collect thousands of 3D points every second at high levels of accuracy and to precisely digitize complicated objects. The 3D laser scanning system GS100, manufactured by Mensi S.A., France was applied; the instrument is depicted in Figure 6. The system is able to measure 5000 points per second. Because it is not possible to have complete 3D coverage for outdoor complex-structured sites based on data collected from a single station, different viewpoints have to be used to resolve the occlusion, as depicted in Figure 7.

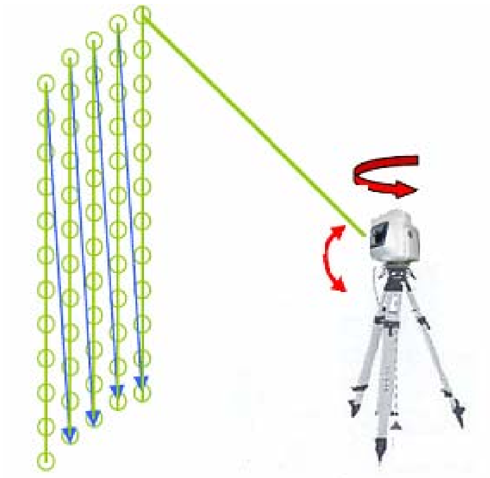
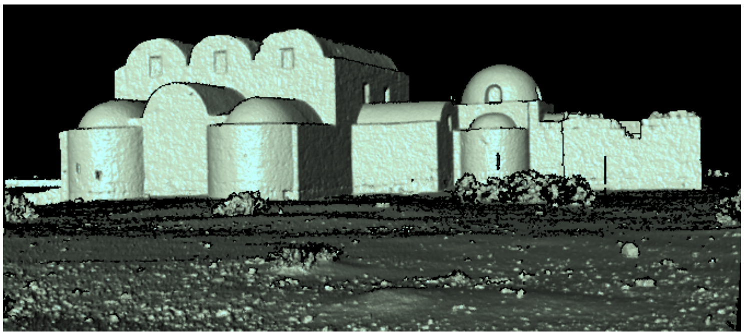
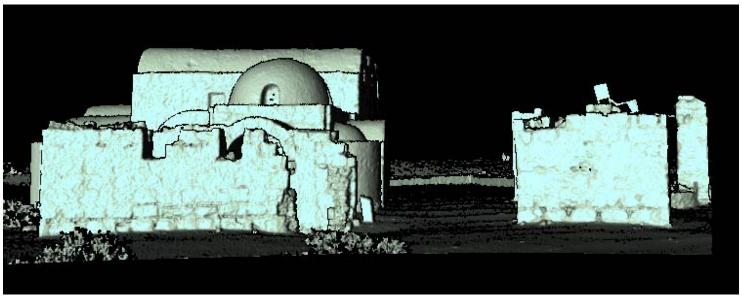


Figure 6. Mensi 3D Laser Scanner

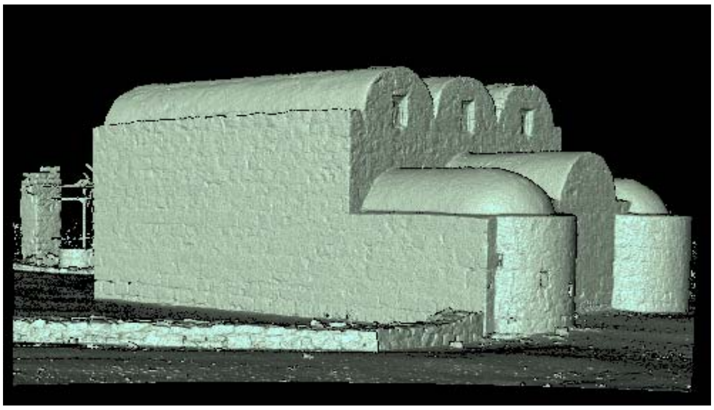


South view



East View

North View



West View

Figure 7. 3D Models of Qusayr Amra, showing views of the four sides

Documentation of the surface decay can be achieved using a high resolution textured model. The Mensi system captures a calibrated video snapshot of 768x576 pixel resolution, which is automatically mapped onto the corresponding point measurements, as depicted in Figure 8. These low resolution images are not sufficient for the high quality texturing that is desired for documentation, monitoring and material visual analysis.

For this reason, additional images were collected with the Canon 400D camera, which provides a resolution of 3888x2592 pixels with a focal length of 20 mm. These images depicted in the bottom row of Figure 7 were collected at almost the same time and have more texture details, as can be depicted in Figure 9.

