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DAMAGE ASSESSMENT OF THE ROMAN NYMPHAEUM IN AMMAN, JORDAN: AN ANALYTICAL AND DIAGNOSTIC STUDY

Mohammed EL KHALILI*

Department of Conservation Science, Queen Rania's Faculty for Tourism and Heritage, Hashemite University, Jordan

Abstract

This research aims to assess the deterioration conditions and their causes that affected the Roman Nymphaeum in Amman. The monument was built over a cave with running spring water. Thus, the damp condition started from the beginning and generated different problems such as the weakness of the foundation, raising damp and the subsequent salt crystallization, erosion and micro-organism growth. The other major problem of the monument is its current location within the modern urban environment of today's city of Amman with high concentration of air pollution, vibration, and necessary urban infrastructural changes such as the installing of a sewage system that goes under the structure and the main streets around the building. Several deterioration features can be identified in the Nymphaeum including stone weathering, rising damp, efflorescence, sub-florescence, erosion, staining, crumbling, chipping, cracking, detachment, and flaking. To determine the deterioration factors in the monument, scientific techniques of analysis and examination were used such as XRD and SEM attached with EDX and it was concluded that this monument is suffering from severe deterioration and damage. As a result this study can provide the basis for establishing a comprehensive conservation plan for saving the monument within a context of a larger urban plan to give it a better role to be defined for the future, especially for tourism purposes.

Keywords: *Roman Nymphaeum; Architectural damage; Physical deterioration; Chemical degradation; Salt damage; Biological growth; Air pollution; XRD; SEM, EDX.*

Introduction

Archaeological sites in any place in the world tend to suffer from different kinds of deteriorations. Some of them are in high levels of risk and others are more stable by the fact that deterioration agents are minimized. Regardless of the importance of the building materials of such monuments as a reason for the levels of their vulnerability, environment and context are key elements for defining the degree of deterioration. Just like any other site in the world and specifically in Jordan, the Roman Nymphaeum in Amman is suffering from complex causes of deterioration due to its hazardous location in a naturally-damp environment and later on, because of the other major effects of the urban development of the city.

This research reveals the real problems of the monument and will contribute to any future and serious conservation plans that maybe undertaken. The approach taken in this research is to study the deterioration conditions and causes affecting the Nymphaeum through a literature review regarding the history of the site, and a field survey with the aim to understand the architectural elements, materials, construction techniques, significance of the monument, and identify and classify the deterioration conditions and their causes.

* Corresponding author: mohd_elkhalili@yahoo.com

The Nymphaeum was one of the main and biggest monumental buildings in the Roman city of Philadelphia [1], currently Amman, the modern capital of Jordan. It is located in the lower part of the city which follows a typical Roman plan with two colonnaded streets along its major valley. The Nymphaeum was built over a cave or grotto with a running water source sacred to the nymphs. The smaller stream runs below the monument before flowing into the Amman downtown stream. At present, the building is located in the Amman downtown near Al Hussieni Mosque.

In 1904 Butler discovered the site; it was in ruins but with several architectural elements still standing [2]. The general plan of the Nymphaeum is half-octagonal with a symmetrical design and is divided in two parts. The lower part includes the foundation and the barrel vaults, while the upper part is the main façade of the building and its back. The structure was built over a cave with a running water source and on an area sloping down to the southwest. A series of vaults were built to enable the water to pass underneath without causing any destruction. These vaults served also as a passageway to reach the stream.

Above the arches is a set of niches, each measuring 1.25m in width and rising about 2.10m high to the level of the platform of the colonnade. Eleven niches were set above the arches. The upper part is a half-octagon of large proportions, but the remaining part is the central section of the structure with a restored length of 68m and consists of three large semi-domed apsidal recesses (Apses). Each of these apses is supported by two square buttresses, which project from the corners of the apses with a height of around 12m.

From the available architectural features it can be seen that each is flanked by two tiers of shell niches, four in each tier. The width of each small niche is 1.25m which must have originally housed the statues. There were a number of columns in front of the apses approximately 10m high and corresponded closely to the height of the large apses in the first story [3, 4].

The roof of the entire upper portion of the building had disappeared prior to the earthquake of AD 747, except for the northern apse, which is still partly in situ. The northern apse shows that the apses were terminated in semi-domes, which probably collapsed in the earthquakes of AD 631, 641 or 659 and the stones were removed [5-7]. In general, limestone is the main building material used for the construction of the Nymphaeum. Two types of lime mortars were used as binding material for the limestone blocks or masonry. The first was used to bond the stone blocks (masonry), where the second mortar was used to bind the agglomerate or Roman concrete to fill between the walls.

Experimental

Sampling

Table 1 describes the limestone samples collected from different locations in the site for the mineralogical analysis and microscopic investigations.

Analytical Techniques

XRD

Two groups of nine limestone samples were crushed and milled in the agate mortar in order to avoid contamination. The powder of the samples was analyzed to determine their chemical and mineralogical composition by using XRD technique which is available at the Faculty of Archaeology, Yarmouk University Laboratories. Powder diffraction patterns were obtained by using a XRD-6000 SHIMADZU X-Ray Diffractometer under the following conditions: CuKα radiation (1.5418Å) with 30KV, 30mA energy and graphite Monochrometer.

