Mediterranean Archaeology and Archaeometry, Vol. 18, No 2, (2018), pp. 49-66
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DOI: 10.5281/zenodo.1297147

SALT DAMAGE AND ENVIRONMENTAL CONDITIONS: A THERMODYNAMIC APPROACH FROM THE NORTHERN ROMAN THEATER IN JERASH, JORDAN

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Received: 15/11/2017
Accepted: 04/05/2018
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ABSTRACT

The salt damage is one of the main decay features in archaeological sites and monuments. The Northern Theater of the Roman archaeological site of Jerash in Jordan is facing considerably this decay agent. The current study is a comprehensive evaluation of the main environmental conditions within the case study area with a detailed assessment of the soluble salt content at varied periods on the theater. The study extended to evaluate the relation between salts content and salt distribution with the main recorded environmental conditions. The current research fieldwork observation and data collection has shown that wind speed had a major role in salt crystallisation and distribution in porous building materials, and thereby in the ultimately stone decay rates. The study has also demonstrated the importance of using thermodynamic calculation in evaluation the salt distribution and behavior as major action in stating the preventive conservation measures in archaeological sites and monuments.

KEYWORDS: Jerash, Environmental Conditions, Salt Damage, The Northern Theatre, Temperature, Relative Humidity, Soluble salt content and Thermodynamic Approach

1. INTRODUCTION

The deterioration of porous building materials due to crystallisation of salts within their pore structure is a widespread weathering process and the main cause of decay of many archaeological sites, including the ancient city of Jerash. The relation between weathering and the presence of salt has been noted since antiquity (Herodotus 420 B.C., in Luquer 1895). Since the beginning of the last century, the salt damage process in porous materials has been given more attention by researchers and has attracted scholars from many different fields including geomorphology, geology, chemistry, conservation, environmental and materials sciences.

Generally, the main factors that cause salt damage in stone materials are well known (Winkler 1994). Generally, salt can originate from a wide range of sources. These sources have been categorised by a number of researchers such as Arnold and Zehnder (1991) and Price (1996). However, Despite the vast range of research in salt damage processes (Correns 1949; Winkler and Singer 1972; Arnold and Zehnder 1991; Steiger and Zeunert 1996; Goudie and Viles 1997; Rodriguez-Navarro and Doehne 1999a &1999b; Scherer 1999; Pender 2000; Sawdy 2001; Flatt 2002a&b; Prooks 2005, Bala'awi 2006, Doehne &Price 2010 and Bala'awi and Mustafa 2016) mechanisms by which this process occurs are very complex and hotly contested .

Arnold and Zehnder (1991) demonstrate that the dynamics of salt damage in porous material is largely determined by the salt solution and the surrounding temperature and relative humidity. So if the surrounding relative humidity at a given temperature is higher than the equilibrium relative humidity of the salt solution, the salt will remain in its soluble condition and the solutions become more diluted. But if the surrounding relative humidity is less than the equilibrium relative humidity of the salt solution, the salt will crystallise out of the solution. The equilibrium relative humidity of salts range between 99.9% for calcium sulfate ($CaSO_4.2H_2O$) and 11% for lithium chloride ($LiCl.H_2O$) (Greenspan 1977).

Angeli et al. 2007 carried out a detailed experimental research aimed to study and predict any alteration to rock by crystallization of salt. They concluded that the shape and the size of samples have major influence in stone alteration.

Doehne and Price 2010 in their evaluation of conservation research and projects in stone conservation sector have a established a comprehensive data base related to stone conservation problems and technical treatment techniques. They also have highlighted the main strength and weakness of stone conservation work and especially in salt damage research.

Gomez-Heras M et al. 2011 presented a comprehensive study in characterizing salt at selected Monuments at the World Heritage Site of Petra where salt sources and intensity were evaluated deeply and thoroughly.

Bala'awi and Mustafa 2016 completed a comprehensive evaluation of microclimate conditions and salt damage in a number of selected case study locations at World Heritage Site of Petra, Jordan.

The current paper will present case study evaluation of the soluble salts concentration, types and distribution at one of the main important sights in the ancient city of Jerash, The South Theatre.

The study will present a detailed microclimate conditions monitoring programme from the main environmental conditions that had a major involvement in the salt damage process at the site. The monitoring of the microclimate conditions included spot readings for wind speed, temperature and relative humidity taken during four fieldwork visits as well as continuous logging. The salt distribution was assessed by analysis of samples that were collected from different locations.

2. THE CASE STUDY AREA: THE NORTHERN THEATRE

The city is about 48 kilometers north of Amman, the capital of Jordan, and considered as one of the largest and most well-preserved sites of Roman architecture in the world outside Italy. However, in the last few decays, some of the city features showed a large number of decay features that raised the alarm that the city sights under a major potential risk. One of the main sights which could be under a massive risk is The North which was built in 165 AD. The theatre originally had only 14 rows of seats, and was used as a performance stage as well as the city council chamber; the names of the tribes represented in the council are inscribed in Greek on some of the seats, along with those of several gods.

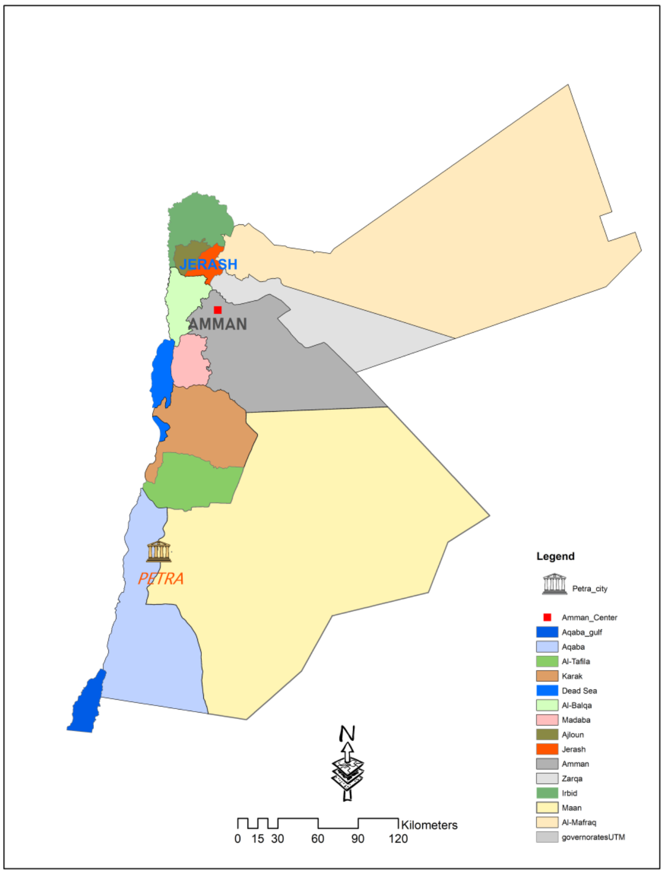


Figure1: Map of the main Archaeological sites and cities in Jordan .

Figure 2: The Northern Theatre, Jerash, taken bu Author 2015.

