Wind speed and Salt simulation tests: What is really needed?

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Abstract

Laboratory simulation tests, where salt damage is accelerated within a short period of time through different procedures, yield vital information regarding salt crystallisation and distribution processes. However, due to the uncertainty of the actual salt damage process at the site and the wide range of variables involved in this process, the results of salt simulation tests vary significantly from one study to another. The commonly used salt simulation tests vary not only in their procedures and materials, but also in the environmental conditions used. Each of these procedures has its strong argument. Consequently, the selection of a simulation procedure to evaluate the wind speed factor in salt damage generally and in salt damage at Petra monuments particularly was a challenging task. The simulation test of the wind speed effect on salt crystallisation and distribution started with a salt crystallisation test in an environmentally controlled chamber. Due to the technical failure of the chamber, a modified salt crystallisation test based on the BRE (Building Research Establishment) simulation test was used as an alternative. The later simulation test is described in great depth in this paper. Finally, a comprehensive approach was formed for what is needed from salt simulation tests.

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سرعة الرياح والتجارب المخبرية المستخدمة فى تمثيل آلية تعرية الأملاح: ما هو المطلوب فعلياً

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ملخص

التجارب المخبرية التى تهدف لفهم تبلور وتوزيع الأملاح فى الأوساط الحجرية والتـى يـتم فيهـا تسـريع العمليـة فـى وقـت قصـير مـن خـلال طـرق مختلـف تعطـى معلومات هامة عن طريق تبلور الأملاح وكيفية حدوث عملية الدمار من الأملاح فى المبانـى الحجرية. التجارية. التجارب المخبرية فى هذا المجال متنوعة بشكل كبير من دارسة لأخرى. هذا الاختلاف ليس فقط فى خطوات العمل بل أيضا فـى المـواد المستخدمة فـى التجارب والظروف البيئية لكل تجربة. كـل طريـق مـن هذه الطـرق المخبية لها مايدعمها من دلائل. وبناءً علـى ذلك فـإن اختيـار طريقـة مخبريـة لتقييم دور الرياح وسرعتها فى عملية تبلور وتوزيع الأملاح فى موقع البتراء الأثرى كان شائكا فى البداية تم اختيار طريقة تبلور الأملاح فى صندوق مسيطر عليه من ناحية الروف البيئية. وبعد ذلك تـم استخدام طريقـة اختبـار أخـرى وهـى عمليـة تقييم دور الرياح فى تبلور الأملاح وتوزيعها باستخدام طريقة تبلور الأملاح التـى استخدمتها هيئة دراسات الأبنية فـى بريطانيـا (BRE)، مـع إجـراء بعض التعديلات علـى هذا الاختبار لتناسب طبيعة الدراسة.

هذا الاختبار والتعديلات التى أجريت عليه مناقش التفاصيل فى هذا البحث. فى نهايـة البحـث تـم وضـع تصـور شـامل إلـى مـا هـو مطلـوب مـن مثـل هذه التجـارب المخبرية فى عملية تقييم العوامل المختلفـة التـى تـؤثر فـى آليـة حدوث الدمار مـن الأملاح فى المبانـى الحجرية وكيفية توزيع الأملاح داخلها.

Keyword

Salt simulation tests, Petra monuments, salt damage, environmental conditions, sodium sulfate, porous materials.

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 World Heritage Site of Petra.

The World Heritage Site of Petra, Jordan has more than 2000 monuments; most hewed into the coloured sandstone and limestone mountains, and is the biggest tourist attraction in Jordan. However, most of its monuments have been deteriorating at a very fast pace over the last few years and in 1995 the site was included on the World Monuments Fund list of the world's 100 most endangered archaeological sites. The city suffers from weathering and erosion problems, both natural and human-in origin. Salt damage is one of the main weathering factors.

A research was taken to evaluate the role of wind speed in salt crystallization and distribution. The research present a detailed monitoring of the microclimate conditions and its role in the salt distribution at selected monuments in Petra, in order to understand the extent and mechanism of salt damage at these monuments. The salt distribution was assessed by analysis of samples that were collected from different locations, depths and heights at the same monuments. The research developed a salt simulation test that would include the effects of wind. The tests were undertaken with sandstone and limestone specimens under controlled environmental conditions, including low, high and fluctuating wind speed.