SEM-EDX

Three limestone samples were coated by platinum using sputter coater (platinum target, Emitech, K550X, England). Coated samples were analyzed to study the morphological feature and the chemical characterization of the samples by using SEM (FEI, FEG (Scottky field emission gun), FP 2031/12, inspect F50, Endhoven, Netherlands), equipped with EDX (Bruker Micro analysis Gmbtt 12489 Berlin, Germany, X flash detector 410-M) located at the Faculty of Science, Yarmouk University Laboratories.

Table 1. Describes the limestone samples collected from different locations in the monument for the mineralogical analysis and microscopic investigations**.**

Sample	Altitude	Description	Sample Size
1A	The sample was taken western edge of the main niche; its high from the ground level is 2.5 m.	Gray hard layer cover large area of the niche.	Cubic 4×5cm
2A	The sample was taken from the center of the main niches of the monuments; its high from the ground is 3.00m.	Gray hard layer cover large area of the niche.	Cubic 4×5cm
3A	The sample was taken from eastern edge of the main niche; its high from ground is 3.00m	Mixture of brown and gray color, its hardness is medium.	Chunk about 4cm
4A	The sample was taken from the sheltered area of the main vault of the building. Its high from the ground is 2.70m.	Mixture of white and gray color, its hardness is medium.	Chunk about 3cm
1A	The sample was taken western edge of the main niche; its high from the ground level is 2.5 m.	Gray hard layer cover large area of the niche.	Chunk about 4cm
2A	The sample was taken from the center of the main niches of the monuments; its high from the ground is 3.00m.	Gray hard layer cover large area of the niche.	Chunk about 3cm
3A	The sample was taken from eastern edge of the main niche; its high from ground is 3.00m	Mixture of brown and gray color, its hardness is medium.	Chunk about 2cm
4A	The sample was taken from the sheltered area of the main vault of the building. Its high from the ground is 2.70m.	Mixture of white and gray color, its hardness is medium.	Cubic 4×5cm
5B	The sample was taken from the western parts of the building (close to the street). Its high from the ground is 1.50m.	Soft gray to white color cover parts of stone surface.	Cubic 4×5cm
6B	The sample was taken from the curve of western wall in the middle of tow vaults. Its high from the ground is 3.00m.	Soft white layer contaminated with gray particles, cover large area of stones.	Chunk about 3cm
7B	The sample was taken from the external left part of middle vaults. Its high from the ground is 3.20m.	Hard gray layer cover the stone surface and changed the stone color.	Chunk about 4cm
8B	The sample was taken from the eastern wall of the building. Its high from the ground is 2.50m.	Soft gray films cover the stones surface.	Chunk about 4cm
9B	The sample was taken from the eastern wall of the building. Its high from the ground is 1.30m.	Powder gray to black layer distributed on the stone surface.	Chunk about 2cm
10B	The sample was taken from the eastern wall of the building. It's high from the ground 2.0m.	Hard gray film wraps the stone surface.	Chunk about 3cm

Results

XRD results

The results of XRD analysis are listed in Table 2, and the X-Ray diffraction spectra for representative samples are shown in Figures 1 and 2.

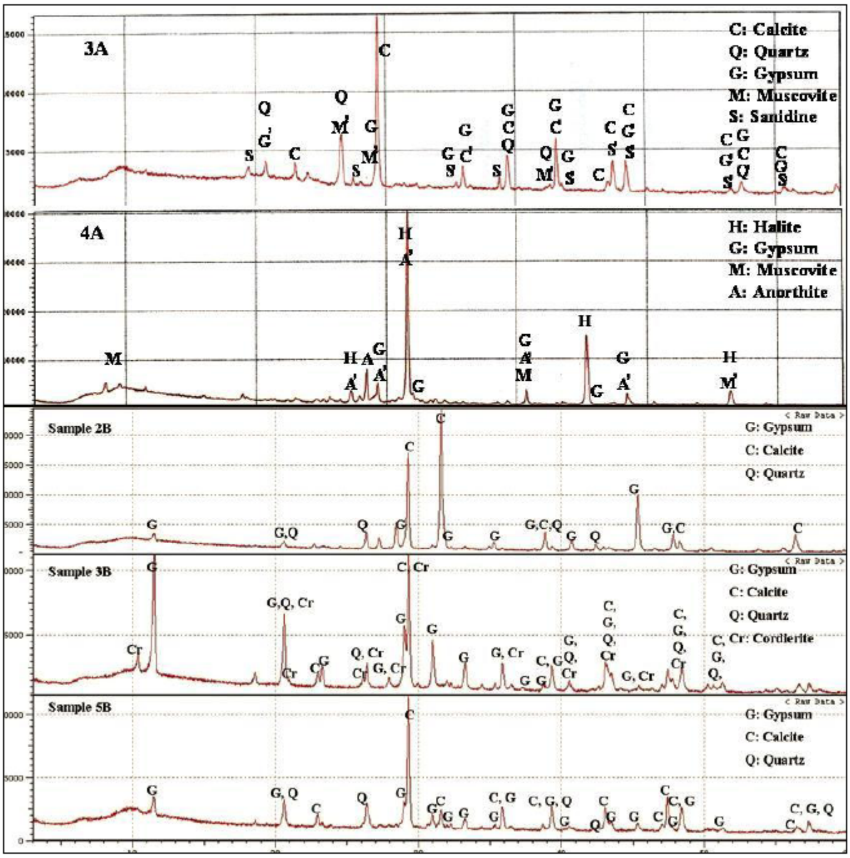

Fig. 1. XRD spectra for powder to medium hard samples for (3A, 4A, 2B, 3B and 5B).