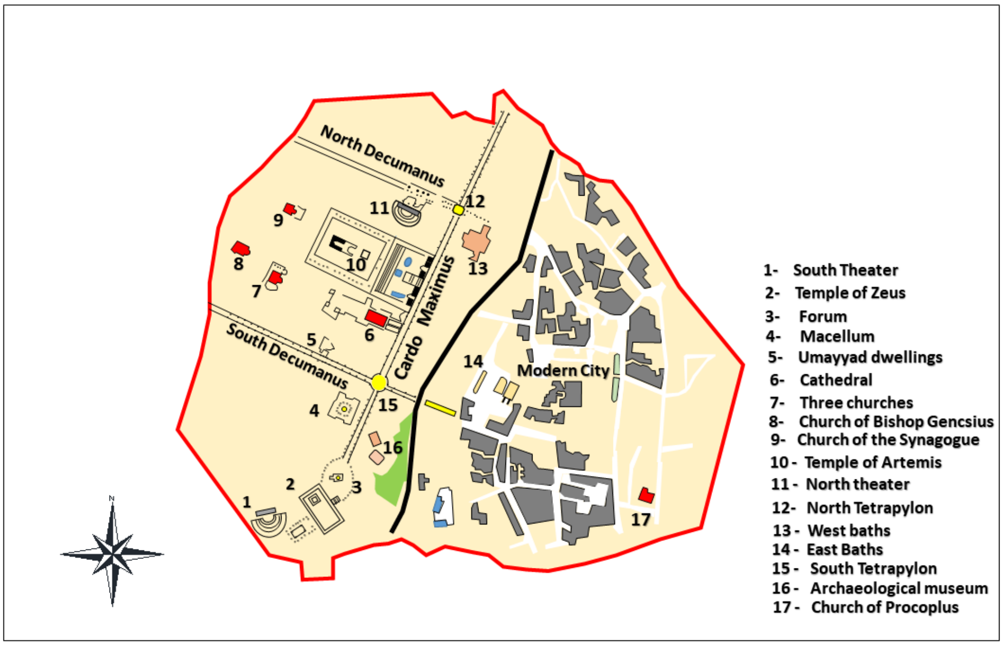


Figure 3: Map of the archaeological site of Jerash

3. ENVIRONMENTAL CONDITIONS AND SALT DAMAGE

The presence of high levels of moisture and salt supply in porous materials is the prerequisite for salt weathering (Goudie and Viles 1997). However, environmental conditions such as relative humidity, temperature and wind speed also play a crucial role in activating the salt weathering process.

The salt solution's behaviour in porous materials is largely controlled by the ambient environmental conditions, namely relative humidity, temperature and wind speed, the salt types and the pore size and structure of the materials.

Each salt solution has its equilibrium relative humidity (ERH), which is the transition point between crystallisation and dissolution. If the ambient relative humidity is lower than the ERH of the solution, then the salt(s) crystallise out of the solution. While, if the ambient RH is higher than the ERH of the solution, the salt(s) stay in solution state. The presence of other salt(s) in the salt solution is another factor that affects the salt behaviour inside a porous system. The presence of other salt(s) in the salt solution will reduce the ERH of that solution and, therefore, change its thermodynamic behaviour (Price and Brimblecombe 1994).

Regarding temperature it is well known that temperature has a strong influence on the relevant phase equilibria. Increase in temperature leads to evaporation of water, which in turn causes increase in salt concentration and decrease in the vapour pressure of the solution until finally the salt starts to crystallise. Also temperature has a direct effect on the equilibrium relative humidity figures (ERH) of soluble salts. Increase in temperature causes a gradual decrease in the equilibrium relative humidity (ERH) of soluble salts.

Wind is another environmental condition that affects the salt damage process through different mechanisms. Bala'awi (2006) summarized these mechanisms into five major categories as it follows:

1- Wind speed has a major effect on the evaporation rate. In windy conditions, the evaporation rate increases, as the wind takes away the moist air and replaces it with dry air. As a result, the water vapour decreases, the supersaturation ratio of saline solutions increases and salt crystals form more rapidly.
2- The wind has a crucial role in the cooling rate of the solution. Wind acts as a factor that removes energy from a surface and therefore affects the cooling rate. High wind speed increases the cooling rate and therefore the solubility of salt(s) decreases. As the solubility decreases, the water vapour decreases as well and a highly supersaturated solution is formed.
3- The wind has a direct influence on the crystallisation location of salts. The location where the salt(s) precipitate(s) out of the solution is a dynamic balance between moisture uptake and moisture loss in the system. If the moisture uptake is higher than the moisture loss, the solution moves towards the surface of the porous material and salts deposit on the outer surface forming what is called 'efflorescence'. But, if the

drying rate is higher than the moisture uptake, then the salt precipitates out of the solution inside the porous system causing what is called 'subflorescence'.

4- It is worth mentioning that the rate of airflow affects the morphology of the salt crystals. In wind-exposed faces, salt crystals are usually non-equilibrium and anhedral, while euhedral or whisker-like crystals usually appear in low airflow rates (Rodriguez-Navarro and Doehne 1999b). The morphology of salt crystals is a direct indicator of the supersaturation ratio before crystallisation (Doehne, Selwitz and Carson 2002). The non-equilibrium crystals are formed from highly supersaturated solutions, while euhedral or whisker-like crystals are formed from solutions with low supersaturation ratios.

5- Wind is also a direct factor affecting the wetting of the stone by wind-driven rain (Smith and McGreevy 2004). This affects the moisture content, which in turn is a crucial factor in salt damage.

From what has been discussed so far, it can be concluded that in order to understand the salt damage process, all the surrounding environmental conditions should be taken into account.

3. CURRENT RESEARCH METHODOLOGIES OF CLIMATIC MONITORING

The methodologies of climatic monitoring programmes vary considerably in the literatures of cultural heritage studies. Some scholars such as Tricio and Viloria (2002) Bala'awi (2006) have undertaken a very detailed microclimate investigation in evaluating the effect of the environmental parameters on historical buildings, while others, such as Al Naddaf (2002), preferred a basic monitoring programme in evaluating the stone weathering behaviour. The detailed monitoring approach was considered more appropriate for the current research because it would provide a more systematic way of evaluating the salt damage process at different locations by comparing the microclimate data of each location with its salts content. Therefore, it was decided to use two climatic monitoring programmes in order to evaluate the microclimate of the studied areas. The first was a spot reading monitoring programme at each site during each fieldwork visit. This included spot readings of the temperature, relative humidity and wind speed. The second monitoring programme involved a more detailed recording of the temperature and the relative humidity over a period of 12 months (April 2015- April 2016), using Tinytag Plus 4500 loggers. The logger was set to take one reading every 30 minutes during the whole recording period (figure 8 explain data logger location as well as samples location.).

Unfortunately, data loggers were not available for the recording of the wind speed and, therefore, spot readings were the basis for the evaluation of this environmental parameter. During each fieldwork visit to the case study locations, a group of detailed wind speed spot readings were taken.

In order to have an initial profile during the first fieldwork visit, spot readings for temperature, relative humidity and wind speed were taken near the case study site. The relative humidity and temperature were recorded using a Digitron SP3R temperature and relative humidity recorder. The temperature range of this recorder is between -20 and 60 ºC with 0.1 ºC resolution, while the relative humidity range is between 0 to 90 % with 1 % resolution. The recorder accuracy for temperature was +1 ºC for temperatures between 0-40 ºC and +2 ºC for temperatures outside this range, while the accuracy for relative humidity was +5 % for relative humidity between 40-80 %, and +7 % for relative humidity outside this range. These features were suitable for the purpose of getting an initial profile of the temperature and relative humidity at case study theatre. A Lutron hand anemometer (Am-4201) was used to measure the wind speed at the case study site. This portable anemometer provides fast, accurate readings with digital readability and the convenience of a remote sensor. It also has a multifunction for air flow measurement: m/s, km/h, ft/min and knots. In this research the airflow measurements were recorded in m/s.