2. Petra: The site and the case study monuments

The city of Petra lies hidden in the Desert Mountains in the southern part of Jordan, half way between the Dead Sea and the Gulf of Aqaba.

Petra has more than 2000 monuments, each of which has different composition, stratigraphy, location, salt content and environment.

Carrying out a detailed survey in each of the monuments was beyond the time scale of this research. Therefore, four different monuments were chosen as representative case study sites, each of which has certain features that could help reveal further information about the salt damage problem in Petra. These monuments are Bab al Siq Triclinium, Palace, Corinthian and Deir Tombs. The Bab al Siq monument was chosen for its topographic location (on the left-hand side of the Wadi), while the Deir Tomb was selected because of its location on the edge of a high mountain and the presence of two different levels of stone decay are the main reasons for selecting this monument for sampling. The locations of Palace Tomb at the edge of a mountain and in a very open area as well as its highly deteriorated state were the main reasons for its selection as a sampling point the Palace. On the other hand, the Corinthian Tomb is the most deteriorated carved monument of the site and thus, having a sampling profile from this monument was considered essential for this research.

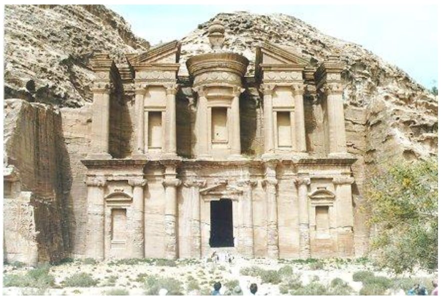
3. Fieldwork investigations

A series of fieldwork investigations was undertaken in order to study the effect of wind speed in the salt crystallisation process. The fieldwork part of the research consisted of four visits to Petra representing two extreme climatic conditions on the site, namely summer (August) and winter (January), and two intermediate intervals (June and April). In each visit, the fieldwork included a collection of powder stone samples from the selected monuments in order to analysis the salt content in these monuments. . The fieldwork visits also included a recording of the wind speed at each sampling point at different times as well as the collecting of other microclimate conditions (i.e. relative humidity and temperature) from two environmental loggers that were installed at two sites (the Corinthian Tomb and the Deir Tomb) in the first fieldwork visit.

The Bab al Siq Triclinium Tomb

The Palace Tomb

The Corinthian Tomb



The Deir Tomb

Figure 1: The case study monuments.

4. Experimental

In order to understand the salt damage process, experimental simulations are needed to replicate and verify the different parameters involved in this process. Because of the uncertainty about the exact mechanism of salt damage, the experimental simulations vary considerably in the literature (see for example, Goudie 1974, Cooke 1979, Smith and McGreevy 1983, Goudie 1986, Ross and Butlin 1989, Goudie 1993, British-European: BS EN 12370, Rodriguez-

Navarro and Doehne 1999a and 1999b, Goudie 1999a and 1999b, Benavente et al. 2001). The variations are mainly due to the use of different methods, tested materials, environmental conditions and simulation techniques. These variations have resulted not only in extreme difficulty in comparing the different salt damage simulating methods, but also in a lack of clear conclusions from their outcomes. Goudie and Viles (1997) presented most of the salt simulation methods and the main differences between them.

4.1. Simulation test conditions

As mentioned earlier, the simulation test used in this research was a modified BRE salt crystallisation test designed to suit the research aims and purposes. The main modifications to the BRE test were the introduction of the wind speed factor, the use of saturated sodium sulfate solution, the introduction of Petra salts solution as the second salt solution, the control of the relative humidity conditions during the test, and the reduction of the drying temperature to 60 °C. The following table (1) summarises the conditions of each run of the test.

Experiment run number	Relative humidity %	Temperature °C	Wind speed condition
1	Low	60	low
2	Low	60	high
3	Low	60	fluctuated
4	High	60	low
5	High	60	high
6	High	60	fluctuated

Table 1. The different environmental conditions for the six runs of the modified salt crystallization test.

