Salt Damage at Petra, Jordan: A Study of the Effects of Wind on Salt Distribution and Crystallisation

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Abstract

The crystallisation of salts in porous building materials is a principle agent of decay in historic monuments and archaeological sites, including the World Heritage Site of Petra, Jordan. Nonetheless, the mechanism of salt damage is still inadequately understood. This research was undertaken in order to examine the role of wind speed in the salt damage process. This paper evaluates the role of wind speed in salt crystallisation 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 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, depths and heights at the same monuments. The tests were undertaken with sandstone and limestone specimens under controlled environmental conditions, including low, high and fluctuating wind speed. The results have shown that wind speed has a significant impact on salt crystallisation and distribution in porous materials, and thus on decay rates, and that fluctuating wind speed enhances salt damage more than steady speeds. In addition, the research has suggested an unexpected relationship between pore structure and the behaviour of salts under different environmental conditions.

Keywords: Petra, salt damage, crystallisation, pore structure, microclimate conditions, wind speed, modified salt crystallisation, preventive conservation measurers.

Introduction

Archaeological sites are an essential part of our cultural heritage, with cultural, historical, architectural, social and economic values. Unfortunately, this important part of the world's cultural heritage is gradually being diminished. This can be due to the nature of the building materials of these sites, which are mainly porous inorganic materials, and the uncontrolled environmental conditions around them.

From a geological point of view, porous materials are more susceptible to weathering agents than non-porous materials. This is related to the fact that porous media are able to exchange their moisture content with the surrounding environments. The change in the moisture content of a porous material, especially stone, usually results in damaging features through a wide range of mechanisms.

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 (American Centre of Oriental Research (ACOR) 1999). The city suffers from weathering and erosion problems, both natural and human-in origin. Salt damage is one of the main weathering factors.

Despite the fact that the crystallisation of salts in porous building materials is a principle agent of decay in historic monuments and archaeological sites, including the World Heritage Site of Petra, the mechanism of salt damage is still inadequately understood. This research was undertaken in order to examine the role of wind speed in the salt damage process.

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. It is 255 km away from Amman (the capital of Jordan). (The international coordinates for the city are 35º 25′ E - 35º 28′ E and 30º 19′ N - 30º 21′ N. The archaeological city of Petra occupies about 15 km^2 and is 900 to 1500 m above sea level.

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.