4. THE MICROCLIMATE DATA: RESULTS AND DISCUSSION

4.1. *Relative humidity and temperature*

This first fieldwork trip to the site took place between the 1st and 7th of April 2015. During this visit, a Gemini Tinytag Plus 2 (TGP-4500) logger was installed in a sheltered area in the site. The reason for choosing this type of logges was mainly because they are designed for tough locations and they are ideal for external environmental monitoring due to their waterproofing and large detection range. (Gemini Data Loggers 2015).

For three consecutive days, spot readings of relative humidity and temperature were recorded every 5 minutes at three different locations on the theatre. One on the left middle part of the theatre, one on the central middle part and the last location was on right middle part of the theatre.

The relative humidity overall daily averages varied slightly from one location to another, with the highest readings at the central middle part and the lowest at the left middle location.

Table 1: Day and night overall averages of relative humidity and temperature spot readings. First fieldwork visit (1-3 April 2015)

Location	RH averages for 24 hours (%)	RH averages for 12 hours (day-time) (%)	RH averages for 12 hours (night-time) (%)	T averages for 24 hours (ºC)	T averages for 12 hours (day-time) (ºC)	T averages for 12 hours (night-time) (ºC)
Left middle part	60.5	55.5	65.3	27.1	28.2	16.30
Central middle part	64.6	57.6	67.3	25.4	27.2	14.46
Right middle part	62.3	56.1	66.4	26.0	27.4	15.76

On the other hand, as it had been mentioned earlier, a one year monitoring programme were carried out using a 4500 tinytage logger. The following is a brief dissuasion of the main outcomes from the recorded data.

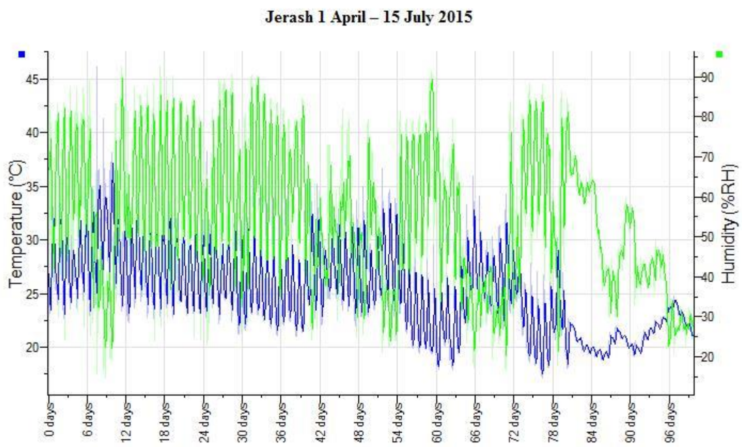


Figure 4: Temperature and Relative Humdity readings from the environmental logger (1 April - 15 July 2015).

Between 1st April 2015and 15th of July 2015, (4790) readings of temperature and relative humidity were recorded. The recorded relative humidity data showed not only significant fluctuation from one month to another, but also wide range of fluctuation within the day (figure). For example, on 1st June2003, the relative humidity increased from (47.5 %) at midday to (76.5%) at midnight. Generally, the relative humidity readings ranged between (46.1 %) and (92.5 %). The relative humidity reached its maximum during April due to heavy rain that affected the site in the second half of April 2015. The overall average in April was approximately (60 %). It is worth mentioning that the overall average was approximately (56%) during May2015, the overall average was approximately (51%) and less than (37%) in July.

The temperature readings were much more stable than the relative humidity ones (figure 4). It should also be noted that, because the logger was installed in a sheltered area, the temperature readings were much lower than the outside temperatures .

During April 2015 the temperature readings were less fluctuated compared to RH readings ranged between (41ºC) and (22.5ºC) with an overall average of (28ºC). During May 2015 the temperature readings showed much more stable readings with an overall average of (26.4 ºC). During June 2015 a very stable temperature readings were recorded with an overall average of less than (23 ºC). Temperature readings were very stable during July with very similar averages to June readings.

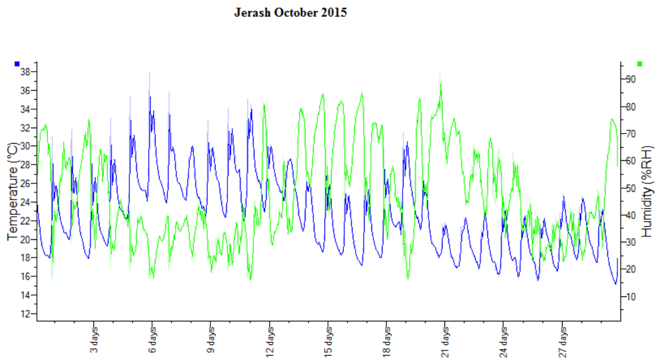


Figure 5: Temperature and Relative Humdity readings from the environmental logger (October 2015).

The recorded data during September and October 2015 (showed a wide range of fluctuation for both temperature and relative humidity, with October being the most fluctuated month in regards to temperature and relative humidity. (Figure 5)

During November, were the second set of samples were collected for salt analysis, the relative humidity reading shows light grade of fluctuation with an overall averages around (40%), while temperature readings were relatively stable with an overall average of (20.4 ºC).

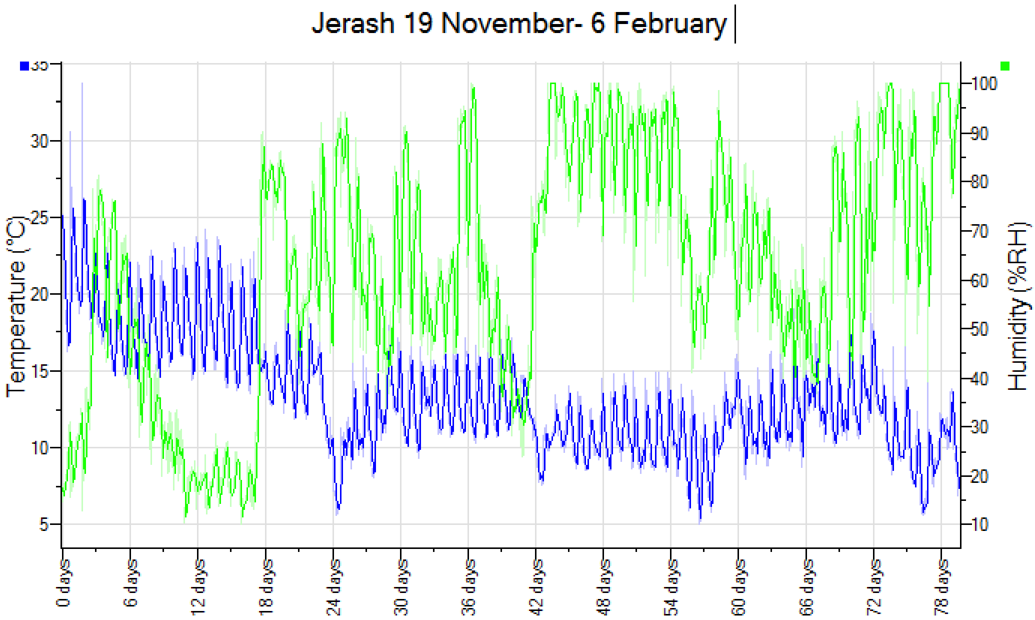


Figure 6: Temperature and Relative Humdity readings from the environmental logger (19 Novermber 2015 - 6 Noverber 2016).