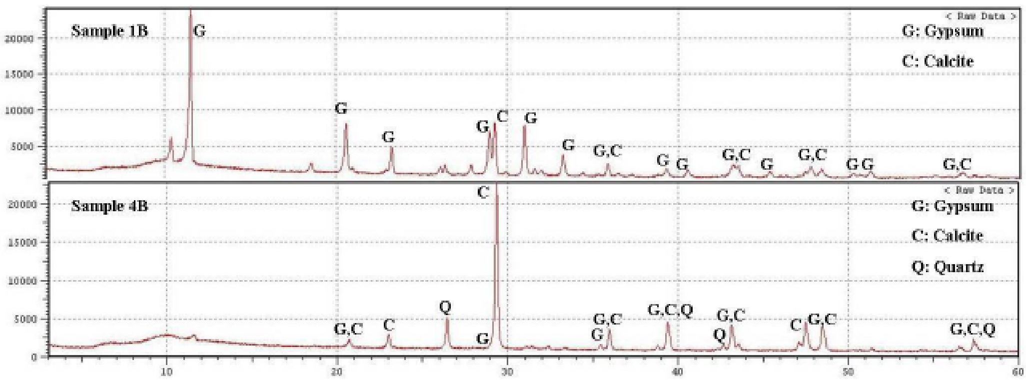

Fig. 2. XRD spectra for hard crust sample (1B and 4B)

Four samples (7B, 8B, 9B and 10B) of 18 samples were analyzed by X-ray diffraction and showed the essential minerals of limestone such as calcite ($CaCO_3$) and traces of quartz (SiO_2). The other resulted data from the X-ray diffraction was divided into two groups according to the description and deterioration state of the samples.

Table 2. The results of XRD mineralogical analysis of limestone samples

Sample	Major Card no.	Mineral Name	Chem. Comp.	Minor Card no.	Mineral Name	Chem. Comp.
1B	21-0816	Gypsum	$CaSO_4 \cdot 2H_2O$	5-0586	Calcite	$CaCO_3$
2B,4B, 5B	47-1743	Calcite	$CaCO_3$	46-1045	Quartz	SiO_2
				33-0311	Gypsum	$CaSO_4 \cdot 2H_2O$
3B	47-1743	Calcite	$CaCO_3$	43-0596	Quartz	SiO_2
				33-0311	Gypsum	$CaSO_4 \cdot 2H_2O$
				12-0303	Cordierite	$Mg_2Al_4Si_5O_{18}$
7B, 8B, 9B, 10B	47-1743	Calcite	$CaCO_3$	46-1045	Quartz	SiO_2
1A, 2A, 6A ,8A, 9A.	5-0586	Calcite	$CaCO_3$	46-1045	Quartz	SiO_2
3A	5-0586	Calcite	$CaCO_3$	33-0311	Gypsum	$CaSO_4 \cdot 2H_2O$
				46-1045	Quartz	SiO_2
4A	5-0628	Halite	NaCl	33-0311	Gypsum	$CaSO_4 \cdot 2H_2O$
				7-0025	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$
				19-1227	Sanidine	$(K,Na)(Si_3Al)O_8$
				33-0311	Gypsum	$CaSO_4 \cdot 2H_2O$
				7-0025	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$
				18-1202	Anorthite	$(Ca,Na)(Si, Al)_4O_8$
5A	5-0586	Calcite	$CaCO_3$	46-1045	Quartz	SiO_2
				25-0201	Augite	$Ca(Fe,Mg)Si_2O_6$
7A	5-0586	Calcite	$CaCO_3$	25-0649	Muscovite	$(K,Ca,Na)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2$
				43-0688	Beidellite	$Na_{0.3}Al_2(Si,Al)_4O_{10}(OH)_2 \cdot 2H_2O$
				29-1493	Talc	$Mg_3Si_4O_{10}(OH)_2$
				18-1202	Anorthite	$(Ca,Na)(Si, Al)_4O_8$

The first group is the samples that are characterized by low hardness from dusty powder deposits to medium hard crusts and their color range from white to gray. This group consists of seven samples (3A, 4A, 5A, 7A, 2B, 3B and 5B), and contain Calcite ($CaCO_3$) as a major mineral. This is "except the sample 4A contains the Halite (NaCl) with traces of other minerals such as gypsum ($CaSO_4 \cdot 2H_2O$), quartz (SiO_2), cordierite ($Mg_2Al_4Si_5O_{18}$), muscovite ($KAl_2Si_3AlO_{10}(OH)_2$), sanidine $(K,Na)(Si_3Al)O_8$), anorthite $(Ca,Na)(Si,Al)_4O_8$), beidellite ($Na_{0.3}Al_2(Si,Al)_4O_{10}(OH)_2 \cdot 2H_2O$), and talc ($Mg_3Si_4O_{10}(OH)_2$), as shown in Figures 1 and 2.