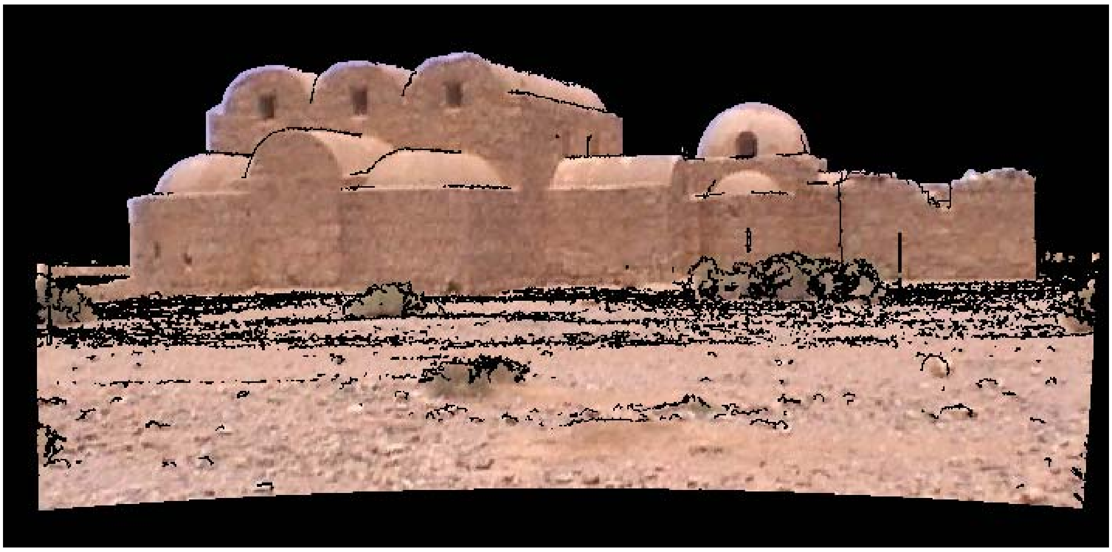


Figure 8. 3D textured model of the south view using images collected from the laser scanner camera (768x576 pixels)

By contrast, the proposed method for mapping high resolution digital images onto the measurements gives a highly realistic appearance to the model and offers a descriptive view of the scene that can be used for measuring and monitoring, as depicted in Figure 8.

Figure 9. Textured model (using close detailed high resolution images)

This research has succeeded in demonstrating the main physical and chemical properties of the stone materials at Qusayr Amra, which is the first step in understanding the decay process at the site. The evaluation of all previous results and their consequences can be summarized in the following points:

1. The calcareous nature of the Qusayr Amra stone building materials and its porosity ratios as well as the fine pore structures are very dangerous rock features for decay mechanisms, especially salt damage. However, the open porosity results could be seen as an advantage in the case of applying certain adhesives to the monument to increase its stability; however these adhesives should be applied after the removal of salts and in low concentration in order to fit the fine pore system of the building materials.
2. The soluble salt results shows that the Qusayr Amra stone building is relatively high in salt content, particularly at the lower and middle parts of the building. These readings suggest strongly that the groundwater is the main source of soluble salts at the site. The landscape features around the site support this potential source of the soluble salts since the building is located in the center of a shallow depression. A simple moisture test carried out at the site by weighing three samples from three different levels before and after drying strongly support the idea of groundwater as a main source of moisture and therefore the potential soluble salt source. A detailed groundwater evaluation in the area is needed to compare salt types in this water and salts at the building.
3. The detailed microclimate evaluation of the site accompanied by the thermodynamic calculation of the movements of soluble salts showed that salt crystallization could be avoided at the site by a slight modification of the current environment, especially the relative humidity ranges at the site. The results showed that the site is relatively safe with relative humidity ranges above 30-35%. Natural shelters, such as trees, or built shelters appear to be the priority for preventive measures. Although the authors are totally aware that these measures could be difficult to implement, both for practical and aesthetic reasons, they still seem vital for the long-term conservation plan of the site.