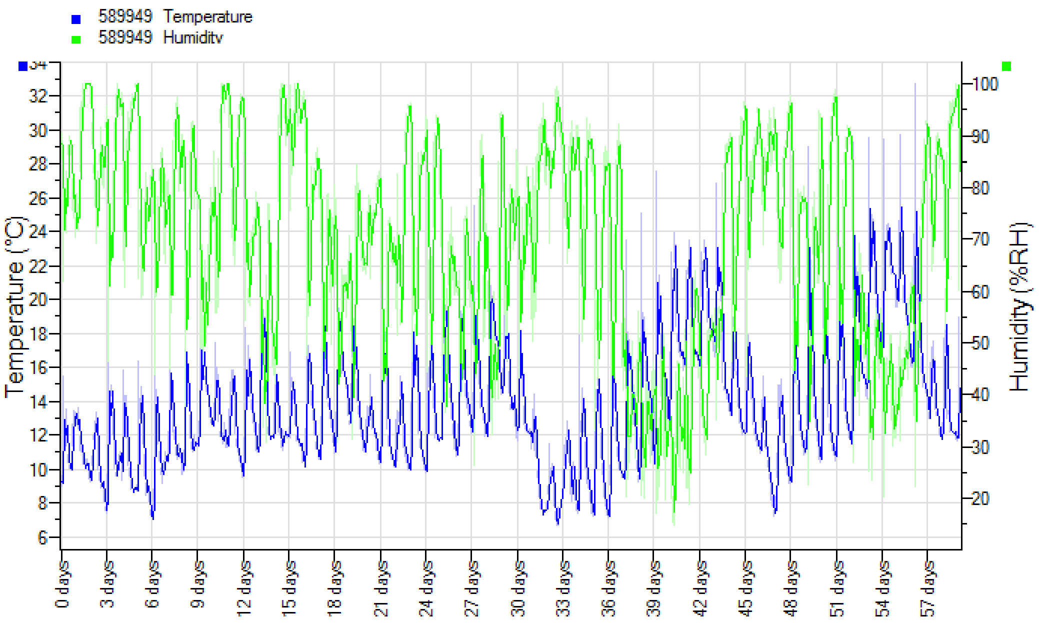
December 2015 was the most humid period with an overall average of RH above (84%). The temperature readings showed very low readings as well as very stable ones with an overall average less than (11ºC) (figure 6).

The January 2016 microclimate date showed a considerable fluctuation of relative humidity readings with high averages on both early and late days of the month and relatively low readings in the middle part of it. The overall averages of relative humidity were slightly lower the December ones and it were less than (65%). Temperature readings showed a slight grade of fluctuation compared to December readings with an overall average around (12.3 ºC).

By combining the relative humidity and temperature readings in one figure (6), the relation between these two environmental factors can be easily seen. Generally, as the temperature decreases the relative humidity increases and vice-versa, but the temperature fluctuation rates are much less dramatic than the relative humidity ones.

The relative humidity recorded its highest readings during February 2016 (figure 7) with an overall average of (76%). The temperature also recorded its lowest rate where temperature readings ranged between (7-22.9 ºC) with an overall average of (12.5 ºC).

March 2016 was a humid month with relative humidity readings ranged between (14.6%) and (99.55%) with an overall average around (65.5%). The temperature readings showed a slight increase compared to February ones with an overall average of (14.1ºC).



7 February 2015- 7 April 2016

***Figure*:7 Temperature and Relative Humdity readings from the environmental logger (7 Feburay 2016 - 7 April 2016).**

4.2. Wind speed readings

Due to the importance of the wind speed factor in this research, sets of wind speed spot readings were taken during the first and second fieldwork visits. Unfortunately, there were no loggers or any other instrument available in order to record the wind speed over a long period as in the case of temperature and relative humidity. Therefore, spot reading profiles were used as the main database for the evaluation of the wind speed factor.

4.2.1 The wind speed spot reading profiles

In order to get a clear indication about wind speed at the studied theatre, wind speed spot readings were taken at each sampling point at the theatre. The readings were taken at approximately 1m distance from the surface of the structure. A total of 13 sets of spot readings were taken at each sampling point, each of which consisted of five spot readings. These covered the whole daytime period (06.30-18.30 (for example, tables 2 &3). The previous work were repeated in the first day of each month for the whole monitoring period (April 2015-April 2016).

Following observation of the wind speed profiles, the following points can be made:

- The wind speed fluctuated significantly at the same sampling point throughout the day.
- The wind speed usually started very low in the early morning, then gradually increased and started decreasing again before midday.

Table 2: Wind speed spot readings, 1 April 2015.

Location	Date	Time	Maximum wind speed (m/s)	Minimum wind speed (m/s)	Average wind speed (m/s)
JNT1	1 April 2015	06.30	0.65	0.10	0.40
JNT1	1 April 2015	07.30	1.80	0.15	0.55
JNT1	1 April 2015	08.30	1.70	0.05	0.50
JNT1	1 April 2015	09.30	2.10	0.25	0.60
JNT1	1 April 2015	10.30	1.55	0.20	0.60
JNT1	1 April 2015	11.30	1.20	0.25	0.55
JNT1	1 April 2015	12.30	1.00	0.15	0.45
JNT1	1 April 2015	13.30	1.10	0.20	0.55
JNT1	1 April 2015	14.30	2.80	0.10	1.60
JNT1	1 April 2015	15.30	3.10	0.30	1.70
JNT1	1 April 2015	16.30	3.55	0.30	1.85
JNT1	1 April 2015	17.30	3.01	0.40	1.88
JNT1	1 April 2015	18.30	4.08	0.61	2.10

- The wind speed started rising again in the afternoon and reached its maximum in the evening.
- In most of the sampling profiles, the wind speed increased generally with the height.
- The wind speed overall averages in most of the monitoring periods showed a very similar trend where that the middle and left sampling points were higher than the left sampling point, with the upper middle sample points (JNT7-JNT10) recording the highest averages.
- The wind speed readings where noticeably higher during winter periods (November 2015 - February 2016)

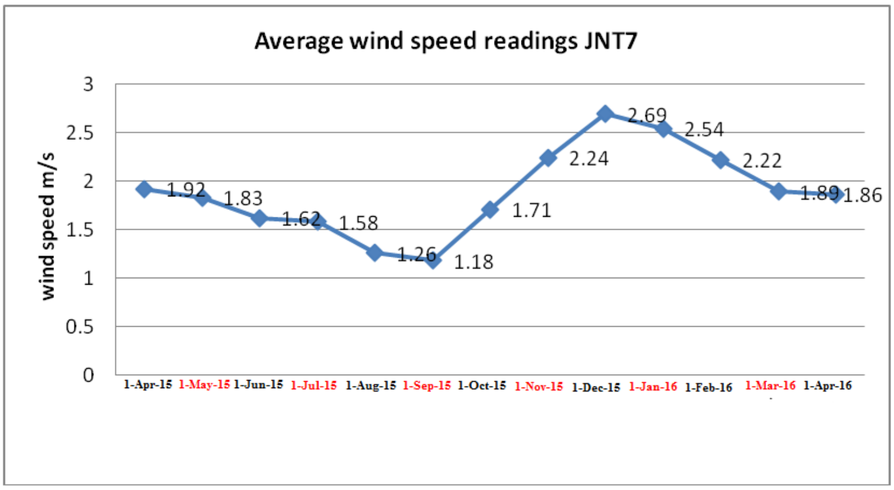


Figure 8: Average Wind Speed Reading JNT& (7 Feburay 2016 - 7 April 2016).

