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Characterization of hydraulic mortars from archaeological complexes in Petra

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Abstract

In the sixth century B.C. Petra was conquered by the Nabataeans, who built an elaborated water system and turned a desert city into an artificial oasis and a prosperous centre controlling the main commercial routes of the region (100 B.C. - 100 A.D.). In 2007, it was added to UNESCO's prestigious list of World Heritage Sites, as one of the seven wonders of the world.

The aim of this research is to characterize samples of mortars lining cisterns, reservoirs and pipelines collected from the archeological site of Petra, focusing in general on the identification of the possible raw materials employed and in particular on those components conferring hydraulicity. Specifically the specimens were sampled from different structures of the Great Temple (cistern and pipelines) and of the Garden and Pool Complex (cisterns and reservoir floor). A mineralogical and petrographic characterization was carried out by Polarized Light Microscopy (PLM) observations to identify the texture and to highlight the hydraulic reaction areas, which underwent subsequently to a more detailed morphological and elemental analysis by Scanning Electron Microscopy (SEM-EDX). X-Ray Powder Diffraction (XRPD) analyses were also performed to complete the petrographic characterization, while Thermal Analyses (DTA-TGA) were carried out to classify the level of hydraulicity of each sample. The data obtained allowed us to achieve for the first time a mineralogical and petrographic characterization of the lining hydraulic mortars present in the two archaeological complexes under study and to provide preliminary hypotheses on the provenance of the raw materials employed for their production.

Key words: mortar; reaction rims; hydraulicity; raw materials.

Introduction

The ancient town of Petra (Jordan) always aroused great interest. In the past, during the Nabataean kingdom, it was one of the most important trading centers and nowadays is one of the most suggestive archeological site of the world.

Petra has a particular geographical and geomorphological position, situated between the Red and the Dead Sea, characterized by the presence of canyons and passages among mountains, which form a "town of rocks" (Franchi et al., 2009). The outstanding value of Petra is, in fact, strictly connected to the magnificent hand-carved rock monuments, as the famous Treasury Palace and several monumental tombs. It has to be also underlined that a peculiar architectural and engineering ingenuity allowed this population to produce as well stonework constructions and several structures related to the everyday life. Indeed, Nabataeans were able to take advantage of the features of the surrounding area and to overcome the obstacles of desert life, building an elaborated water management system, for rainfall collection and supply, and for flash flood prevention, constituted by a network of channels, pipelines, pools, cisterns, dams and stilling basins, which has been object of several studies because of its complexity and efficiency, in terms of building technology and function (Joukowsky, 1998; Akasheh, 2002; Bedal, 2003; Bellwald, 2003, 2006; Shaer, 2004; Ortloff, 2005; Gabrielli, 2008). The Petra National Trust and the Hashemite University carried out a study to realize a pattern of the Nabataean water installations, in order to achieve a deeper understanding of how the water management system may likely affect the geological stability of the Siq (i.e. landslides, flooding), and thus the tourist access and fruition (Akasheh, 2002). Bellwald (2006) documented all the visible remains of the water-system belonging to the entire Petra area, and through its subsequent evaluation and elaboration, produced a preliminary model and first relative chronology of Petra's hydraulic infrastructures development over time. Gabrielli et al. (2008) started a 3D modeling reproduction of the territory morphology, in order to obtain a detailed spatial visualization of the channels network and to determine the state of degradation.

Both rock carved monuments and stonework buildings were frequently characterized by the presence of different kind of mortars and plasters, in relation to their diverse function. Studies have been previously carried out and published reporting a classification based on their structural and architectonic role: covering plasters and stuccos decorated both the façades and the interior walls of tombs and rock-cut caves (Shaer, 2000, 2002a, 2003); binding mortars applied at stone courses and walls, or embedding the pipelines and stone insets (Shaer and Aslan, 2000); finally lining mortars for the waterproofing of the water-system elements, such as cisterns, dams and channels (Shaer, 2002b, 2004).

Even though preliminary studies on the hydraulic mortars employment in Petra exist, the mineralogical and chemical composition of hydraulic mortars from the sites here under study started to be investigated only within the "PRODOMEA Project" (Project on High Compatibility Technologies and Systems for Conservation and Documentation of Masonry Works in Archaeological Sites of Mediterranean Area) (Sabbioni et al., 2004). According to this study mortars from monumental complexes in Petra were compared with other ones belonging to archeological sites of the Mediterranean Basin, of the same period (100 B.C. - 100 A.D.), in order to realize, as final aim, guidelines for a whole and compatible restoration work (Bonazza et al., 2004).

The research in the field of ancient hydraulic mortars rapidly increased in the last decades, mainly concerning their characterization, the identification of their hydraulic origin, linked in particular to the raw materials used (burning of marly and/or siliceous limestone, addition of potential hydraulic materials, etc.), reconstruction of ancient production recipes and working technologies, and damage evaluation due to environmental impact (Moropoulou et al., 2000, 2005; Sabbioni et al., 2002; Crisci et. al., 2004; Pecchioni et al., 2008; Diekamp et al., 2010; Fratini et al., 2010; Miriello et al., 2010). It should be pointed that the difficulty in proposing and realizing compatible restoration works is mainly due to the lack of knowledge concerning ancient methods of hydraulic mortar production, which manufacturing closely depends on the raw materials available in situ, both from stone outcrops/quarries and/or commercial supply.

The aim of this work is to carry out an accurate mineralogical and petrographic characterization of mortars from hydraulic structures belonging to two monumental complexes of Petra, which have been excavated in the last two decades, and to formulate first insights on the possible provenance of the raw material utilized.