Conclusion

Salt crystallization is the most powerful weathering agent for rocks. The rocks lose weight due to the harmful effect of salt, which also causes visible surface deterioration. During salt crystallization, pressure crystallization occurs within the pores of rocks, and the degree of weathering depends on the degree of salt saturation of the solution and the pore size. The stone conservation principles that must be adopted in Qusayr Amra should be appropriate for the original building technology, partly to preserve the integrity of the original design but also for practical reasons. The results discussed above showed that the total salts soluble in tested samples are generally low. However, calcium and sodium are the main cations, and chloride, nitrate, sulfate and phosphate are the main anions. The total soluble salts are slightly higher at the lower levels of the building. This may suggest that the most likely source of the salts in the building is due to groundwater; the fieldwork investigation showed that an artificial water well is part of this Umayyad bath at a distance of about five meters, where a large amount of water has accumulated that could result in raising the groundwater level and thereby the amount of total soluble salts in the building.

Analytical work should commence with the consideration of the building stonework, since the occurrence of salt is related to specific deterioration phenomena and to particular microclimates, as well as hydrological conditions. However, except for the physical and mechanical tests, deterioration and weathering morphologies should be also mapped by visual inspection. This is an important step, since these morphologies are considered an effect of stone alteration and weathering processes. A detailed visual inspection at Qusayr Amra should be carried out for the stone deterioration in relationship with the four orientations.

References

- Al-Asad, M. and Bisheh, G. 2000. *The Umayyads. The Rise of Islamic Art. Amman and Vienna: Ministry of Tourism, Department of Antiquities, Amman, Jordan and Museum With No Frontiers*. Vienna (2000), pp. 50–51.
- Bianchin, S., Umberto, C., Monica, F., Pietro, A. 2007. Painting technique and state of conservation of wall paintings at Qusayr Amra. Amman.
- Binda, L. and Barronio, G., 1985. Deterioration of porous materials due to salt crystallization under different thermohygrometric conditions. Proceedings of *5th*

International Congress on Deterioration and Conservation of Stone, Lausanne, Vol. 1 Brick, pp. 279-288.

- Clegg, S.L. and Whitefield, M., 1991. Activity coefficient in natural waters. In Pitzer, K.S., (ed.), *Activity Coefficient in Electrolyte Solutions*. Baca Raton: CRC Press. pp: 279-434.
- Clegg, S.L., 1993. PITZ93: a FORTRAN program for determining activity in electrolyte solutions available from S. L. Clegg or P. Brimblecombe at the School of Environmental Sciences of the University of East Anglia, Norwich, UK.
- Creswell, K.A.C., 1989. A Short Account of Early Muslim Architecture. Rev. ed. Allan, J. W. Allan. Aldershot: Scholar Press, pp. 105-117. .NOT CITED IN ARTICLE.
- Elgohary, M.A. 2008. Air Pollution and Aspects of Stone Degradation "Umayyed Liwân – Amman Citadel as a Case Study", *Journal of Applied Sciences Research* 4(6): 669-682.
- Ettinghausen and Grabar 1987 The Umayyads and Their Art, *The Art and Architecture of Islam 650–1250*, New Haven: Yale University Press (1987) pp. 26-74.NOT CITED IN ARTICLE.
- Flatt, R., Giradet, F. and Crovisier, J., 1995. Modelling of sulphur dioxide deposition on the Bern sandstone. *Proc. 1995 LCP Congr. Preservation and Conservation of Cultural Heritage*. Lausanne, pp. 401-406.
- Hillenbrand, R. 2000. The Palace in Islamic Architecture: Form, Function and Meaning, Edinburgh University Press, Edinburgh (2000) pp. 443-446. http://ArchNet.org (accessed 10 July 2008). NOT CITED IN ARTICLE.

- Moon V, Jayawardane J (2004). Geomechanical and geochemical changes during early stages of weathering of Karamu Basalt, New Zealand. Eng. Geol., 74, 57-72.
- Naif A. Haddad,. 2009. The Architecture of Umayyad Palaces in the Great Syria *(Badiya):* Analytical Study in the Particularity, *The Emirates Journal for Engineering Research (EJER*), Vol.14 No. 1, pp.1-8.
- Nicholson, D., 2001. Pore properties as indicators of breakdown mechanisms in experimentally weathered limestone. *Earth Surface Processes and Landforms.* Vol. **26**. Pp. 819-838.
- Ordóňez, S., Frot, R. and García del Cura, A., 1997. Pore size distribution and the durability of a porous limestone. *Quarterly Journal of Engineering Geology*. Vol. **30**. pp: 221-230.
- Penkett, S.A., Jones, B.M., Brice, K.A. Brice and Eggleton, A.E. 1979. The importance of atmospheric ozone and hydrogen peroxide in oxidizing sulphur dioxide