Table 3: Wind speed spot readings, 1 October 2015

Sample Number	Location	Date	Average wind speed (m/s)
JNT1	First Left row	1 October 2015	1.02
JNT2	5th Left row	1 October 2015	1.23
JNT3	10th Left row	1 October 2015	1.25
JNT4	15th Left row	1 October 2015	1.56
JNT5	20th Left row	1 October 2015	1.81
JNT6	First middle row	1 October 2015	1.08
JNT7	5th middle row	1 October 2015	1.55
JNT8	10th middle row	1 October 2015	1.69
JNT9	15th middle row	1 October 2015	1.85
JNT10	20th middle row	1 October 2015	2.61
JNT11	First right row	1 October 2015	1.10
JNT12	5th right row	1 October 2015	1.39
JNT13	10th right row	1 October 2015	1.62
JNT14	15th right row	1 October 2015	1.74
JNT15	20th right row	1 October 2015	2.09

5. SOLUBLE SALT CONTENT

The determination of the salt types and their distribution in the case study Location at Jerash Northern Theatre has a great importance in understanding and evaluating the weathering process at this unique monument. . The type of salts, their depth of accumulation, the pore structure and moisture regimes as well as the surrounding microclimate conditions are the main features controlling the decay of stone materials (Nicholson 2001; Winkler 1994; Doehne 1994 and Rossi-Manaresi & Tucci 1991).

The cation and anion content of each fieldwork sample were analysed. Before carrying out the analysis, the samples were diluted with distilled water. A sample of 0.2 + 0.0005 g was diluted with 10 + 0.05 ml of distilled water. The samples were filtered in order to avoid any metal debris from the drills affecting the results. The cation analysis was carried out by using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). . The cation analysis was carried out by using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). The machine was capable of measuring the following cations: calcium, sodium, iron, aluminium, magnesium, potassium, titanium and zinc. The machine was calibrated automatically every tenth sample. The anion content was measured by using Ion Chromatography (IC). The experiment was carried out with the same diluted samples that were used for the ICPAES in order to maintain homogeneous results. The samples were diluted further when the anion concentration exceeded the capacity of the machine reading. A standard solution was analysed at the beginning of each test and after every tenth sample. The machine could measure the following anions: fluoride, chloride, bromide, nitrate, phosphate and sulfate.

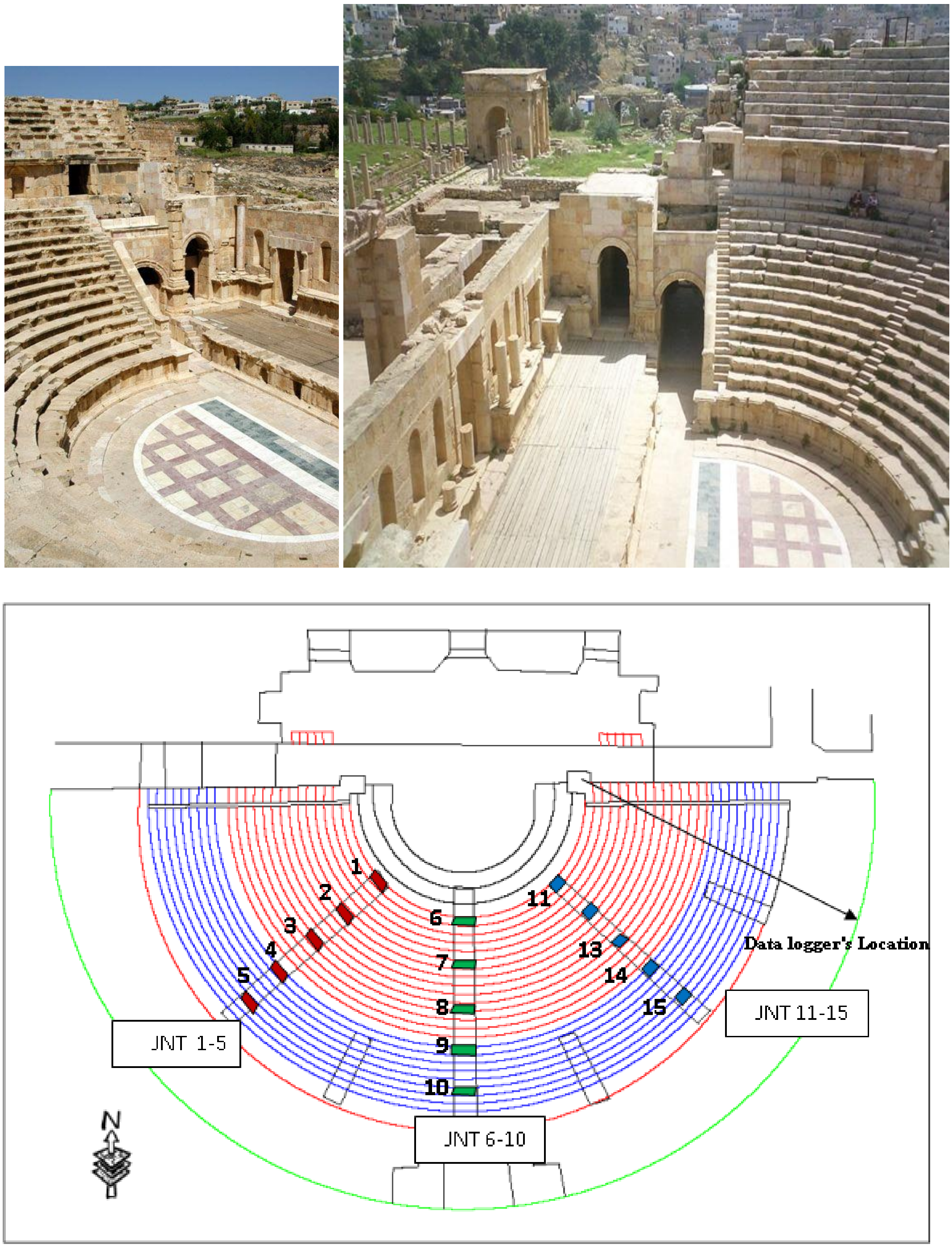


***Figure 9**: The case study Theartre and sample location*

The content of soluble salts in porous building materials varies with time; therefore, the evaluation of the ions content in the case study theatre should follow a set procedure. A total of 15 samples were collected from the same location where wind speed spot reading were measured (Figure 9). The samples were collected during 2 fieldwork visits in different seasons, represented the extremes of the area's climate, summer (September 2015: first fieldwork visit) and winter (January 2016: second fieldwork visit). The samples were in powder form and a manual drill was used for their collection. The samples were collected exactly from the same location in the two fieldwork visits. Moreover, the ions content of the samples collected from the case study theatre was examined in detail.