In particular the archeological sites sampled are: the Great Temple (1st excavation started in 1993), which is comprised of a *Propylaeum* (monumental entryway), a lower and an upper *Temenos* (sacred area) (Figure 1). It was built at the beginning of the last quarter of the 1st century B.C. by the Nabataeans and continuously used until the Byzantine period (5th century) (Joukowsky, 1998; Kouki, 2012). The Garden and Pool complex, dated at the end of the 1st century B.C., was erected by Nabateans and functioned as a royal *paradeisos* until the 106 A.D., when it was transformed in a public park (Bedal, 2003). A preliminary survey and excavation of the latter site started in 1998.

The collected data here presented undoubtedly enhance the available knowledge on the hydraulic mortars composition used in Petra, in the 100 B.C.- 100 A.D. period, and, once integrated with the existing data on this topic, may contribute at the formulation and development of new materials suitable for short and long term

Figure 1. View of the Great Temple Complex at Petra.

compatible restoration works. Nevertheless it should be pointed that this topic still requires further analyses for being exhaustively faced.

Materials and Methods

The mortar samples were collected from several hydraulic structures belonging to the two archaeological complexes in Petra (Figure 2): pipelines and cistern being part of the Great Temple; cisterns and a reservoir floor from the Garden and Pool Complex.

On the collected specimens a series of laboratory investigations were carried out. Petrographic characterizations were obtained by polarized light microscopy (PLM) observations, performed with an Olympus BX 51 microscope, equipped with scanner and the MICROMAX software "Primoplus_32" vers. 8.11.02. X-Ray Powder Diffraction analyses (XRPD) were performed on those samples which amount of material was adequately available, to integrate the mineralogical characterization obtained by PLM. The instrument used for the XRPD investigations is a Philips PW 1730 diffractometer equipped with a copper anticathode and a nickel filter. The measurement conditions have a diffraction interval of 2θ, between 5° and 50°, and a 2°/minute step at 40kV voltage and 30 mA current intensity. The XRPD analysis allowed the acquisition of qualitative and semi-quantitative data on the crystalline phases present in a concentration of at least 3-4%. Scanning Electron Microscopy and microchemical investigations (SEM-EDX) were carried out to determine the elemental composition of the reaction areas, already highlighted by PLM observations. A ZEISS 1530 SEM equipped with a Schottky emitter, with two different secondary electrons (SE) detectors (the InLens and the Everhart-Thornley), and operating at 10 keV was used, while an Energy Dispersive X-Ray spectrometer (EDX), for the x-ray microanalysis, was utilized. Differential and Gravimetric Thermal Analyses

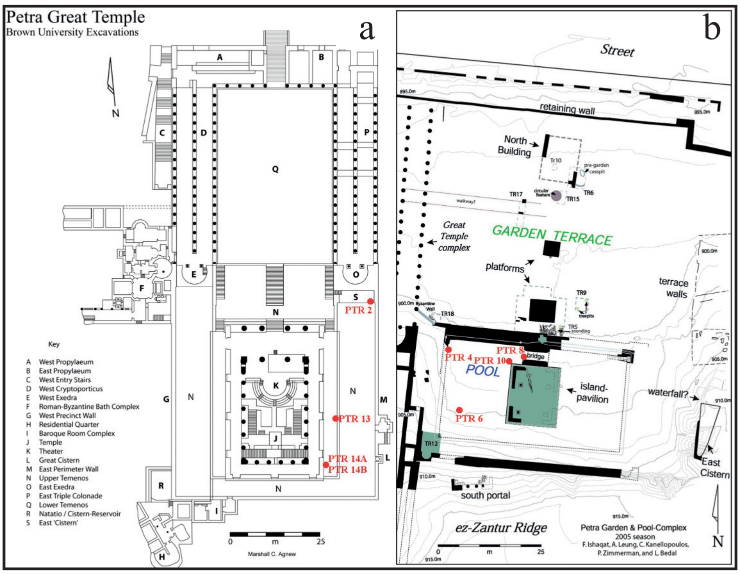

Figure 2. a) the plan of Petra Great Temple site with indications of sampling points (from Agnew, 2006). b) the plan of Petra Garden and Pool Complex with indications of sampling points (from Isaqat et al., 2005).

(DTA-TGA) were carried out with Mettler Toledo TGA/SDTA 851e instrument and Mettler Toledo STARe SW 7.01 software, with the main objective of determining the hydraulicity level. For XRPD and DTA-TGA analyses a partial separation of the coarse aggregate fraction was performed by soft mechanical grinding and manual removal with tweezers.

The area of sampling, a brief description of each sample and the analyses executed are summarized in Table 1.

Results and Discussions

The mineralogical and petrographic characterization performed by PLM observation

Table 1. Site of sampling, description of samples and analyses performed.