4.2. Materials

4.2.1. Stone

Five different types of stone were used in each run of this experiment and these were:

- Locharbriggs sandstone (S): This stone was chosen because its chemical composition and open porosity content are similar to Petra stone. Unlike Petra stone though, this stone has no clay minerals.

- Monks Park limestone (L): This stone was used in this test because it is the most common tested stone in many salt crystallisation tests, including the BRE test.

- Disi sandstone (D): This stone was selected because the Bab al Siq Triclinium Tomb is carved from this stone.

- Upper Umm Ishrin sandstone (U): This stone was selected because the Deir Tomb is carved from this stone.

- Middle Umm Ishrin sandstone (M): This stone was selected because the Palace and Corinthian Tombs are carved from this stone.

4.2.2. Salt solution

Saturated sodium sulfate and saturated 'Petra' salt solution were the two salt solutions used in the test. By using the saturated sodium sulfate solution in the crystallisation test the dissolution of the existing sodium sulphate that had crystallised in the stone sample at earlier cycles was avoided.The Petra salt mixture was based on the overall averages of cations and anions weights of samples taken from one site (Palace Tomb) during the four fieldwork visits.

4.3 Experiment procedure

A modified salt crystallization test based on the BRE salt crystallization test was developed to continue the experimental part of the research. The test consisted of six different runs, each run consisting of 16 day cycles. In each cycle, the specimens were immersed in a salt solution (two salt solutions were used: saturated sodium sulfate solution and saturated Petra salts solution) for two hours and then subjected to a 24-hour cycle of drying at certain environmental conditions. The evaluation of each run was carried out by measuring the weight gain or loss of the tested specimens. The salt distribution was also evaluated at the end of each run, in order to assess the impact of the different environmental conditions on the distribution of different types of salts. The salts distribution was evaluated by two means: analysis of the main cations and anions of drilled samples using IC and ICP-AES, and thin section study using the ESEM. The weight change (gain or loss) was correlated with the salts distribution.

The test procedure was modified and developed in order to respond to the purposes of this research. The main modifications to this test were the drying temperature and duration, the solution concentration and, more importantly, the introduction of the controlled wind speed and relative humidity to the test procedure.

The drying temperature was reduced from 103 $\pm$ 2 °C to 60 °C. This change was made in order to have a drying condition closer to that in Petra. Though one could argue that the chosen temperature was still higher than in Petra, the reason for not having the exact Petra drying conditions is the fact that under those conditions the complete drying would take a very long time, and, due to the time limit of this research, this was not possible. In addition, the drying duration of each cycle was changed from 16 hours to 24 hours. The increase of the drying period was fundamental to balance the reduction of the drying temperature.

A saturated solution was used in this modified crystallization test instead of the 14 % weight concentration used in the BRE. A saturated solution could produce more damage than the unsaturated ones and due to the limited time period for each set of tests (around 15 days) and the slightly low drying temperature, this type of solution was considered more suitable for this experiment. Therefore, a saturated solution of sodium sulfate and a saturated solution of Petra salt mixture were used in this test.

Furthermore, as the study and evaluation of the wind speed factor is a crucial part of this study, it was essential to introduce this factor into the crystallization test. The wind speed was controlled using an electrical air pump that was connected to the vacuum oven by a plastic tube. The experiment was carried out at three different wind speed conditions: low, high and fluctuating wind speed.

Moreover, previous studies of the salt crystallization test (as reported in Price 1978) showed that the variations in the behaviour of different types of stone were much clearer, when a tray of water was placed in the drying oven. However, no explanation was given for such a phenomenon. Consequently, introducing a controlled relative humidity was necessary not only in order to compare the test results at different relative humidity conditions, but also to reduce the variables of the testing conditions, thereby increasing the accuracy of the test. The test was carried out under low and high relative humidity conditions. The relative humidity was introduced and controlled by connecting the air pump to gas wash bottles filled with water and placed in a controlled water bath. For the high relative humidity conditions, the water bath was adjusted at 70 °C, while for the low relative humidity conditions the air pump was connected directly to the vacuum oven without passing through the gas wash bottles.