5.1. Soluble salts results and discussion

In the 15 analysed samples from the three sampling profiles at Northern Theatre at Jerash taken in the first fieldwork visit (summer visit), sodium and calcium were the major cations, while magnesium, potassium, aluminium and iron were secondary components. On the other hand, chloride, nitrate and sulfate were the main anions.

The total soluble salts content at first fieldwork ranged between (0.38 and 0.81%) with an average of (0. 57%). By looking at the total soluble salt contents from different heights at this visit (Table 4), a general trend of salt distribution can be observed. The total soluble salt content was obviously higher at higher level and especially at middle of the theatre (samples JNT 5-10). The highest content of soluble salts was in measured at the middle upper samples (JNT 9 & 10).

Table 4: Soluble salt content in the sample (%) of dry weight in Northern Theatre in Jerash. First fieldwork visit September 2015.

Sample Number	Location	Depth (cm)	Soluble salt content in the sample (%) of dry weight First fieldwork visit September 2015	Soluble salt content in the sample (%) of dry weight Second fieldwork visit January 2016
JNT1	First Left row	0-1	0.41	0.51
JNT2	5th Left row	0-1	0.44	0.54
JNT3	10th Left row	0-1	0.69	0.56
JNT4	15th Left row	0-1	0.65	0.61
JNT5	20th Left row	0-1	0.72	0.68
JNT6	First middle row	0-1	0.43	0.39
JNT7	5th middle row	0-1	0.44	0.62
JNT8	10th middle row	0-1	0.73	0.81
JNT9	15th middle row	0-1	0.81	0.79
JNT10	20th middle row	0-1	0.81	0.89
JNT11	First right row	0-1	0.38	0.41
JNT12	5th right row	0-1	0.41	0.62
JNT13	10th right row	0-1	0.57	0.63
JNT14	15th right row	0-1	0.55	0.65
JNT15	20th right row	0-1	0.58	0.68

The total soluble salts content at second fieldwork ranged between (0.39 and 0.89%) with an average of (0. 63%). By looking at the total soluble salt contents from different heights at this visit (Table 4), a smaller trend to the previous fieldwork visit of salt distribution can be observed. The total soluble salt content was obviously higher at higher level and especially at middle of the theatre (samples JNT 5-10). The highest content of soluble salts was in measured at the middle upper samples (JNT 9 & 10).

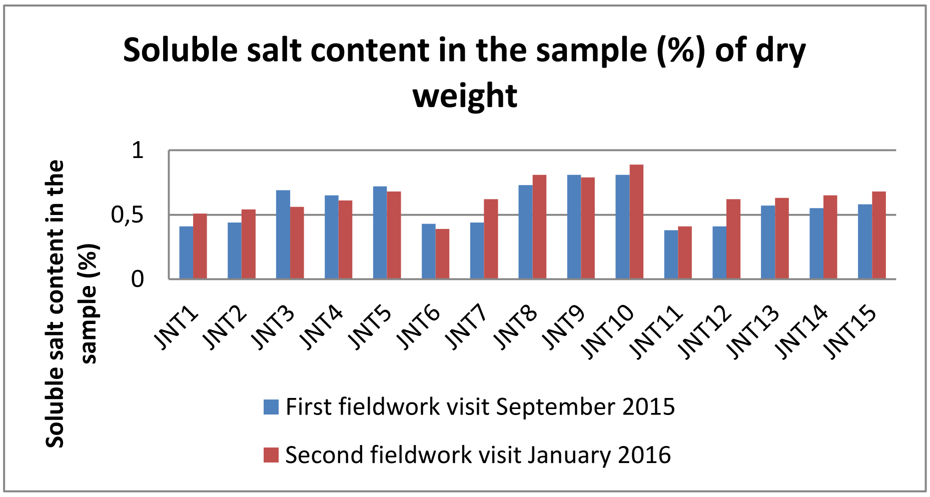


Figure 10: Soluble salt content in the sample (%) of dry weight in Northern Theatre in Jerash

The results of the anion and cation analysis of the collected samples showed a wide range of variation. The full results of the ICP-AES and IC analyses are shown in appendices Table and Figure. The following is a brief discussion of these results, throughout the two sampling fieldwork visits. In the 15 analysed samples from the sampling profiles at the Northern Theatre Tomb taken during the first fieldwork visit sodium and calcium were the major cations, while magnesium, potassium, aluminium and iron were secondary components. On the other hand, chloride, nitrate and sulfate were the main anions. Regarding the salt types and salt origins, the results showed a correlation between calcium and sulfate in most of the samples. The calcium and sulfate concentrations mainly increased with height and decreased with depth. Despite the fact that calcium sulfate is a sparingly soluble salt and, therefore, should concentrate in the lower parts of the monuments, its higher concentration at higher levels has two possible explanations. The first reason could be the washout of the calcium sulfate salt by running water in the lower part of the sampling profile during winter, since the sampling profile is just above a valley where rain water accumulates. It is also quite probable that different cations and anions formed very soluble salts that interacted with calcium sulfate and changed its thermodynamic properties (Bala'awi 2006).

In summary, the total soluble salts content in these tombs was controlled by two factors: the level of the water table which is a fundamental reference surface in the study of groundwater (salt supplier) and the surrounding environmental conditions. The high concentration of soluble salts were during winter can be explained by the fact that Jerash is reportedly as a heavy rain area during winter. Therefore, the water table in that area may rise considerably during the winter and, despite the relatively low evaporation rates during this season, the higher rates of accumulation of soluble salts from the groundwater source result in higher soluble salts content. In summary, rate of accumulation of soluble salts from the groundwater resulted in high soluble salts content during the winter season.

The most notable environmental factor that has a direct link with salt crystallization was the wind speed where high salt content were linked with high wind speed profiles. The salts content were relatively high at the studied area with a major increase at upper levels of the theatre where high wind speed profiles were noted (Figure 11). The Sketch diagram showing the relation between total salt content and wind speed feature at the case study Location (figure 11) explains clearly the direct link between salt content and wind speed readings with a considerable increase of salt content at sampling point location with high wind speed readings.

