Thesis

Booklet

PhD

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Diagnosis and Analysis of Monument Deterioration Classification and Investigation

Study Case: The Medieval Fortifications of Syria/ Crac Des Chevaliers/

Doctoral School of History

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1. **The aim of the thesis:**

The primary goal of this research is to investigate the state of conservation of Crac des Chevaliers castle.

The investigation is mainly consisting of two parts: field and laboratory investigations. The field investigation includes identify the most common types of deterioration and how they spread at the castle; the in-situ classification of stone lithotypes; and the use non- destructive techniques (Rilem tube penetration test and Schmidt hammer) on different kind of lithotypes. The field investigation is ended by taking ten stone core specimens as well as stone deposits. The laboratory investigation includes determining the stone properties (petrographic, chemical, physical, and mechanical properties) of core stone samples. The behaviour of stone samples under various drying conditions is also studied, in addition to that the behaviour of stone samples in salt aging tests (the stones are subjected to salt solutions of NaCl, Na_2SO_4, KNO_3, and $MgSO_4$). The effect of the weathering crust on water vapour permeability is also examined to determine whether the weathering crust can serve as a protective coat from a conservation standpoint or not.

2. **The literature and the methods of the research**

This research begins with gathering the necessary data about the building site and its conditions, such as meteorological data, climate characteristics, and geological and environmental settings. One of the important data that is investigated is restoration history of the castle.

The in-situ and field investigations are divided into several steps. First, the identified stone deterioration cases are classified into various categories [the most serious issues are mechanical (impact) damage, microorganism colonization, salt efflorescence, discoloration, cracks, graffiti, splitting, erosion, and encrustation]. Then, identifying the castle's building stone based on the various lithotypes to which it belongs, along with a macroscopic description of those lithotypes. By the naked eye investigation, the castle was built mainly by carbonate stone in addition to the use of basalt stone in some buildings. This study is focused on examining carbonate stones because they are less resistant to weathering than basalt. By the field investigation, the carbonate stones are categorized into four lithotypes as follows: 1) homogenous porous stones (HPS); 2) homogenous dense stones (HDS); 3) laminated stones (LS); 4) newly built stones (NBS). Finally, the field investigation is completed by using non-destructive techniques that are useful for determining the properties of many stones in situ while causing no damage to any part of this valuable building. One of these techniques is deterioration mapping, which helps to provide a general overview of the distribution of stone decay cases; how they spread and prevail according to the direction of the façade; and it is useful to know which decay cases dominate in the castle. The deterioration mapping is performed on the external south façade of the building (46), as well as on the external east and north façades of the building (36). Rilem tube is also used as one of the non-destructive techniques. By that tool can figure out how the deterioration type and its intensity can affect the wettability property of the stone. In addition, it can help to estimate to what extent can the weathering crust protect the stone from the wind-driven rain. In this study, the different kinds of lithotypes as well as several decayed stone surfaces, are examined by this technique. Schmidt hammer, one of the non-destructive techniques, is used to test the same stones that were tested by Rilem tube.

It is critical to collect stone samples from the castle for laboratory analysis. Ten stone core samples (S1, S2, S3, S4, S5, S6, S7, S8, S9, S10) are collected from the castle, where the number and location are limited to administration recommendations and technical issues. These stone cores belong to different historical building periods (First Frankish period at the beginning of the 12^{th} century; the Second Frankish period from the beginning to the half of the 13^{th} century; and the Mamluk building period around 1271). In addition, many stone deposits and weathering powder were collected to be analysed.

The physical, mechanical, petrographic, and chemical properties of the stone cores are determined in the laboratory. Many tests are carried out on the stone specimens, including water absorption under atmospheric conditions and drying under different conditions.

3. The results

3.1 Field investigation results:

I. Rilem tube penetration test

The results of the Rilem tube penetration test demonstrate that the microorganism colonization and presence of salt efflorescence modify the wettability of stone property. The tested stones colonized by colonizations /grey and red-orange microorganisms/ mainly show no absorption behaviour or in some cases very low absorption behaviour. However, the stones previously exposed to mechanical shock (such as missile fragmentation) and colonized by microorganisms exhibit enhanced absorption behaviour (moderate one). As such the microorganism colonizations play a protective role in preventing the capillary water absorption of wind-driven rainwater.