A vacuum oven connected to gas bottles placed in a water bath, which were connected at the other end to an air pump, was used to provide the required conditions. The conditions in both parts (the sodium sulfate and the 'Petra' solutions) were based on the collected microclimate data from the studied monuments.

5. Results and discussion

The highest disintegration rate in all tested specimens was recorded under fluctuating wind speed and low relative humidity (run 3), followed by high wind speed and low relative humidity (run 2). Also, it was observed that the weight loss was generally higher at low relative humidity (runs 1-3) compared to high relative humidity (runs 4-6). In the high relative humidity runs, the weight loss was higher in high and fluctuating wind speed conditions compared to the low wind speed conditions, with the highest in fluctuating wind speed conditions.

In the second part of the modified salt crystallisation test, where the Petra saturated salt solution was used instead of the sodium sulfate solution, the rate of disintegration was much lower. But as regards the role of wind speed conditions in the weight loss or gain of the samples, similar results to the sodium sulfate solution test were observed. The highest weight loss in both low and high relative humidity conditions was recorded under fluctuating wind speed conditions. It should be stated that, apart from the Petra specimens, most of the specimens showed weight gain rather than weight loss in most of the simulation runs. Based on the laboratory observation, this weight gain does not suggest that there has been no weight loss from the original specimens, but that the amount of the crystallised salts was higher than the amount of the lost particles of stones. In order to evaluate the durability of the specimens that showed weight gain rather than loss, the stone with the highest weight gain was regarded as the most durable one. This was based on the fact that the amount of salt uptake in all runs was very similar and, therefore, it seems logical that the specimen with the lowest salt content was the stone with the highest disintegration rate.

Disi sandstone specimens were the most vulnerable in all tests. The high clay content, the pore space geometry (small and coarse pore spaces) and the high porosity of this stone are the most likely explanations for such vulnerability.

The correlation between the water and salts uptake of the different specimens showed that all sandstone specimens (Petra and Locharbriggs) had a very similar capacity, while the limestone specimen (Monks Park) had a much higher capacity for water and salts uptake. Generally, the salt uptake was higher in the sodium sulfate solution test than in the Petra salt solution test. However, the weight loss was higher in the sandstone specimens and not in the limestone specimens that had the highest water and salt uptake. The small pore size and the lack of clay minerals in the Monks Park limestone are the most likely reasons for such behaviour.

In addition to the evaluation of the weight loss or gain of the samples, the research studied the distribution of soluble salts at the end of each run in both modified salt crystallisation tests (sodium sulfate and Petra salt solution tests). The results of the test using saturated sodium sulfate showed that sodium and sulfate ions were distributed differently under different wind speed conditions, with generally higher amounts in the surface intervals at low wind speed conditions and higher contents in deeper intervals under high wind speed conditions. These variations were more obvious under low relative humidity conditions. At fluctuating wind speed, sodium and sulfate were distributed uniformly throughout the tested specimens, but it should be remembered that under these conditions the specimens suffered a massive loss of material and therefore lost most of their salt content. At high relative humidity conditions, sodium and sulfate were in higher concentration near the surface of the specimens, with generally higher amounts in high and fluctuating wind speed conditions.

In the modified salt crystallisation test using Petra salt solution, the salt distribution analysis did not reveal a major role for the different wind speed conditions in the distribution of salt ions in the tested samples. Generally, the highest percentages of salt ions were concentrated in the surface samples and then were distributed uniformly at the deeper depth intervals. The ESEM investigation showed that the sodium-chloride system distribution was uniform, while the potassium-sulfate system was slightly higher at deeper intervals at high and fluctuating wind speed conditions.

The post-test petrographic studies and ESEM investigation showed that the pore sizes and the total porosity of the tested samples increased massively by the end of sodium sulfate test, with the highest increase under fluctuating wind speed and low relative humidity conditions. In addition, at the end of the modified salt crystallisation test using Petra salt solution, the Petra samples suffered a considerable loss of their clay minerals matrix. The loss was observed mainly at high relative humidity conditions.

