HD Laser scanning for the evaluation of salt decay laboratory simulations of building limestone

M. Gomez-Heras1, B.J. Smith1, H.A. Viles2, J. Meneely1, S. McCabe1

1School of Geography, Archaeology and Palaeoecology, Queen's University of Belfast, UK
2Oxford University Centre for the Environment, Oxford University, UK.

Abstract

Laboratory salt decay simulations are a well established method to assess the relative durability of stone. There is still, however, very much scope to implement improved monitoring techniques to investigate the changes experienced by the materials during these experiments. Non-destructive techniques have acquired over recent decades a preferential status for monitoring change samples during salt decay tests, as they allow cumulative tests on each sample. The development of HD laser scanning permits detailed mapping of surface changes and, therefore, constitutes an effective technique to monitor non-destructively surface changes in tested samples as an alternative to other monitoring techniques such as traditional weight loss strategies that do not permit any degree of spatial differentiation that can be related, for example, to underlying stone properties.

Keywords

Stone decay, Salt weathering, Laser scanning, Laboratory simulations

1. Introduction

Salt crystallization is undoubtedly one of the main agents causing decay of stone-built heritage and its effectiveness to generate severe damage in building stone has been long recognized. In this sense, laboratory tests involving salt crystallization are frequent and present in almost every study concerning stone decay from a general
point of view, both as a part of durability tests aiming to characterize or predict the performance of stone masonry in use, or of laboratory simulations that try to replicate more accurately the dynamics of salt crystallization for a determined environment.

Salt crystallization tests have a long tradition as a way of assessing the relative quality of building stone. Well before the classic works from Correns (1939, 1949) recognized and individualized the effects of salt crystallization pressure as disruptor of the stone integrity, salt crystallization tests, with sodium sulphate, were routinely used to assess the performance of building stone as a way of modeling ice crystallization due to its recognized effectiveness in generating damage by crystallizing in stone pores (De Thury, 1828). Nowadays, resistance to salt crystallization is still one of the main parameters in the commercial assessment of natural stone quality (EN 12370) or recommendations for building materials (RILEM, 1980). Within the context of academic research, salt crystallization is also one of the most common parameters to include in combinations of decay factors in laboratory weathering simulations (e.g. McCabe et al., 2006).

Testing the effects of the salt weathering simulations can be done either by comparing initial and final state before and after the tests, or preferably by monitoring non-destructively the evolution of samples during laboratory tests. Several parameters have been proposed to evaluate numerically the effects of salt crystallization during laboratory tests. These range from visual coefficients, based on the extent of the observed damage of the samples (e.g. Ruedrich & Siegesmund, 2007; Van et al 2007), or weight loss during tests (as for example the above mentioned EN 12370 standard), to other durability estimators based on petrophysical properties such as ultrasounds velocity, (e.g. Ruedrich & Siegesmund, 2007), porosity (e.g. Ruiz-Agudo et al. 2007) and mechanical properties (Benavente 2004).

Most of these indicators are based on destructive testing and act on ‘black box’ type experimentation (i.e. they only take into account initial and final state) and do not take into account the individuality of each block as they use as comparators ‘undecayed’ blocks that have not been experimented on and cannot access the actual original characteristics of the test blocks. They also give a ‘non-directional’ measure of the decay and often use methodologies which cannot be extrapolated to on-site testing.

Therefore, it is important to find techniques which are non-contact, non-destructive and allow a continuous monitoring of the samples throughout, especially to identify precursor surface modifications that appear in tested blocks prior any visible decay happens. Some attempts have been made through point contact methods lowering a dial gauge to pre-selected points (Smith et al. 2002) or more recently by means of laser based systems (e.g. Moropoulou et al. 2003, Swantesson, et al. 2006). Laser scanning offers a non-contact method to monitor the surface changes in a very detailed way of a block subject to weathering. While the use of ground LIDAR for building survey has accelerated in recent years, especially when associated with fluorescence techniques (Cecchi et al. 2000; Palombi et al. 2008), the use of HD laser for laboratory monitoring is still limited, yet deserves further exploration.

This paper aims to present preliminary results from two samples of a bioclastic limestone subject to a combination of salt crystallization cycles and different
conditions of debris removal for the purpose of evaluating HD laser scanning as a non-destructive aid to monitor non-destructively the evolution of salt weathering tests.

2. Methods

Experiments were carried out on Jurassic limestone samples from the Bath region of the trade-named Stoke Ground Base Bed (SGBB). Stoke Ground is a porous (27.1 %), sorted oosparite used in construction across central and southeast England. The samples were cut into two ashlar blocks measuring approximately 18x24x10cm. Brass screws were fixed to the sides of the blocks as reference points for the laser scanning and the blocks were insulated with expanded polystyrene on five sides to leave one exposed 18x24cm face through which salt, moisture and temperature could be cycled. The blocks were placed with their exposed faces horizontally in a commercial salt corrosion cabinet that allows for the samples to be wetted with a fine mist of salt solution. The salts were a mixture of 5% by weight sodium chloride and 5% by weight magnesium sulphate. This combination was chosen as representative of urban environments and, combines sulphate hydration and/or chloride crystallization (Kamh, 2007). The blocks were initially subjected to a series of relatively mild temperature regime cycles followed by a short series of more extreme temperatures regimes before returning to the ‘mild’ regime. This was to test if the different laser scans were able to detect subtle variations in the weathering regime as a consequence of this simulated seasonal variation. The final distribution of cycles was 40 ‘mild’ temperature cycles – 20 ‘extreme’ temperature cycles – 20 ‘mild’ temperature cycles. The ‘mild’ temperature cycle is based on previous weathering studies carried out by McCabe et al. (2006) and consist of 10-hour diurnal equivalents between 15 and 30 ºC with 3 hours of salt mist sprayed on alternate cycles. The extreme temperature regime cycle is based on the Negev cycle (Goudie & Viles, 1997) and comprises a 12-hour diurnal equivalent between 15 and 40ºC in which salt solution is sprayed in alternate cycles during 3 hours just before the heating phase.