The results of the Rilem tube conducted from salt efflorescence stone show that salt thickness is an important factor. Some stones do not exhibit any absorption behaviour because the water pressure applied from the type is not enough to penetrate the thick salt layer. However, In other tested stones, the absorption behaviour of which changes, where the absorption increases after a while. Firstly, the water pressure inside the tube allows to penetrate (dissolve) the salt layer, then the absorption enhances because the remaining salt cannot obstruct the capillary water absorption.

II. Deterioration mapping

The results of the deterioration mapping of three external facades with different directions (south, east, and north facades) show that the orientation of the façade is a key factor in the presence of some distinct deterioration types. The discoloration with orange is a characteristic stone deterioration type that is found in the south and east external facades. However, the grey microorganisms colonization is dominated in north and west facades. The red-orange microorganisms colonization can be found in the north façade in shaded moisturized areas.

3.2 Laboratory investigation results:

I. Water absorption under atmospheric conditions

In my results, the ultrasound velocity vs dry or saturated densities of all specimens exhibit a positive linear relationship. The regression equation between dry density (X1) and ultrasound velocity (Y1) is [Y1=2.9X1-2.5; R2=0.87]; and the one between saturation density (X2) and ultrasound velocity (Y2) is [Y2=5.6X2-9.5; R2=0.83]. However, the ultrasound velocity does not always relate to saturation degree by a positive trend. My specimens exhibit two different trends in the relationship between ultrasound velocity and saturation degree, the first one is a decreasing trend and the other is decreasing to a certain saturation degree and then it changes to an increasing trend. In S2, S5, S8, and S10, the relationship between ultrasound velocity and saturation degree is negative in that the velocity decreases with the increase of saturation degree during the water absorption under atmospheric conditions experiment. In the other specimens, S1, S3, S4, S7, and S9 the ultrasound velocity decreases with the increase of saturation degree up to 70% saturation degree in S1 and to around 80-90% in S3, S4, S7, and S9. Then they exhibit an increasing trend.

II. Drying characteristics

In my results of Group 1 (drying at fixed temperature), the specimens (S1 and S9 are not included), exhibit the same behaviour (the evaporation rate of which is about 1.72 kg/m2*h0.5 on average). The specimens S3, S4, S7, S8, and S10 have approximately the same open porosity (around 28v/v% on average) which implies the same drying behaviour (approximately the same evaporation rate).

My results of the drying characteristics Group 3 (non-sealed specimens under room conditions) demonstrate that more porosity implies more prolonged drying period, i.e. ability to retain water inside pores. S3 has the highest porosity (32 v/v% total porosity and 31.7 v/v% open porosity), where it has the low closed pores and high percentage of tiny pores (see thin section description). By the end of the experiment (after 52 h), all the specimens are water saturated between 1-4%, however S3 has 10% saturation degree at the end of that period.

In Group 2 (sealed specimens), which simulates the drying behaviour of the stone block in the building, the stage of the capillary water mechanism is delayed due to the evaporation from one surface. However, in Group 3 (with no sealing) that stage starts earlier comparing with Group 2.

Regarding the specimens with higher porosity (S3, S4, S7, S8, and S10), the drying behaviours of S10 and S8 are fast because of their high percentage of big pores (250-500 žm, as the thin section reveals) and well-connected pore system, which lead to more effective drying characteristics compared with other specimens.

III. Water vapour permeability

My results show that the specimens with approximately the same porosity (28v/v% open porosity and 30v/v% total porosity, in average) /S2, S3, S4, S7, S8, and S10/ have different values of water vapour permeability rate and these values are not close to each other / 3.8 E-11, 1.96 E-11, 2.6 E-11, 1.5 E-11, 1.3 E-11, and 2.45 E-11, respectively/. Thus my results confirm that the open and total porosity is not the key factor that controls the water vapour permeability.

In the field of conservation, the recommendation for using coating material is the water vapour permeability of the coating material should be equal to or 20% less than the water vapour permeability of the coated surface. My results demonstrate that in the crusted specimens of S1, S2, S3, S8, and S9 the water vapour permeability of which is 20 % less than the reference specimens(the same stones with no crust) regardless of the thickness of the crust (the crust thickness of these specimen ranges from very fine 0.08 to 3 mm). As such the cruts of S1, S2, S3 S8, and S9 can play a protective role from a conservation point of view regardless of the deteriorative role of the crust components. The crusts of S4, S7, and S10 (the crust thickness in S4 and S7 about 2 mm and 0.1 mm in S10) reduce the water vapour permeability between 40-45% compared to the water vapour permeability of the reference stones. Therefore, the crusts of S4, S7, and S10 contribute to forming condensation areas inside the stone blocks, which will increase the weathering effect of those crusts.