	SITE	SAMPLE	DESCRIPTION	ANALYSES			
				PLM	XRPD	DTA-TGA	SEM-EDX
GREAT TEMPLE	CISTERN	PTR 2	Lining mortar collected from the southern wall at 2.00 m below the ground level	X	X	X	
GREAT TEMPLE	PIPELINES	PTR 13	Internal lining mortar (th. 0.5 -1.5 cm) from pipeline system of the cistern located in the southern area of the theatre	X			X
GREAT TEMPLE	PIPELINES	PTR 14A	External layer of the lining mortar (th. 1 cm), collected from the well connected to the pipeline system	X	X	X	
GREAT TEMPLE	PIPELINES	PTR 14B	Coherent covering mortar layer underneath the PTR 14A	X	X	X	
GARDEN AND POOL COMPLEX	CISTERN	PTR 4	Very thick lining mortar (maximum th. 20 cm) collected from eastern area of the cistern	X			X
GARDEN AND POOL COMPLEX	RESERVOIR FLOOR	PTR 6	Covering mortar collected from the reservoir floor	X	X	X	
GARDEN AND POOL COMPLEX	CISTERN	PTR 8	Lining mortar (th. 1 cm), probably belonging to the ancient vault structure of the cistern	X	X	X	X
GARDEN AND POOL COMPLEX	CISTERN	PTR 10	Lining mortar with abundant coarse aggregate, collected from one of the lowest areas of the cistern wall	X	X	X	

th.=Thickness; PLM = Polarized Light Microscopy; XRPD = X-Ray Powder Diffraction; DTA-TGA = Differential and Gravimetric Thermal Analyses; SEM-EDX = Scanning Electron Microscopy- Energy Dispersive X-Ray spectroscopy underlined similarities and differences among mortars belonging to the two archaeological complexes.

Concerning the Great Temple structures (pipelines and cistern), the PLM observations showed textural and mineralogical differences among mortars collected from the cistern (PTR 2) and pipelines (PTR 13, PTR 14A and PTR 14B).

The PTR 2 sample, a cistern lining mortar, exhibits a binder with brownish-grey color and a non-homogeneous and anisotropic aspect of micritic and microsparitc areas; furthermore, it results compact without any fractures and with a medium porosity. The aggregate is well sorted, showing quite homogeneous dimensions with a range from 200 μm to 500 μm, mainly constituted by quartz grains with shapes varying from sub-angular to sub-rounded (Figure 3). The binder/aggregate ratio is estimated to be 1:3, ascribable to a slim mortar.

The PTR 13, PTR 14A and PTR 14B are lining mortars of pipelines. These samples are characterized by a binder similar to PTR2 (with a brownish-grey color and a non-homogeneous and anisotropic aspect, due to micritic and microsparitc areas) and by a medium-high porosity. The more evident difference respect to PTR 2 sample is the aggregate, which is very heterogeneous and very poorly sorted (ranging from 30 μm to 3.9 mm in PTR 13, and from 30-40 μm to 11-13 mm in PTR 14A and PTR 14B) and consists mainly of rounded/sub-rounded fragments of carbonate rocks (biomicritic and biosparitic limestone as shown in Figure 4a - PTR 14B sample) and of sandstone, and sub-angular crystals of quartz and rare chert (Figure 4b). It is interesting to underline also the presence of rare vegetable fibers (Figure 4c) and of lumps (Figure 4d), detected in the PTR 14B sample. The binder/aggregate ratio is difficult to determine due to the presence of very large clasts, so it may be approximately of 1:2, attributable to a fat mortar.

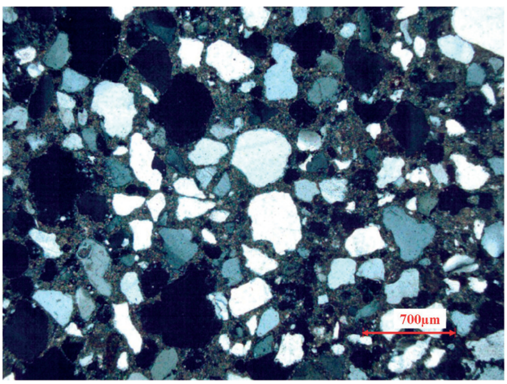

Figure 3. Optical micrograph of PTR 2 sample: scarce brown-greyish binder and quartzitic aggregate well sorted (xpl).

In the Garden and Pool Complex there are samples from different hydraulic structures (cisterns and reservoir floor). The PTR 6 sample, collected from the reservoir floor, shows, under PLM observations, a binder characterized by hues varying from greyish to yellowish-grey, and a non-homogeneous and anisotropic aspect of micritic areas. The aggregate is very poorly sorted (ranging from 30-40 μm to 8 mm), consisting mainly of sub-rounded fragments of carbonatic rocks (biosparite and biomicrite as shown in Figure 5a). Abundant fragments of sandstone and of others siliceous rocks (quartzite and rare chert) (Figure 5b) showing reaction rims (Figure 5c), crystals of quartz and rare volcanic rock fragments (Figure 5d), each of them with angular/sub-angular shape, were also identified. In addition the presence of rare vegetable fibers is detected (Figure 5d). The mortar is quite compact, with a medium-high porosity. In this case the binder/aggregate has 1:1 ratio (fat mortar).

The PTR 4, PTR 8 and PTR 10 samples, belonging to two different cisterns, exhibit a binder with non-homogeneous and anisotropic aspect of the micritic/microspatic areas, as all the other samples analysed, with a general brownish-

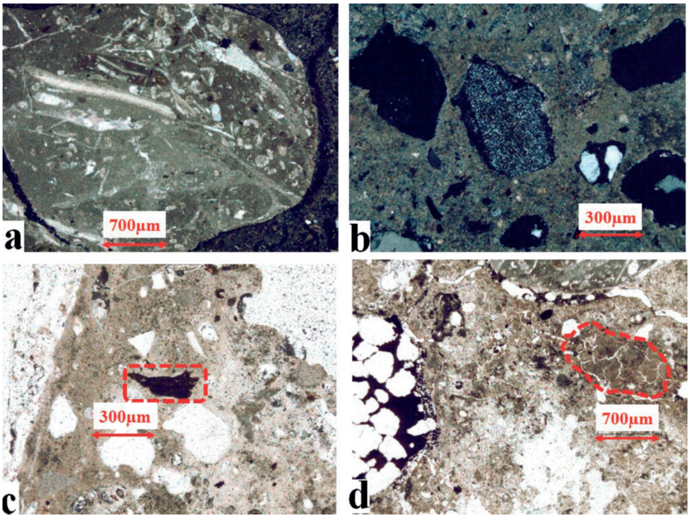

Figure 4. Optical micrographs of: a) PTR 14B (xpl): millimetric fragment of biomicritic limestone; b) PTR 14A: chert fragment (xpl); c) PTR 14B (ppl): vegetable fibers (dashed line); d) PTR 14B (ppl): lump (dashed line).