The second group is the samples that are characterized by high hardness of crust layers and their color ranges from gray to dark, and this group of consists of seven samples (1A, 2A, 6A, 8A, 9A, 1B, and 4B), which contain calcite($CaCO_3$) as a major mineral. This is "except the sample 1B contains gypsum ($CaSO_4 \cdot 2H_2O$) as major mineral with traces of other minerals such as quartz (SiO_2) and gypsum ($CaSO_4 \cdot 2H_2O$), as shown in Figure 2.

SEM-EDX results

Three samples of limestone were selected according to the result of XRD analysis. The first sample is hard crust gypsum covered with sooty films collected from the sheltered area of the building represented by the sample (4B). The second sample is soft white layer contaminated with gray particles represented by sample (6B); this sample was not analyzed by XRD test. The third sample is a hard gray layer covers the stone surface, collected from the external part of the building which contain simply calcite and quartz according to XRD and represented by sample (7B).

All of these samples (4B, 6B, and 7B) were prepared and coated with platinum to study the morphological feature by using a scanning electron microscope. Two samples (4B and 7B) were analyzed to study the chemical characterization by using energy-dispersive X-ray spectroscopy (EDX) in the laboratory of the Faculty of Science at the University of Jordan, the results of chemical characterization are shown in Table 3 and Figure 3, and the morphological features are shown in Figure 4.

Table 3. The analytical results of the sample 4B and 7B by EDX.

Sample no.	Analytical results			
	S	Ca	C	O
4B	--	--	26.74	73.26
7B	12.87	24.33	--	62.80

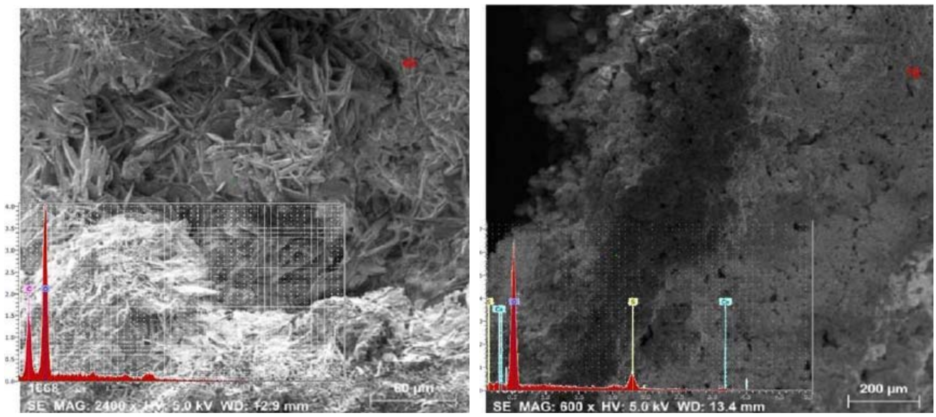

Fig. 3. Chemical characterization of sample (4B) By SEM with EDX

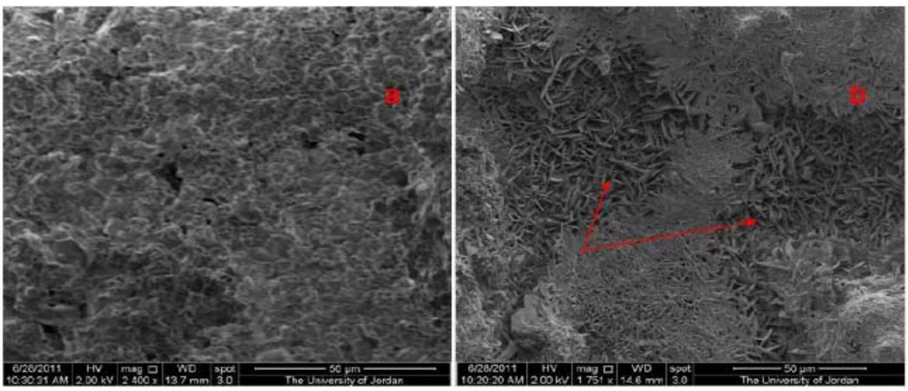

Fig. 4. SEM micrographs of sample (4B) a) showing the accumulation of Gypsum with calcite. B) Showing the needle like shape (gypsum) on the surface of the stone.

The chemical characterization of sample (4B) as in Table 3 shows the presence of (26.74%) carbon and (73.26) oxygen. The presence of these elements indicates the formation of a layer of hydrocarbon that resulted from direct burning of organic materials. The sample (7B) shows the presence of sulphur (12.87%), calcium (24.33%) and oxygen (62.80%). These elements give an indication on the formation of gypsum ($CaSO_4 \cdot 2H_2O$).

However the morphological features of three samples were characterized by SEM technique and can be discussed as follows:

a) The micrographs of sample (4B) show the growth of gypsum covered with hydrocarbon on it and the presence of undefined material mixed with it (Fig. 5).

b) The micrographs of sample (6B) show the halite (NaCl) crystals and sectional analysis illustrating the separation of halite layers during formation (Fig. 6).

c) The micrographs of sample (7B) show the presence of secondary calcite crystal ($CaCO_3$) and halite crystal (NaCl). The second micrograph for the same sample shows the presence of gypsum ($CaSO_4 \cdot 2H_2O$) (Fig. 7).