Table 5: Salt contents main cations and anions for Northern Theatre in Jerash. First fieldwork visit September 2015

Sample Number	Location	Depth (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Cl (ppm)	NO_3 (ppm)	SO_4 (ppm)
JNT1	First Left row	0-1	16.16	7.95	0.88	1.22	5.59	6.21	5.53
JNT2	5th Left row	0-1	19.32	7.04	0.86	1.24	6.31	6.43	7.21
JNT3	10th Left row	0-1	23.01	8.01	0.93	1.41	7.59	6.30	7.49
JNT4	15th Left row	0-1	18.04	8.31	0.85	1.53	9.12	6.01	5.55
JNT5	20th Left row	0-1	18.32	9.11	0.78	1.59	8.87	7.10	5.53
JNT6	First middle row	0-1	14.91	7.73	0.91	1.29	6.02	6.31	5.09
JNT7	5th middle row	0-1	18.36	7.49	0.88	1.39	6.38	6.22	6.04
JNT8	10th middle row	0-1	20.88	8.33	0.81	1.58	7.91	6.11	6.13
JNT9	15th middle row	0-1	19.77	8.84	0.86	1.61	8.08	6.52	5.94
JNT10	20th middle row	0-1	17.91	9.21	0.83	1.59	8.79	6.43	5.13
JNT11	First right row	0-1	17.03	6.38	0.79	1.01	4.76	5.57	5.72
JNT12	5th right row	0-1	16.22	6.45	0.80	1.23	5.15	5.49	5.70
JNT13	10th right row	0-1	17.61	6.91	0.77	1.22	5.81	5.41	5.63
JNT14	15th right row	0-1	15.91	7.03	0.81	1.28	5.93	5.71	5.62
JNT15	20th right row	0-1	14.78	7.09	0.83	1.33	6.11	5.18	5.19

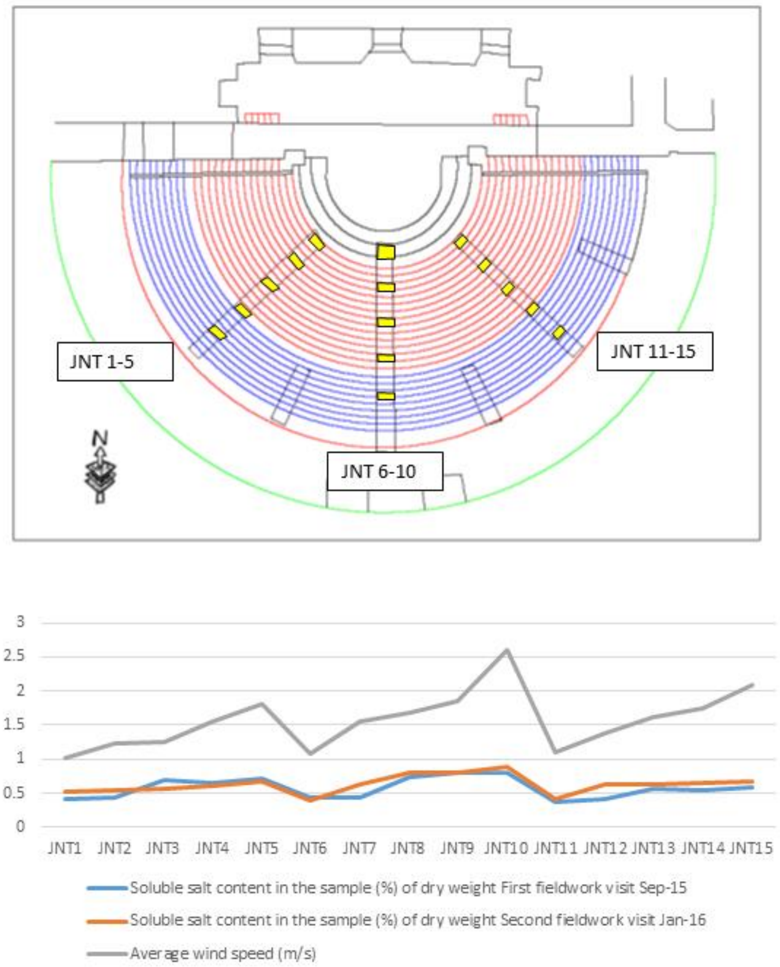


Figure (11): Sketch diagram showing the relation between total salt content and wind speed feature at the case study Location, Jerash: Northern Theatre

Moreover, Ca-SO_4 and Na-Cl correspondence was observed in most of the profiles at the two different seasons, with the former at the lower parts of the profiles and the latter towards the middle and the upper parts. The Ca-SO_4 concentration at the lower parts of the sampling profiles increased towards the upper part during winter due to the rise in the water table.

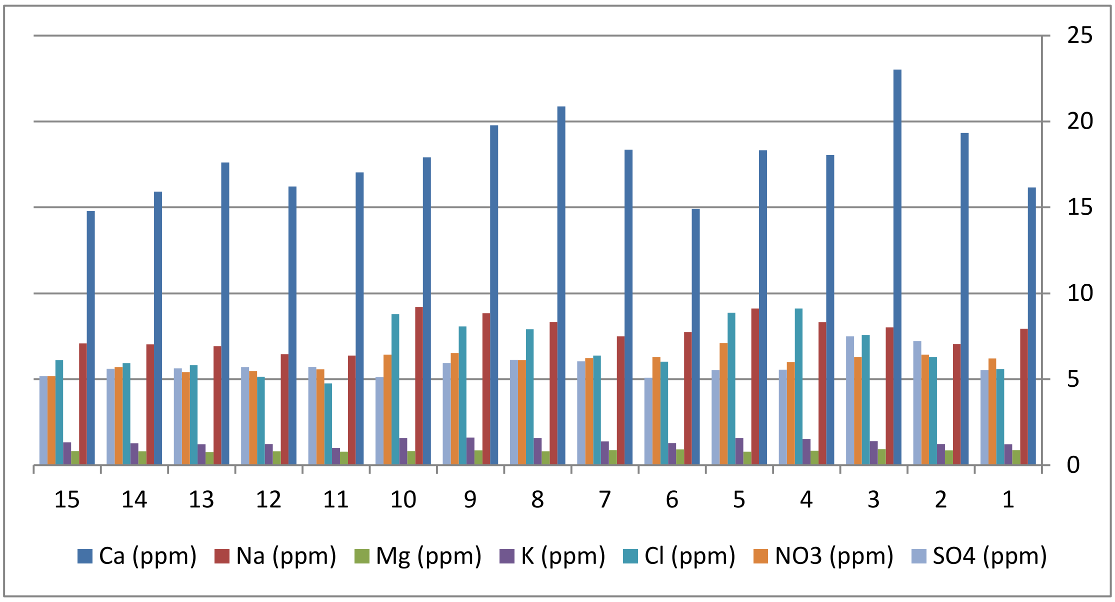


Figure (12) Main cations and anions for Northern Theatre in Jerash. First fieldwork visit September 2015

6. THERMODYNAMIC CONSIDERATION AT CASE STUDY LOCATION

The analysis of cations and anions of samples collected during the two cycled fieldwork visits has revealed very useful information about the salts content and distribution at Northen theatear at Jerash, but a more needed understanding of the dynamics of these soluble salts is still lacking. In other words, the relationship between soluble salts content, types and distribution 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. In order to achieve that the current study used an expert chemical model called RUNSALT based on another software called (ECOS) (Environmental Control of Salts)for determining the environmental conditions needed to prevent salt damage in porous materials (Price 2000).

The ECOS program requires the input of three types of data, a 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). Also, the literature review of the ECOS applications showed that temperature did not significantly affect the salt solution's behaviour, while relative humidity had the greatest impact. Therefore, the current research has used similar software to ECOS which is RUNSALT, which is a graphical user interface to the ECOS thermodynamic model for the prediction of the behaviour of salt mixtures under changing climate conditions, as described in Price (2000) (Bionda 2005).

In each selected location, a 2g powder sample was collected using a manual drill to collect surface sample (less than 0.5cm depth). Then every sample were mixed with 10ml of distilled water and divided to two different sample were cations and anions content were measured using Ion Chromatography(IC) and Inductively coupled plasma atomic emission spectroscopy (ICP-AES).