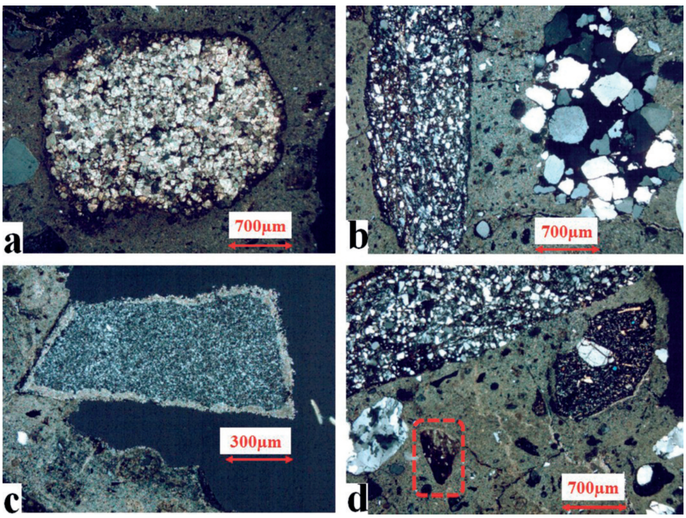

Figure 5. Optical micrographs of PTR 6 sample (xpl): a) biosparite fragment; b) siliceous rock fragments; c) chert fragment with reaction rim; d) on the right a volcanic rock fragment and on the left vegetable fibers (dashed line).

grey color. Generally, the aggregate shows the same composition of the PTR 6 sample, constituted principally by fragments of silicatic and carbonatic rocks, both types with shapes varying from sub-rounded to sub-angular (Figure 6a and 6b), nevertheless in these samples volcanic rock fragments and vegetable fibers are not observed. The clasts dimensions are various, showing a very poorly sorting, with a range between 40 μm and 4.2-4.3 mm in the PTR 8 and PTR 10 samples; 40 μm and 9 mm in the PTR 4 sample. The binder/aggregate ratio is difficult to determine and it may be approximated to 1:2 (fat mortar). Furthermore, PTR 4 sample shows the presence of lumps and quartz grains with reaction rims, the latter ones are evidenced in reflected light observation of the polished section (Figure 6e), while PTR 8 and PTR 10 are characterized by fractures and a widespread porosity presenting recrystallizations of minerals, showing high interference colors under crossed polars, likely identifiable as calcite (Figure 6c and 6d).

The PLM results are in agreement with the investigations published by Shaer (2004), which indicated an aggregate of the same morphology and petrographic composition in Nabataean mortars lining the walls of cisterns and dams in Petra and al-Bayda areas, highlighting a brownish color of the matrix and large-sized coarse aggregates in the form of limestone, sandstone and chert fragments. The author also observed the presence of charcoal and crushed bricks in the aggregate.

Besides the petrographic results above presented, optical analyses lead us to highlight a partial hydraulic nature of the mortars, as revealed by the presence of reaction rims concentrated near several quartz grains and chert fragments observed in several mortar specimens (Figure 5c).

The X-Ray Diffraction Analyses, performed on representative samples listed in Table 2, confirmed and integrated the PLM observations. Quartz is identified as the dominant mineralogical phase in the PTR 2 sample, which has mainly quartz as aggregate, and in the PTR 8

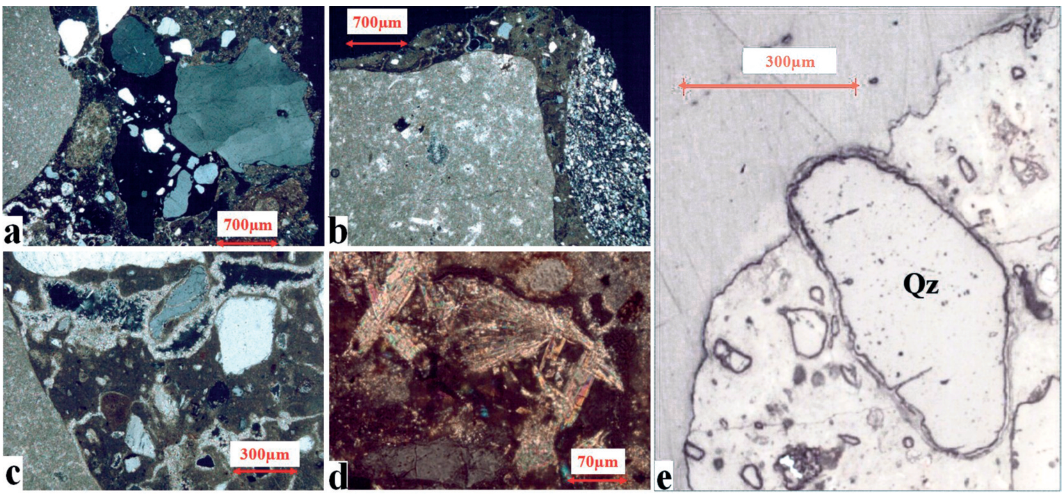

Figure 6. Optical micrographs (xpl): a) PTR 8: on the left fragment of a carbonate rock, in the centre fragment of siliceous sandstone; b) PTR 10: on the left fragment of carbonate rock and on the right fragment of siliceous rock; c) PTR 10: diffused precipitations in fractures and pores; d) PTR 8: needle-like crystals within a fracture; e) PTR4 (ppl): polished section showing a quartz grain with reaction rim.