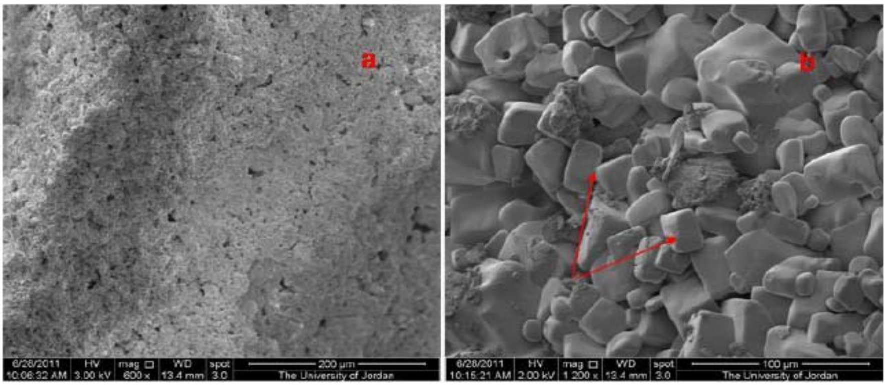

Fig. 5. SEM micrographs of sample (6B), a) show the surface of sample, b) showing the halite salt crystals.

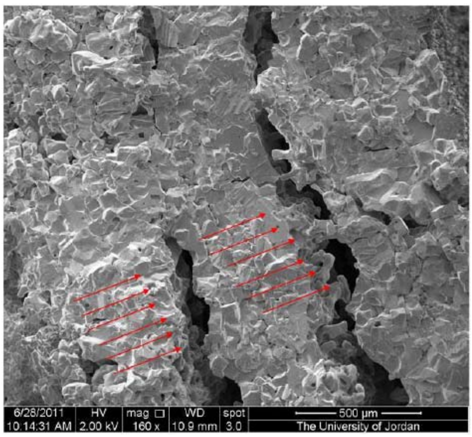

Fig. 6. SEM micrographs for sample (6B) showing the formation layers of Halite crystals.

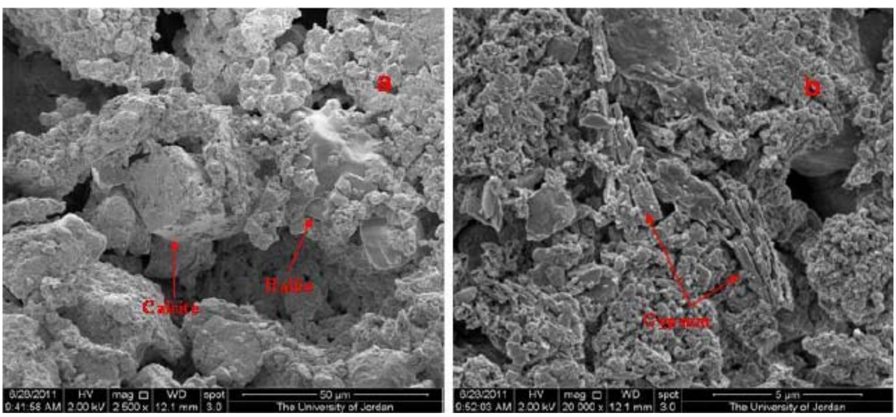

Fig. 7. SEM micrographs of samples (7B), a) showing traces of halite and calcite, b) showing the traces of gypsum.

On the other hand XRD results for dusty (powdered) deposits and medium hard crust show the presence of some minerals for igneous and metamorphic rocks such as augite, sanidine, cordierite, and anorthite, which may come from construction fields in Amman or from the sandy and dusty storms in specific time of the year. All of these minerals had deposits on the surface of the Nymphaeum limestone building material. These minerals accumulate on the surface of the stone and are incorporated, resulting in the dissolution process of acidic pollutants to form colored crusts on the surface of this stone, disfiguring the aesthetic appearance of the Nymphaeum structure.

The results of dusty samples also showed calcite, quartz and traces of gypsum. The dusty granular shape of calcite, quartz and gypsum may be the result of the granular disintegration of the stone itself by different mechanisms such as salt crystallization, salt hydration or wetting-drying cycle as mentioned by Clayton (1978) [8], Bradley and Middleton (1988) [9], Winkler (1994) [10], Abd El-Hady (1995) [11], Goudie et al (1997) [12] and Charola (2000) [13]. However these minerals are deposited on the surface from atmosphere and from the quarrying sites around Amman and other nearby construction activities. The calcite particulate may react with the sulphur dioxide to form aerosols of sulphate as discussed by Winkler (1994) [10]. In XRD spectra some traces of Beidellite and Talc are detected, which are the main constituents of clay mineral and all of it used in ceramics, pottery and cosmetic industries. These minerals point to the movements of the particulate and its deposition in the area.

Halite (NaCl) also presented in the XRD spectra, which originates from rock, soil and industrial activities as mentioned by Winkler, (1994) [10] and Elgohary (2008) [14]. Halite can be crystallized under the surface when the stone dries causing mechanical stresses. Such crystal form and grow from the pores and cracks, filling the void area, and expanding outwards into the space created by separation of the flake, as discussed by Fitzner et al (2002) [15] and El-Gohary (2010) [16]. The halite crystals presence also proved by the SEM micrograph of samples (6B and 7B). The micrographs of sample (6B) gives an indication of disruptive stress, causing stone damage by the formation of the salt layers as shown in Figure 7 that begins with forming crust layers of salt on the stone surface followed by another crystallized layer of salt in the restricted area between the stone and salt crust. This causes stress to delaminate the first one with traces of the stone surface which is combined with wetting drying cycle [17].