At the current study, the main cations and anions of the selected sampling point were used on the software alongside with the average temperature of each sampling period as the fixed parameter, and with the entire available range of relative humidity (15-98 %). This is mainly because it has been proved that the relative humidity variations have more impact on the salts composition and behaviour than the temperature variations (Sawdy 2001, Bionda and Storemyr 2002 and Prokos 2008).

During the first fieldwork sampling campaign, the sum of the cations charge at the lower part of the profile was significantly higher than the anions charge, which prohibited the usage of the ECOS program. The excess of the cations charge was mainly due to a high percentage of calcium ions. As discussed earlier, removing the gypsum from the samples does not affect the thermodynamic behaviour of the salt solution substantially, since gypsum is a sparingly soluble salt and leaves the salt system at early stages. It was found that, due to the high content of calcium and sulfate together in these samples, the ECOS program could not operate. The removal of gypsum was indicated and performed by the program itself..

In the tested samples Halite (NaCl) was the first salt to participate out of the solution at around (65 %) relative humidity while calcium nitrate precipitated next at a relative humidity of (36.5 %). Carnallite (Hydrated Potassium Magnesium Chloride) precipitated finally at (34.6 %) RH. (Figure 13).

The salt crystallisation profile (figure 13) clearly state that the most dangerous range of relative humidity is between (30- 40%) since the majority of soluble salt content crystalize at these ranges, where the range (60- 65 %) is the second dangerous rates since sodium sulfate crystalize at this range. The Profile clearly state that there is no salt crystallization at the case study sample where relative humidity exceed (65%).

Additionally, the Runsalt thermodynamic calculations confirmed the observations from the cation and anions analysis from the Theatre where the more soluble salts crystallized at higher levels of the profile than the less soluble ones.

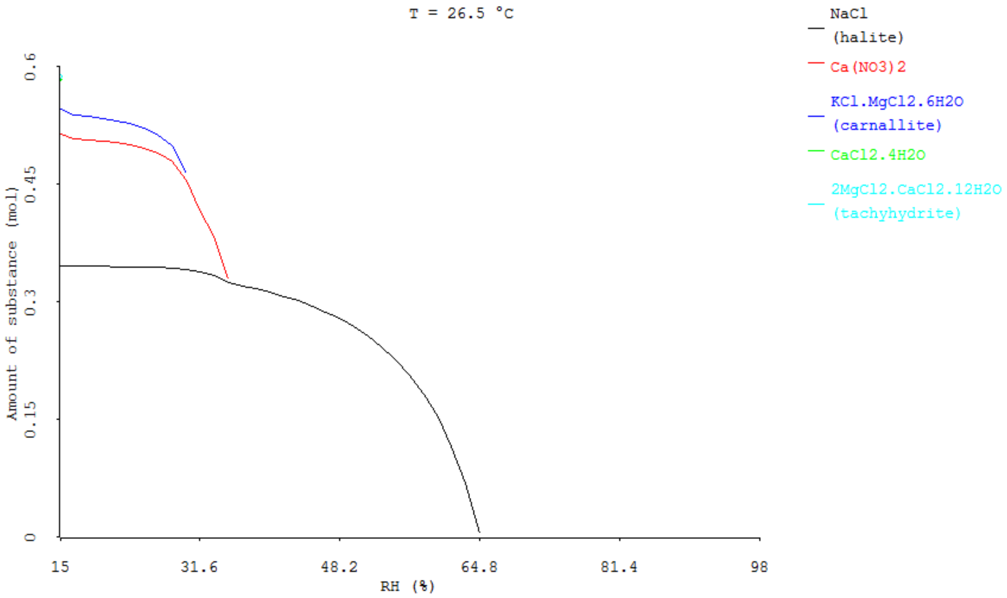


Figure 13: Thermodynamic analysis using Runsalt software (ECOS). Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). Sampling number (JNT1). First field work visit September 2015. Location: Jerash Northern Theatre (JNT1). (After the removal of Gypsum)

The observed thermodynamic results from selected samples at the Northern Theatre revealed the importance of including the thermodynamic considerations in the evaluation of the salt composition and behaviour of a certain salt solution. Therefore, the evaluation of the salt composition and behaviour should consider not only the types of cations and anions but also the interaction between different anions as well as their interaction with the surrounding conditions. It is clearly stated that the ultimate purpose of applying the Runsalt program to the cation and anion content of a porous material is to predict the environmental conditions needed to prevent salt damage of this material. In order to prevent the damage from a salt solution, the surrounding relative humidity conditions should be kept either above or below the transition points of the different salts in the solution. Relative humidities within these ranges, where no change in the volume or phase took place, could provide relatively 'safe' conditions.

Based on these results, it could be concluded that in order to minimise salt damage in the Palace Northern Theatre at the archaeological site of Jerash, the relative humidity should be kept above (65%) throughout the year. This ideal 'safe' relative humidity conditions are unachievable in reality. The term 'safe' in this study is used to refer to the relative humidity ranges in between the transition phase limits of the soluble salts in the solution, where no transition or volume change happens but the salts remain either in solid form or in solution.

The best way out in this cases to state what we call as a relatively safe condition relative humidity conditions, where salt stats are relatively stable and finally by comparing our result with collected environmental conditions at the site we come up with a third suggestion as what we called achievable relatively safe relative humidity. In another words, we could suggest three levels of relative humidity where salt damage could be minimised at the site. The formal is the ideal but it is difficult to achieve in such huge monuments, while the other suggestions are less relatively less safe but within our capacity to achieve. And since we are talking about a reality solution in the site we could focus on these alternatives.

Following the thermodynamic behaviour of the studied samples and collected environmental conditions at the site it could be concluded that the ideal case is to keep relative humidity above 65 throughout the year which is very difficult to achieve in such open location. The second suggestion the relatively safe condition is to keep the relative humidity between (15-30 %) throughout the year which is also difficult especially during winter and spring. The most practical suggestion is to attempt to keep relative humidity conditions between (40 - 60 %) which the most realistic suggestion with given environmental conditions at the site. In addition, the wind speed factor should be kept in mind while we are attempting to apply the achievable relative safe relative humidity ranges. In other words, the wind speed should be controlled side by side with applying the suggested relative safe relative humidity ranges. A simple, flexible, and aesthetically well designed shelter could be the ultimate solution at the Northern Theatre at the site of Jerash. The application of such solution need further investigation where reliability, landscape impact and stakeholders opinion should be studied in details.

7. CONCLUSION

The current research study has shown that the Northern Theatre at the archaeological site of Jerash is under significant risks from salt damage hazards. It was clearly noted that the environmental condition around the site play a major role in intensifying the salt damage problem at the site. The microclimate data have mainly shown light to moderate grade of fluctuation of relative humidity readings with rather steady rates of temperature readings. The most notable environmental factor that has a direct link with salt crystallization was the wind speed where high salt content were linked with high wind speed profiles. The salts content were relatively high at the studied area with a major increase at upper levels of the theatre where high wind speed profiles were noted. The Runsalt program proved to be a useful tool in understanding Northern Theatre salt compositions and behaviour. It demonstrated the effect of the surrounding environmental conditions on the thermodynamic behaviour of the salts in the tested samples. All in all the study did concluded that any attempt to minimise the salt damage should consider all environmental conditions at the site side by side, and especially the wind speed factor.

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