Table 2. X-Ray Powder Diffraction data of PTR samples.

SAMPLE	CALCITE	GYPSUM	QUARTZ	HALITE	PHYLLOSILICATES
PTR 2	+	-	+++	traces	traces
PTR 14A	+++	+	++	+	+
PTR 14B	+++	+	++	++	traces
PTR 6	+++	-	+	-	traces
PTR8	++	-	+++	traces	traces
PTR 10	++	-	+++	-	+

+++ = dominant; ++ = abundant; + = present, traces; - = absent.

and PTR 10 samples, with an aggregate constituted principally by quartz and siliceous rocks. Calcite is the dominant mineralogical phase in PTR 14A, PTR 14B and PTR 6, which showed a predominant carbonatic aggregate under PLM observations. In addition, the presence of phyllosilicates is highlighted in all samples. Abundant halite is identified in PTR 14B, whereas PTR 2, PTR 8, PTR 14A show it in traces. Gypsum is present in samples PTR 14A and PTR 14B.

The data here obtained correspond to the experimental analyses performed on mortar samples, collected at the same monumental complexes, by Akasheh et al. (2005), who indicated a similar crystalline composition. The sodium chloride and gypsum identification is in agreement with the results obtained by analyses carried out in Petra and Beida area, which underlined that monumental tombs and geological outcrops in sandstones are characterized by salt crystallization (sodium chloride, potassium chloride and calcium sulphate) as one of the major weathering phenomena (Gabrielli et al., 2008; Franchi et al., 2009). Considering that Petra is 120 km far from the Red Sea and 150 km from the Dead Sea, where there is also the presence of salt pools, the most creditable hypothesis on NaCl origin found in the samples under investigation is attributed to sea-spray deposition (Al-Khashman, 2005).

The reaction and recrystallization areas, previously identified by PLM in PTR 8 and PTR 4 of the Garden and Pool complex, were subsequently investigated by Scanning Electron Microscopy coupled with the Energy Dispersive X-Ray Spectroscopy (SEM-EDX). The analysis of the PTR 8 sample showed the presence of needle-like crystals composed by a core of calcium and magnesium hydroxide/carbonate, surrounded by calcium and magnesium silicates and/or aluminates (Figure 7a, 7b and 7c). In addition in this sample tabular crystals, with a prevalent composition of O, Ca and C, were detected (Figure 8a and 8b). The shape and the composition detected allowed us to attribute these crystals to portlandite [$Ca(OH)_2$]; this result is further supported by the fact that PTR 8 was sampled in an ancient vault structure of cistern, which microclimatic condition, characterized by high percentages of relative humidity, could have inhibited the carbonation reaction (Moropoulou et al., 2005). In addition, EDX investigations revealed the presence of

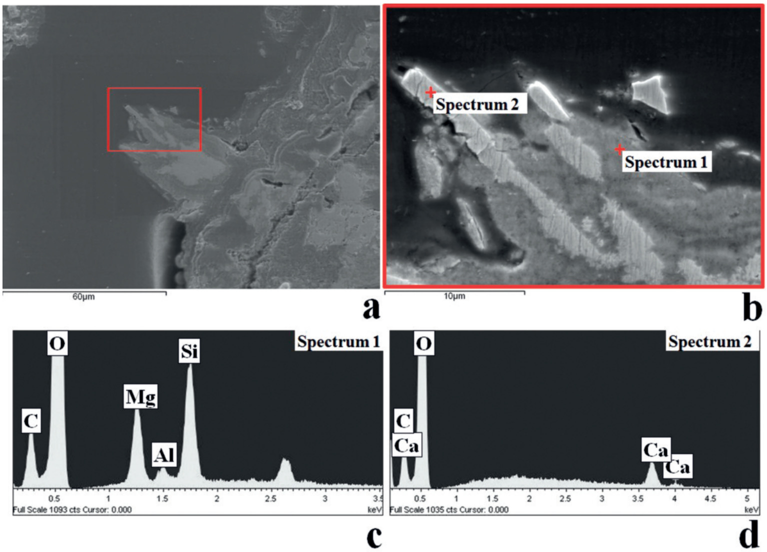

Figure 7. a) and b) PTR 8 SEM micrographs of needle-like crystals; c) EDX spectrum of the outer part of crystals; d) EDX spectrum of the crystals core.

halite in this sample, also clearly recognizable by the typical cubic shape, confirming the previous XRPD results.

Analyses on PTR 4 sample showed that the reaction rims, surrounding a quartz grain (Figure 9a), are mainly composed of Si, Ca and O, followed by Al and Mg, related to calcium and magnesium silicates and aluminates (Figure 9b, 9c and 9d). The data obtained highlight the typical reaction of hydraulicity between the silicatic clast and the carbonatic binder.

On the PTR 13 sample of the Great Temple, analyses on a quartz-sandstone fragment have been carried out. The EDX data on the matrix of the sandstone showed the presence of Fe, O, Si, Al, characteristic of a clayey matrix (kaolinite) of a sandstone, rich in iron oxides and/or hydroxides (Figure 10a, 10b and 10c).