Discussion

According to the field observation, optical investigation, microscopic examination, chemical and mineralogical analysis of the limestone samples from the Nymphaeum, the deterioration features and their causes can be assessed and discussed as follows:

Building Material

Most of the Nymphaeum was built out of limestone. It is widely used in architectural applications for walls and decorative elements. It is less frequently used as a sculptural material, because of its porosity and softness; however, it is a common base material. It may be found in both bearing (structural) and veneer applications [18]. Limestone is subjected to several deterioration processes when exposed to water. The rate and symptoms of such processes are influenced by a number of variables, partly depending upon the properties of the material itself and upon several environmental factors, acting separately or in various combinations. As a consequence, the rate and symptoms of deterioration can vary within a wide range and direct relations of cause to effect and are not easy to define. The Nymphaeum, which is a part of the damped context, is subject to several processes and exposure to water that actually played a major role in the deterioration of the monument. It can be clearly identified from the field survey that capillary suction and rise, and soluble salts are the two major processes affecting the limestone building material of the Nymphaeum.

The Nymphaeum is sunk in water. Therefore, there is active suction force supported by the nature of the limestone and its porosity with little evaporation, making the level of capillary rise high in many parts of the structure. The height that water can actually reach in the structure is influenced mainly by the balance between the water intake and the evaporation from the wall surfaces. However, the structure is always waterlogged and with low evaporation and withthe capillary rising to reach the uppermost parts of the Nymphaeum.

In the long run, soluble salts also played an effective role in the capillary rise because they are accumulated in the masonry on the evaporation surfaces. Besides causing damage when they crystallize, salts attract water by osmosis and can determine a further rise of the water level. As accumulation of salt never stops, it is likely that a stable equilibrium is never reached; other conditions being equal, the height of the rise should increase with the age of the Nymphaeum walls [19, 20].

Deterioration factors, conditions and mechanisms

Weathering may have a degrading effect on the appearance and structural soundness of the Nymphaeum limestone. Factors include rain, snow, temperature, wind and atmospheric pollutants. Generally, these factors act in combination with one another or with other agents of deterioration (Fig. 8).

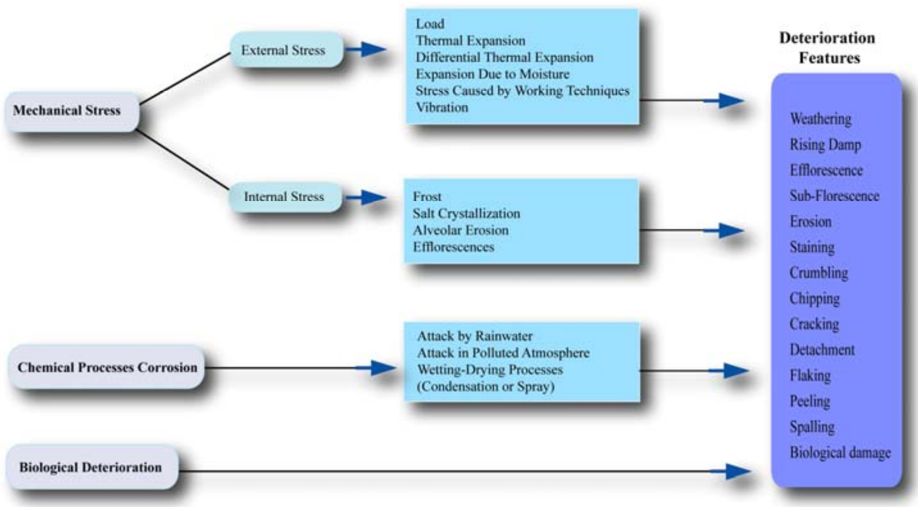

Fig. 8. Types of identified deterioration features at the Roman Nymphaeum in Amman

It was observed that rainwater, especially in combination with atmospheric gases resulted in the dissolution of the Nymphaeum limestone, and creating higher levels of salt movements within the stone structure. Also it was noticed that the temperature affected the rates of deterioration and—in larger stones– movement of the pieces, as well as patterns of salt migration within the stone. Most of the natural or inherent problems occurred to the Nymphaeum limestone are by moisture and wind erosion. However, the deterioration conditions within the Nymphaeum include weathering, rising damp, efflorescence, sub-florescence, erosion, staining, crumbling, chipping, cracking, flaking, and spelling. These cause general weakness and destruction to the monument, in addition to creating vulnerable parts, which are defined as critical parts of the structure, most of which are lost now (Figs. 9 and 10).

Fig. 9. Identification of the main deterioration causes and features at the Roman Nymphaeum in Amman: **a –** Weathering features in the lower part of the Nymphaeum, b – Rising Damp problem represented by the wet conditions of the stone, c – Efflorescence on the external parts of the Nymphaeum (right) and other features from the subterranean parts (left)

The most damaged parts of the monument are observed in the frontal facade of the Nymphaeum. Limestone blocks of the lower rear facade also suffered from many deterioration forms such as dissolution, hard crusts formation, salt crystallization and biological growth and contamination deposits.