Considering all results, it can be concluded that the simulation tests were mainly in agreement with the research's hypothesis that the fluctuation in wind speed enhances the salt damage behaviour in porous materials. However, the exact mechanism of this process has not been identified. The evaluation of the test results points towards three possible mechanisms that can lead to salt damage under fluctuating wind speed. One is the crystallisation of a high percentage of salt ions during high wind speed conditions and the dissolution of some of these ions during low wind speed conditions. The succession of high and low wind speed results in a succession of crystallisation and dissolution cycles causing higher damage than a steady rate of crystallisation would cause. The other mechanism is based on the relationship between different wind speed conditions, pore structure and type of salt solution. The fluctuating wind speed can enhance the salt damage by creating a combined pressure during high and low wind speed cycles. During high wind speed, the evaporation rate at larger pores will increase resulting in higher crystallisation pressure than in the smaller pores compared to a low evaporation rate during low wind speed. During low wind speed, however, once the salt solution enters the small pores of the stone, it will be capable of less movement and will therefore have more time to crystallise within the small pores, thereby creating higher crystallisation pressure there. As a result, at fluctuating wind speed conditions, the porous materials will be subjected to a continuous pressure at both high and low wind speed intervals, which will result in more damage. In addition, another explanation for the higher weight loss ratio at fluctuating wind speed conditions could be the way salt distributes inside the pores, since the relatively sound samples showed higher sodium sulfate content at deeper depth intervals during fluctuating wind speed than at low and high wind speed conditions.

6. Salt damage and simulation tests: what is really needed?

In the current research, discussion of the different simulation tests for salt damage has shown the diversity and complexity of the used tests and the confusion caused by the correlation of their results. Also, it has been demonstrated that each test, including that applied here, was formed according to the particular needs of each study. The author believes that it is time to establish one standard salt damage simulation test procedure that will include all possible factors with more realistic testing conditions and will thus have a wider applicability. The idea behind this suggestion is to minimise the impact of the simulation test procedure on the overall results making results more easily comparable and also to provide a salt simulation test that is able to evaluate the effect of all factors involved in salt damage. The identification of these factors should be based on a comparative evaluation of salt damage as it happens in nature. For instance, despite the fact that many scholars have pointed out the role of wind speed in salt damage, none of the commonly used standards, such as the BRE and ASTM standards, have included this factor in their simulation procedures. In addition, many studies that have developed simulation tests with environmental conditions based on fieldwork observations, such as the simulation test of this research, have not attempted to make their tests applicable to other environmental conditions. In this respect, a test with one standard procedure but also with a certain flexibility that would simulate the salt behaviour in porous materials under different environmental conditions would be ideal. This could be achieved if a single procedure were designed to operate under three or more test environments, each representing a particular climate type. The simulation test of the current research, which has been designed to include possible factors relating salt damage to its environments, was based on a field survey at the site of Petra and represented a typical dry, arid climate. It could however be made more applicable for other sites with different climates by introducing two or three more test phases, each simulating the environmental conditions of a particular climate.

7. Conclusions

The results of the present research have shown the importance of including the wind speed factor in the salt weathering simulation tests, since both the salt decay rate and the salt distribution were found to vary significantly at different wind speed conditions. Fieldwork observation and data analysis as well as laboratory experiments in this research have shown that wind speed conditions have a major impact on the salt crystallisation and distribution in porous building materials. While the fieldwork data and samples analysis have revealed a strong relationship between salt content in the collected samples and wind speed at the sampling locations, the simulation test has indicated that wind speed affects the rate of stone decay, with the fluctuating wind speed conditions causing the highest damage. In addition, the depth of salt distribution in the samples varied under different wind speed conditions, especially in the experiment that used a single salt solution (sodium sulfate). The research has also emphasised the need for standard procedures in the salt weathering simulation tests that will incorporate all factors involved in the salt damage process and will have wider applicability by including conditions that represent more than one climate type.

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