It is important to underline that both PTR 4 and PTR 8 samples show the presence of magnesium in the reaction products; this observation lead to presume the use of a limestone, partially

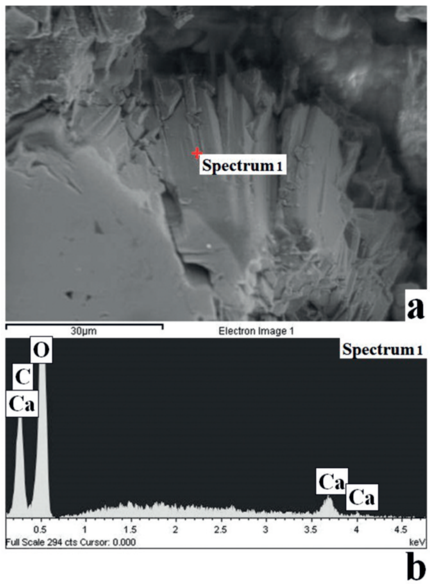

Figure 8. a) PTR 8 SEM micrograph of tabular crystals; the marker indicates the EDX analysis point; b) EDX spectrum of the spot analysis.

containing dolomite, as raw material for the binder production.

Thermal Analyses DTA-TGA detected phenomena of loss of hygroscopic water, carbonates decomposition, α→β phase transition of quartz and the presence of gypsum and clay minerals (Figure11).

The structural bound water (SBW) values, representing the weight loss percentage of H_2O due to dehydration of calcium silicates and aluminates hydrates and occurring between approximately 200 °C and 600 °C, as well as the weight loss percentage associated to CO_2 production related to calcite decomposition are represented in Table 3. As it can be noticed (Table 3), the weight loss of CO_2, due to calcite

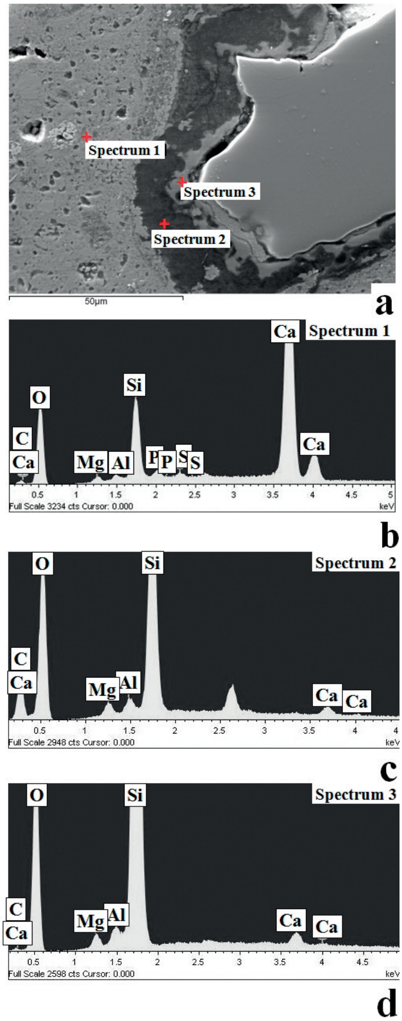

Figure 9. a) PTR 4 SEM micrograph of a quartz crystals which exhibited a reaction rim, characterized by different grey hues; the markers show the EDX analysis points; b), c) and d) EDX spectra of the spot analyses.

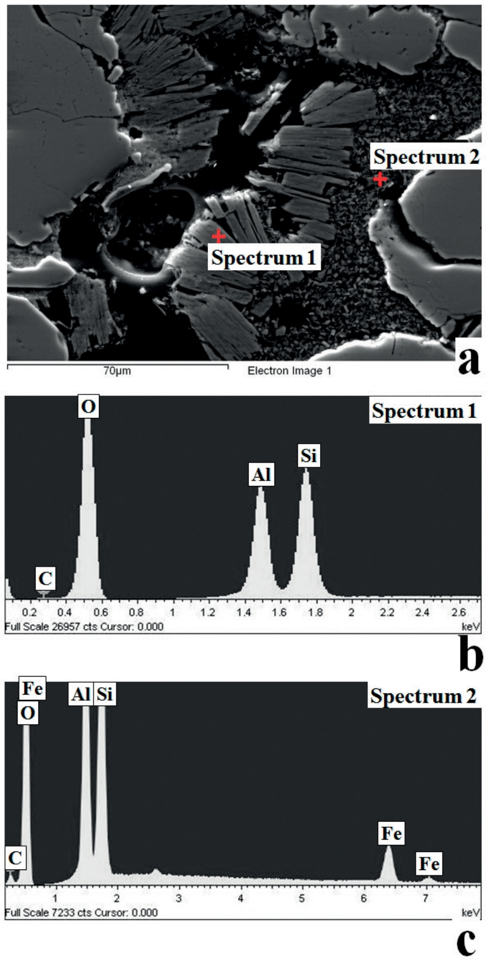

Figure 10. a) PTR 13 SEM micrograph of a sandstone fragment; the markers indicate the EDX analysis points b) and c) EDX spectra of the spot analyses.