There are several mechanisms that generate high stresses in the building materials of the Nymphaeum. In the structure some parts are subject to higher stresses than others. The design of the Nymphaeum was originally aimed to minimize the tension stresses and allow materials to work mainly under pressure and strain [21]. However, it is demonstrated that parts under particular stress deteriorate rapidly. In this regard, the distribution of load was disturbed by the demolishing of important parts of the structure, including the main pillars along with the apses. This disturbance generated unbalanced loads on the structure and resulted in the tensile stress for the whole monument (Fig. 11).

Fig. 10. Classification of deterioration causes and features at the Roman Nymphaeum in Amman:
a – erosion, b – staining, c – crumbling, d – chipping, e – cracking, f – detachment, g – flaking, h – peeling, i – biological damage.

On the other hand, Amman has intensive fluctuation in temperature and relative humidity, so the building materials in the city were subject to effective shrinkage and expansions that generated stress on the limestone and increased the micro and macro cracks in the Nymphaeum structure. The insertion of unsuitable materials especially within old stonework can generate huge tension for the structure by increasing the deterioration of the old materials.

The moisture within the Nymphaeum along with the capillary suction and rise increase the problem of the limestone saturation, and therefore, the expansion of the stone, creating cracks and gradual damage to the structure. Furthermore, vibration caused by traffic induces rapidly alternating tensile and compressive stresses in the Nymphaeum.

From the fact that limestone is a porous material, stresses can grow inside when crystals of ice or salt are formed inside the pores and become frost and salt crystallization as a result of water evaporation). In both cases the growing crystals exert a stress which is balanced by the resistance of the material to compression. Under the surface, a thin section of the material can be subject to a thrust from inside which is equivalent to a tensile stress pulling from outside, a situation that can easily cause the material to become brittle and can easily break [22].

Efflorescence is an extensive problem in the whole monument, where salt crystals formed on the surface of the limestone blocks. This phenomenon occurs when water evaporates and the water feed is huge or the wind speed is low. Therefore the salt crystals are formed mainly outside the pores and the crusts of salt formed [23].

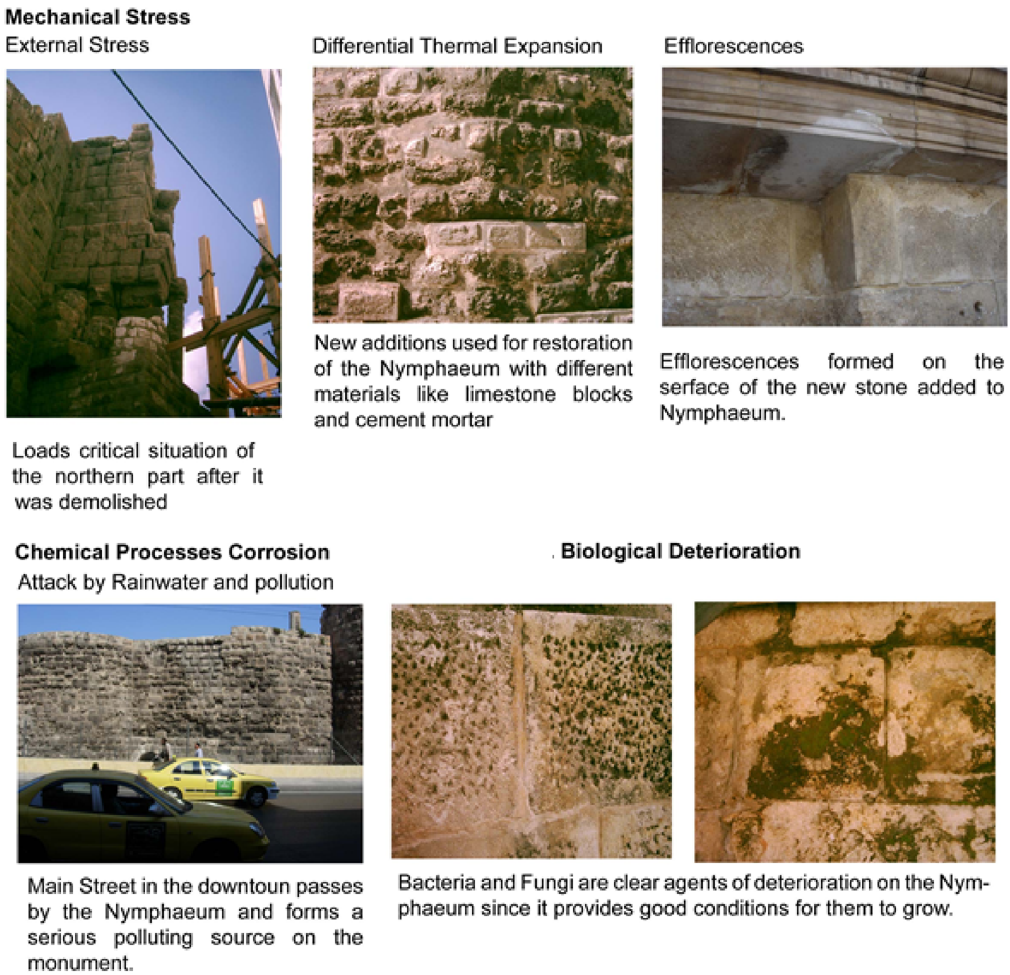

Fig. 11. Further deterioration causes and features at the Roman Nymphaeum in Amman

The other building material affected and subjected to intensive decay due to the impact of deterioration factors is the lime mortar. Mortar loses its cohesion and can become fragile and decomposed due to a chemical reaction, acidic environment and wind erosion.