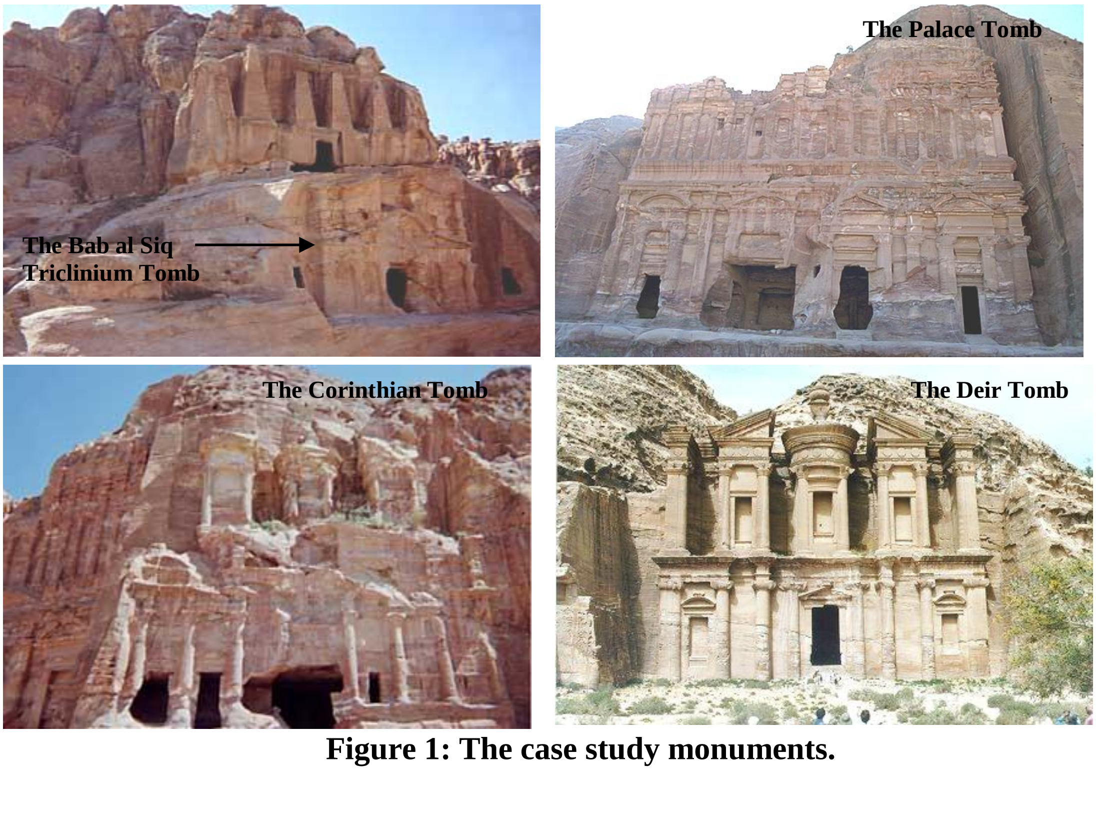

Figure 1: The case study monuments.

Petra: The Problem

Natural processes and human activities as well as lack of maintenance in the ancient city are all involved in the weathering process. Tectonic movement, water erosion, wind erosion, thermal shock and human activities are the main weathering agents in the site. Salt crystallisation is another, if not the major, weathering agent in Petra monuments. Previous studies, such as Al Naddaf's (2002), showed that drilled samples from the Petra monuments are rich in sodium chloride and calcium sulfate, while the scraped samples were dominated by calcium sulfate.

The observation of the current research determined the main weathering forms in the case study monuments and special photogrammetric maps were produced for each case study. Break out, spalling, washout, loose salt deposits, biological colonisation, flaking, granular disintegration, cantour scaling, pitting, relief and Fractures were the dominating weathering forms in the four case study monuments.

This study carried out a detailed survey of the salt types, locations and variations within the four case study monuments.

Fieldwork and laboratory investigations

A series of fieldwork investigations and laboratory work 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.

Figure 2: The main weathering groups, weathering forms and individual weathering forms at the Deir Tomb, Petra, Jordan

On the other hand, the first laboratory experiment was designed as follows: firstly, sandstone specimens were immersed in certain types of salts for a certain period, and then the saturated specimens were monitored in an environmental chamber under controlled microenvironment conditions. The experiment started with using a single salt solution of sodium sulfate, since this type is well known as a major damage-causing salt. After that, the other salt mixtures that were used for the experiment were chosen according to the types of salts that were detected present at the case study sites. Both experiments (single and mixed salts) were carried out at fixed temperatures and relative humidities and under different wind speed conditions. During the sodium sulfate experiment, three tests were carried out at different temperature and relative humidity conditions. Each test was carried out at four different wind speed conditions: no wind, low, high and fluctuating wind speed.

Figure 2: The microclimate experiment chamber

Figure 3: The microclimate experiment chamber

The second experiment was a modified version of the sodium sulfate crystallisation test that introduced the wind speed as a significant factor in the test. Two different salt solutions were used in the modified salt crystallisation test. The first was a saturated sodium sulfate solution and the second was a saturated salt solution similar to the salts solution found at Petra. This test was mainly based on the BRE (Building Research Establishment) test for the evaluation of stone building materials, especially limestone (Ross and Butlin 1989). 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 ± 2 ºC to 60 ºC. 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 crystallisation 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 crystallisation test. The wind speed was controlled using an electrical air pump that was connected to the vacuum oven by a plastic tube (this equipment and its function are discussed in detail in the following section). The experiment was carried out at three different wind speed conditions: low, high and fluctuating wind speed.

Moreover, previous studies of the salt crystallisation 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 (see the experiment equipment section). For the high relative humidity conditions, the water bath was adjusted at 70 ºC, while for the low relative humidity conditions the air pump was connected directly to the vacuum oven without passing through the gas wash bottles.