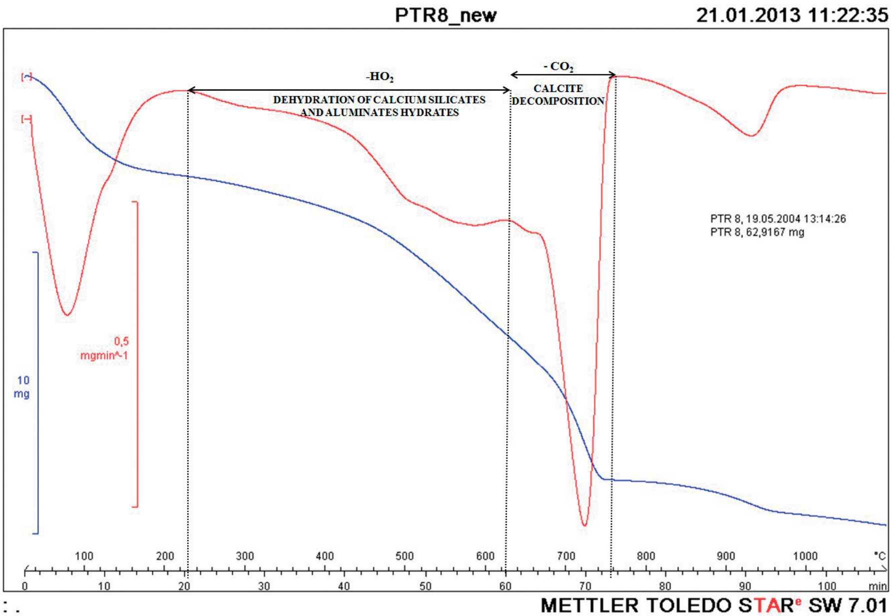

Figure 11. DTA-TGA spectrum of PTR8 sample: dehydration of calcium silicates and aluminates hydrates and calcite decomposition are highlighted.

Table 3. Summarizing table of DTA/DTG analyses. (SBW = Structural Bound Water).

SAMPLE	SBW	CO_2	CO_2/SBW
PTR 2	2.09%	6.29%	3.01
T range (°C)	233-590	590-754	
PTR 6	4.85%	17.55%	3.62
T range (°C)	200-602	690-818	
PTR 8	7.29%	8.21%	1.13
T range (°C)	231-591	631-764	
PTR 10	3.80%	13.70%	3.61
T range (°C)	200-601	685-820	
PTR 14A	8.47%	11.33%	1.34
T range (°C)	190-591	667-824	
PTR 14B	9.98%	8.21%	0.82
T range (°C)	188-577	667-783	

decomposition, starts in a range from 590 °C to 690°C, lower than the usual carbonates decomposition which generally starts at about 800-850°C. It has to be taken into account that in PTR 2, PTR 8, PTR 14A and PTR 14B samples, this shift to lower temperatures could be also due to the presence of halite, detected with XRPD and SEM-EDX analysis, which may influence the temperature onset of the decarbonation reaction.

Using the data obtained by DTA-TGA the CO_2/SBW ratio was calculated, showing the inverse of hydraulicity level. Binary diagrams of CO_2/SBW vs. CO_2 (%), shown in Figure 12, allowed us to classify the mortars on the basis of their hydraulicity (Moropoulou et al., 1995, 2003, 2005 and Cantisani et al., 2002).

According to this classification, the mortars can be defined as high hydraulic lime mortars, except for PTR 6 which is a hydraulic lime mortar. Observing Table 3, it can be argued that the CO_2 percentages are slightly lower compared to the data of hydraulic mortars (natural pozzolanic/cementitious) reported by Moropoulou et al. (1995, 2003, 2005). These values may be explained considering the mortars function and environmental conditions to which these materials were exposed. Indeed they were applied in the water management system, as previously written, in order to collect rainwater for the hydro-supply and to prevent flooding, mitigating the effects of monument degradation produced by rainwater runoff (Franchi et al., 2009). The presence of water, together with the lack of maintenance for a long time, may determine the partial dissolution of calcite, explaining the high porosity and the partial carbonatic recrystallizations areas within pores, also previously identified by thin section observations.

Following the obtained results and the geology

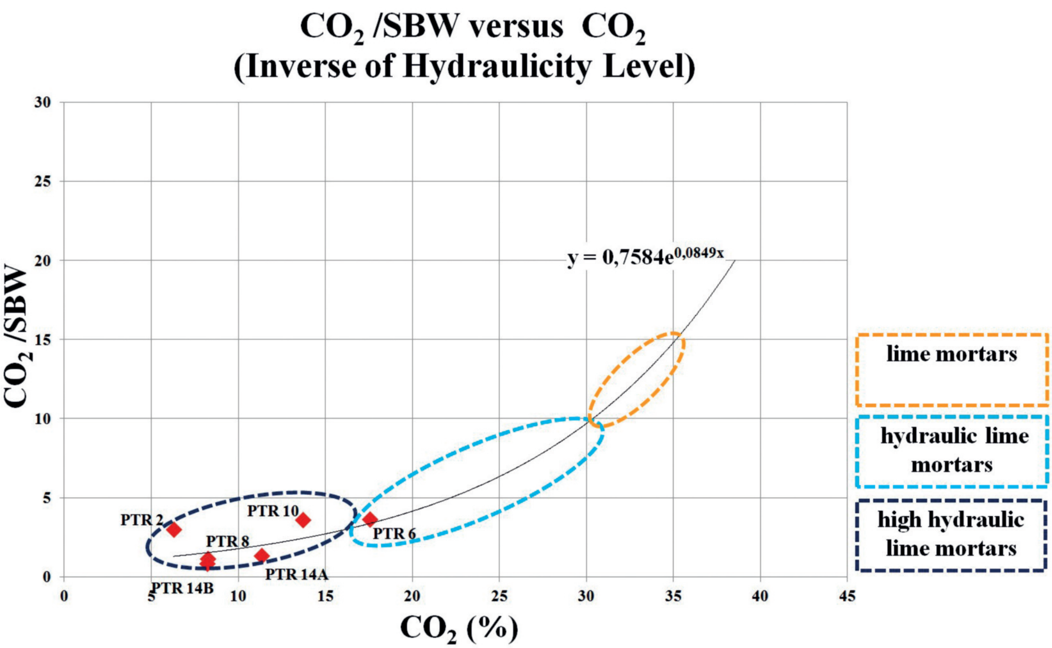

Figure 12. Binary diagram of CO_2/SBW vs. CO_2. (yellow dashed line: lime mortars; light blue dashed line: hydraulic lime mortars; dark blue dashed line: high-hydraulic lime mortars).