in cloud and rainwater. *Atmosphere Environment* 13: 123-137.
- Pitzer, K, S., 1973. Thermodynamics of electrolytes, I. Theoretical basis and equations. *Journal of Physical Chem*istry **77**. pp: 268-277.
- Price, C.A. and Brimblecombe, P. 1994. Preventing salt damage in porous materials. In Roy, A. and Smith, P., (eds.), 1994. *Preventive Conservation, Practice, Theory and Research***.** London: International Institute for Conservation of Historic and Artistic Works. pp: 90-93.
- Price, C.A., (ed.) 2000. *An Expert Chemical Model for Determining the Environmental Conditions Needed to Prevent Salt Damage in Porous Materials***.** European Commission Report 11, Protection and Conservation of European Cultural Heritage. London: Archetype Publications
- Ritchie, T. 1976. Moisture Degradation of Masonry Walls, DBR Paper No. 693, Division of Building Research Reprinted, with permission, from *Proceedings, First Canadian Masonry Symposium held at the University of Calgary, Calgary, Alberta* pp. 66-71.
- Robertson, E., 1982. Physical properties of building stone. In the report of the Committee on Conservation of Historic Stone Buildings and Monuments, 1982. *Conservation of Historic Stone Buildings and Monuments*. Washington, D. C.: National Academy Press. pp: 62-86.
- Ross, K. and Butlin, R., 1989. Durability test for building stone. *Building Research Establishment Report*. Watford: Building Research Establishment.
- Steiger, M. and Dannecker, W., 1995. Hygroskopische Eigenschaften und Kristallisationsverhalten von Salzgemischen. In Snethlage, R., (ed.), 1995. *Jahresberichte Steinzerfall: Servierung 1993*. Berlin: Ernst & Sohn. pp: 115-128.
- Steiger, M. and Zeunert, A., 1996. Crystallization properties of salt mixtures: comparison of experimental results and model calculation. In Riederer, J., (ed.), 1996. *Proceedings of the 8th International Congress on the Deterioration and Conservation of Stone*. Berlin, 30 September - 4 October 1996. Berlin: Möller pp: 535-544.
- D. Benavente, M.A. Garcia del Cura, R. Fort and S. Ordonez. 1993. Thermodynamic modelling of changes induced by salt pressure crystallisation in porous media of stone, *Journal of Crystal Growth* **204**, pp. 168–178.

الخصائص الفيزيائية و الميكانيكية لحجارة البناء في قصير عمرة التاريخي : خطوه باتجاه التوثيق و المحافظة

فادي عبدا بلعاوي*، فراس محمد علاونة* ، يحيى سليمان الشوابكة* ونايف عادل الحداد*

ملخـص

في هذا البحث تمت عملية دراسة الخواص الكيميائية والفيزيائية لحجارة البناء المستخدمة في قصير عمرة إحدى مواقع التراث العالمي في الأردن. تم قياس تأثير التجوية الكيميائية الناتجة من عمليات تبلور الأملاح على هذا المبنى . الدراسة تهدف إلى التعرف والوقوف على المشاكل التي يتعرض لها هذا البناء وبالتالي إيجاد آلية للمحافظة عليه. وأظهرت بيانات الديناميكا الحرارية التي أجريت على مختلف العينات باستخدام برنامج (Runsalt) بأن كل من كلوريد الصوديوم (NaCl) ، السلفيت (KCl) ونترات الكالسيوم (Ca(NO3)2) من أبرز الأملاح الذائبة المحتملة في العينات المدروسة. البحث استخدم تطبيقات نظام الليزر الماسح ثلاثي الأبعاد (GS100 3D) لإنتاج نموذج ثلاثي الأبعاد لتحسين عمليات المراقبة و المتابعة الرقمية للتغيرات التي تطرأ على البناء. نتائج الدراسة أشارت إلى أمكانية التقليل من المشاكل الموجودة في المبنى من خلال العمل على تعديل الظروف البيئية المحيطة بالمبنى و التي لها دور مهم في تقليل واحدة من أهم المشاكل الموجودة حاليا و هي عملية تبلور الأملاح الذائبة و توزعها.

الكلمات الدالة: قصير عمرة،علم المحافظة، الخصائص الفيزيائية، الديناميكية الحرارية للأملاح، نموذج ثلاثي الأبعاد.

---

* معهد الملكة رانيا للسياحة والتراث، الجامعة الهاشمية.

تاريخ استلام البحث ٢٠١١/٦/٢م، وتاريخ قبوله للنشر ٢٠١١/١٢/١٥م.