IV. Salt ageing test

My results of the salt ageing test of different salt solutions reveal that the salt solution are not at the same level of damaging to stone specimens. Potassium nitrates is the less damaging salt, where all specimens show no weight loss. Sodium chloride is a moderate damaging salt where the weight loss ranges between 0 w/w% (S1 and S9) to 8w/w% (for S2); except for S5 and S7 that are broken during the test. Magnesium sulphate has more damaging effect than sodium chloride. The weight loss of the specimens ranges between 0 w/w% (S1 and S9) to 27 w/w% (for S3), except for S4 that is broken during the test. Sodium sulphate is the most damaging salt. S5 and S7 are broken in the very first cycles (12th and 9th cycle out of 50 cycles); however The weight loss of the spcimens ranges between 0 w/w% (S1 and S9) to 50 w/w% (for S2).

My results conclude that the more compact stones are less susceptible to damage than the more porous ones. S1 and S9 are the most resistant specimens under the used salt solutions (sodium sulphate, magnesium sulphate, sodium chloride, and potassium nitrates), where they do not exhibit any weight loss, because they are the less porous stones among the tested stones (the open porosity of them are 18v/v% and 11v/v%). Furthermore, the specimens with similar or approximate effective porosity have the same amount of absorbed salt solution. However, they do not induce the same damage degree (weight loss percentage). S2, S3, S4, S7, S8, and S10 (50w/w%, 45w/w%, 10 w/w%, 100 w/w %, 20 w/w%, and 15% weight loss under sodium sulphate solution); the effective porosity of which around 28v/v% on average, do not exhibit the same degree of resistance. My results show that S4, S8, and S10 are more durable and resistant than the others (S2, S3, and S7) because they have a high percentage of closed porosity (around 4v/v%) compared with S2, S3, and S7 that the closed porosity of which about 0.5v/v% in average.

The observation of specimen behaviour under the hydrated salt solutions (sodium sulphate and magnesium sulphate) in my experiment reveals that the breakdown of the specimen (such as S7 and S5 in sodium sulphate solution and S4 in magnesium sulphate) occurs during the immersion period. The disintegration of stone material characterizes the specimens immersed in sodium sulphate solution. The specimens immersed in magnesium sulphate exhibited layer detachment.

However, the specimens experience salt efflorescence with a visible thickness on the surfaces with no weight loss under potassium nitrate solution. On the other hand, the specimens under sodium chloride experience a process called “self-cleaning”; which means that they do not experience salt efflorescence, rather visible salt crystals can be seen near the bottom of the specimens inside the tray of the oven after the drying period in each cycle.

4. Publications

- Ola Bilal, Rozgonyi-Boissinot Nikoletta: Stone deterioration on limestone from Syria, a case study: Damascus Citadel. In: Török ākos (ed.) MERNOKGEOLOGIA UJ EREDMENYEI. Magyarhoni Foldtani Tarsulat. Budapest. (2020) pp. 37-45.

- Ola Bilal, Rozgonyi-Boissinot Nikoletta: Diagnosis of stone deterioration in Crac des chevaliers, In: Siegfried, Siegesmund; Bernhard, Middendorf (eds.) Monument Future: Decay and Conservation of Stone. Proceedings of the 14th International Congress on the Deterioration and Conservation of Stone, Mitteldeutscher Verlag (2020) pp. 765-770.
- Ola Bilal, Nikoletta Rozgonyi-Boissinot: The evaluation of stone deterioration state by using the non-destructive techniques on a medieval fortress in Syria. In: José Delgado Rodrigues and Marluci Menezes (eds.) International Symposium Stone Consolidation in Cultural Heritage, LNEC, Lisbon, 23-25 March, 2022 (2022) pp. 105-118.
- Ola Bilal, Nikoletta Rozgonyi-Boissinot: Assessment of the Resistance of Dolomite Stone from Crac des Chevaliers Against Salt Crystallization. Periodica Polytechnica Civil Engineering (2023).
- Ola Bilal: Water vapor permeability of the dolomite from the Crac des Chevaliers Castle in Syria. In: Takács, Ván, Vásárhelyi (eds.) Engineering Geology-Rock Mechanics, (2023) pp. 169-178.
- Ola Bilal, Nikoletta Rozgonyi-Boissinot: Documentation and in-situ stone deterioration diagnosis: A case study Damascus citadel. Pázmány Péter Catholic University. In press.