Restoration works of some parts of the Nymphaeum were carried out systematically to fill the cavities caused by *alveolar erosion* and other mentioned factors with cement mortar that is incompatible. As well, the role of evaporation in the process was overlooked and shifted to the surrounding surfaces of the original material which started deteriorating. Chemical reactions are always active in this building since the presence of water and high rates of air pollution persists. Several air pollution studies were conducted in Jordan by the Royal Scientific Society and the Ministry of Environment related to the measurement of different pollutants in Amman where two pollution readings were taken for the two indicators of SO_2 and NO_2 (Table 3). They show relatively low levels of SO_2 despite the "black spots" found to the south of the city, clearly influenced by the fixed industrial sources. They also show elevated levels of NO_2 at the city-center points, affected by traffic emissions [24].

In the first place, other pollutants besides sulphur dioxide are always present, and some of these can cause the formation of other acids (hydrochloric acid, nitric acid, hydrofluoric acid) which also exert a corrosive action to the monument [25]. The deterioration by biological agents is widely spread because of the damp environment of the Nymphaeum which is a suitable environment for the growth of different kinds of micro-organisms, such as fungi, algae and lichens. Therefore strains of bacteria draw the energy necessary for taking away vital activities from inorganic chemical reactions of reduction or oxidation which have the ability to produce acidic reactions. Such reactions can result in the formation of both strong and weak acids which can corrode building materials that are sensitive to acids. Moreover, the formed patina from micro-organism colonies on the surface of the Nymphaeum attracts all kinds of pollutants, droplets, and dust (Fig. 10) [26].

However, starting from 1970s the situation of the monument became more dangerous when the Amman Municipality decided to lay down a sewage system for the modern city of Amman. The idea of the planner was to take advantage of the natural course of the ancient dried small streams that passed through the monument and the river that passed behind it, exploiting the natural slope for the drainage system. This system consists in creating non-waterproof canal and just covering it by reinforced concrete and where in the past, the two streams intersected behind the edge of the Nymphaeum, now it is a junction point of the two main canal of the sewage, creating a big well of black water before it runs again into the main canal. Consequently the Nymphaeum became once more in a waterlogged environment, but this time with polluted water.

Therefore this is considered a major problem related to the hydrological phenomenon that may affect soil subsidence as stated by a 2005 Jordan's Ministry of Water and Irrigation report where the characteristics of waste water in Jordan are different from other countries. Hence, the average salinity of municipal water supply is 580 parts per million (ppm) of the Total Dissolved Solids [TDS]) and the average domestic water consumption is low (around 70 liter/capita/day country-wide) resulting in high organic loads and above normal salinity levels in wastewater [27]. This new situation represents dangerous causes of decay affecting the weak structure and weathered surfaces.

Conclusions

The critical context for the building could be identified as an aquatic environment defined by the underground springs and the water streams upon which the Nymphaeum was constructed on. Therefore the structure suffered from different damages especially salt crystallization, contamination and rapid weathering process that set the Nymphaeum and whose situation became critical.

Mineralogical analysis characterized the Nymphaeum limestone by hardness of the crust layer and its color range from gray to dark, and this group consists of seven samples (1A, 2A, 6A, 8A, 9A, 1B, and 4B), which are composed of calcite ($CaCO_3$) as a major mineral except the sample 1B that contains gypsum ($CaSO_4 \cdot 2H_2O$) as a major mineral with traces of other minerals such as quartz (SiO_2) and gypsum ($CaSO_4 \cdot 2H_2O$). In addition to that, EDX elemental analysis showed the presence of contamination of SO_2 and CO_2 that damaged the Nymphaeum limestone, physically and chemically. The SEM investigation showed the limestone as fragile material and less coherent in structure due to the effect of moisture and salt damage.

The deterioration features within the Nymphaeum include weathering, rising damp, efflorescence, sub-florescence, erosion, staining, crumbling, cracking, detachment and flaking. This causes general weakness and even destruction of the monument, in addition to creating vulnerable parts, which can be defined as critical parts of the structure, and which in any case most of them are lost now. Today, the Nymphaeum continues to suffer the same problems. Thus, urgent intervention should consider preventive and curative measures of action. This can be achieved through a comprehensive conservation plan as part of a holistic urban plan for the city. Another cause of decay is the mechanical stress caused by the overloading of the structure from previous restoration works where usually, in Jordan, the practice was to embark on restoration without having a comprehensive conservation plan and with no scientific approach. Such works did not aim to reconstruct and replace the collapsed parts as in Anastyolosis but in many cases it became targeted to reshaping the building which caused overloading upon the fragile structure.

Finally, we should note that today a great project for the restoration and rehabilitation of the Nymphaeum is being carried out by a scientific consortium from The University of Jordan and The Hashemite University, funded by the USA Ambassador Fund for Preservation of Cultural Heritage in cooperation with the Department of Antiquities of Jordan. This project will solve many of the above-mentioned problems affecting this important monument from the Roman period in Jordan through a scientific and practical field works of investigation, chemical analysis and conservation treatments.

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