of the area (Geological Map of Jordan, Geological Survey of the Federal Republic of Germany, 1974), hypothesis on the provenance of the raw materials employed in the production of the studied mortars can be drawn. It is known that almost all of the stone monuments in Petra were entirely hand-carved from sandstones belonging to the *Umm Ishrin* and *Disi* formations, and there is also evidence that these stones had been quarried for being used as blocks in masonries or other building structure (Shaer and Aslan, 2000; Franchi et al., 2009). *Umm Ishrin* and *Disi* formations are mostly composed of quartz (in percentage as high as 80%), with a matrix formed by kaolinite, iron oxides and hydroxides as hematite and goethite, and subordinate calcite (Abu-Jaber et al., 2007; Franchi et al., 2009). These features are in agreement with EDX analysis carried out on the matrix of a sandstone fragment, within the PTR 13 sample (Figure 10), where the chemical analysis confirmed a kaolinitic matrix with iron oxides. In addition, within the geological succession, other outcrops are present, which are formed by: limestones characterized by siliceous levels as *Amman Silicified Limestone* Formation, besides *Wadi Umm Ghudran* Formation (with sequences of carbonatic rocks going upwards to thin siliceous levels and to more thick levels of sandstones, limestones and dolomitic limestones), marls and marly-limestones also characterized by peculiar gypsum fills as *Muwaqqar Chalk Marl* and *Umm Rijam Chert Limestone* Formations (Franchi and Raffaelli, 2007).

Therefore on the basis of the results achieved in this work and the geological formations present in the studied area, it is plausible to formulate the hypothesis that fragments of sandstone, calcareous rocks and chert were used to realize the aggregate, while dolomitic/chert/marly limestones were probably burned for the binder production (Cantisani et al., 2002). On the basis of the shape of the clasts constituting the aggregate, it may be argued that sandstones and siliceous stone and quartz grains, which showed sub-angular contours, derive from rock grinding, while calcareous stones, exhibiting mainly rounded and sub-rounded forms, may be attributable to the use of loose sediments. Sporadically it has been detected sub-angular shapes even for carbonatic rocks, letting us assume a rock grinding origin or material reuse. Further specific investigations, such as additional microchemical analyses (SEM-EDX) on the mortars binder, are undoubtedly necessary to exactly define the typology of raw materials used to realize them. The high level of hydraulicity shown by all the mortar samples of the hydraulic structures (see the binary diagram CO_2/SBW vs. CO_2 in Figure 12), could be ascribed to the addition of a silicatic aggregate (as chert or silicatic rock fragments) to air hardening or magnesium lime, or to the burning of marly/chert limestone.

Conclusions

In this study mortar samples from pipelines, cisterns and a reservoir of the Great Temple and the Garden and Pool Complex in Petra have been collected and analyzed, with the objective to:

- characterize the mortars lining the structures by the mineralogical and petrographic point of view;
- identify the raw materials employed;
- achieve a better understanding of the materials used for conferring hydraulic properties.

Characterization highlights similarities and differences among the samples, depending on their belonging complex and structures (cisterns, pipelines and reservoir). The majority shows a very poorly sorted aggregate consisting in fragments of carbonate rocks and sandstone, quartz crystals and rare chert. In specimens from both complexes, the presence of rare lumps and vegetable fibers was also observed. Analyzing the shapes of the aggregate clasts, it may be supposed that sandstone, silicatic rocks fragments and quartz grains derive from a grinding process of the raw materials, while the carbonate fragments could be mainly due to the employment of loose sediments.

The most relevant characteristic detected in all samples is the evident hydraulicity of these mortars, as shown by the reaction rims, formed by calcium and magnesium silicates and/or aluminates, concentrated near several chert fragments, and around quartz grains. Furthermore, this property is supported by DTA-TGA investigations, allowing us to classify samples as high hydraulic lime mortars, except for PTR 6 which is classifiable as hydraulic lime mortar.

Analyses lead also to the identification of deterioration phenomena such as the partial dissolution of calcite probably due to flooding and rainwater runoff effect and salt crystallization because of sea spray deposition (halite and gypsum).

On the basis of the results achieved, we may suppose that the hydraulicity of the studied mortars is due to an aware selection, preparation and mixing of the raw materials supplied by the geological features of the local area surrounding the archeological site. Therefore, it is plausible to state that the aggregate is constituted by sandstones coming from the *Umm Ishrin* and *Disi* Formations and by carbonatic rocks probably belonging to the *Amman Silicified Limestone* and *Wadi Umm Ghudran* Formations; in addition from the siliceous layers of these two latter formations, hydraulic materials (i.e. chert) may have been quarried.

Finally the hypothesis on the raw materials used for the binder production, can be drawn: dolomitic limestone or chert limestone of the *Wadi Umm Ghudran* Formation or marls and marly-limestones from *Muwaqqar Chalk Marl* or *Umm Rijam Chert Limestone* Formations may have been likely employed.

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