Before the experiments began the surface of both blocks was scanned at a 0.05mm resolution with a HD-laser Konica Minolta object scanner (VI-91 3D Digitizer) and after cycles 10, 40, 60 and 80 the blocks were removed from the cabinet and re-scanned. Then, one of the blocks was left intact (SG-NB) while the other block was placed vertically and lightly brushed (SG-B) to remove the debris formed. This block was subsequently re-scanned after debris removal. Data from the scans were used to calculate several quantitative morphological indices on a 17cm circle centered in the centre of the block. The selected indices are: Surface area, volume above an arbitrary datum plane and the Hurst exponent (H) of the surface.

Surface area was calculated as the surface of the Triangular Irregular Network generated by the successive laser scanners by means of the Leica Cyclone 3D Point Cloud Processing Software. Therefore, this value is an indication of the Specific Surface Area of the stone before any process of crystallization takes place. Thereafter, as the scan does not differentiate between salts crystallized within pores and stone, the surface area measurement will be a function of both of them. The volume above datum corresponds to the volume of solid between the Triangular Irregular Network and a datum plane situated parallel to the surface and fixed for all the measurements,
calculated at a 1mm spacing and a depth resolution of 0.05mm using the above-mentioned software.

The Hurst exponent (H) is a concept related to fractal geometries that has been previously used to characterize surface roughness for stone structures (Schmittbuhl et al. 2004, Broustea et al. 2007). H is directly related to fractal dimension, D, such that $D = 2 - H$. On the assumption that surface topography is appropriately defined by a statistically self-similar surface, the fractal dimension provides an indication of how rough a surface is. It must be noted that the Hurst exponent indicates roughness as a
factor of the complexity of the surface and does not take into account, as do other roughness indices, the absolute difference between peaks and valleys in the rock surface. The values of the Hurst exponent vary between 0 and 1, and a small Hurst exponent relates to a higher fractal dimension and corresponds to a rougher (more complex) surface. D was calculated using Rockware GS+ software.

![Graphs showing the values of volume, surface area and roughness during the experiments. Higher values of H represent smoother surfaces, hence the inverted scale.](image)

**Figure 2**: Graphs showing the values of volume, surface area and roughness during the experiments. Higher values of H represent smoother surfaces, hence the inverted scale.

3. Results and discussion
The results of laser monitoring for both the non brushed (SG-NB) and successively brushed (SG-B) tested blocks are presented in Figures 1 to 3. Figure 1 shows the 17cm diameter HD laser scans of the weathered blocks for the initial pre-weathering conditions, after 40 and 60 cycles (which are coincidental with the moments in which cycle type was changed) and for the end of the experiment after 80 cycles. Scans before and after brushing are presented for the SG-B block. Figure 2 shows the changes in the different indices selected to monitor the evolution of the blocks during the experiments, including the values before and after brushing for SG-B, while Figure 3 shows the graph of weight loss for this latter block.

All of the graphic information highlights the impact of the changes of environmental cycles between the ‘mild’ and the ‘extreme’ cycles and vice versa, as well as the dramatic changes consequent upon the removal of the surface debris from the samples. In this way, three sectors, which are coincidental with the different experimental regimes, can be clearly identified in all graphs.

![Accumulated weight loss for SG-B.](image)

The first sector corresponds to the first 40 ‘mild’ cycles. This sector represents the same conditions for both of the tested blocks, as blocks did not show any loose debris until cycle 40 and therefore brushing was not performed on SG-B until that cycle. Hence, this first sector shows similar trends for both blocks in terms of volume above datum and roughness, which are consistent with the swelling shown by the HD laser images (Figure 1). However, surface area trends vary from the block SG-NB to the SG-B. While SG-NB shows an initial decrease and a subsequent increase in surface area, SG-B shows an increase and subsequent stabilization of this parameter. The dissimilarity of the trends shown in surface area is interpreted as the result of two different processes of salt crystallization in surface pores. Salt crystals will tend to fill partially large pores at the beginning of the experiment resulting in a diminution of surface area (SG-NB 0-20 cycles). In contrast the rapid filing of smaller pores can lead to the development of an efflorescence (positive relief) that increases overall surface area (SG-B 0-20 cycles) After this initial stage of pore filling, the progressive swelling would be reflected in an increase of all the parameters.

Comparison of the results before and after the first brushing of SG-B reveals a decrease in volume above the datum and of roughness, coupled to an increase in
surface area. The decrease in volume above the fixed datum is associated to with debris removal caused by brushing. Equally, the removal of loose grains causes an increase in surface area. The roughness decrease (H increase) could appear contradictory to the increase of surface area, but it must be taken into account that H measures the complexity or ‘randomness’ of the surface topography, as opposed to other roughness indexes used in the context of stone decay studies that measure roughness on the basis of height differences between peaks and valleys (for example Rz – sum of the vertical distance between the five highest peaks and the five deepest valleys within the sampling length). H decrease (roughness increase) during the salt cycles could be a response to the generation of blisters that create localized complexity on the surface. Following brushing after cycle 40, these localized heterogeneities disappear, thus, ‘smoothing’ the general topography of the surface. Therefore a decrease in roughness determined by the H increase is compatible with an increase of surface area.

![Figure 4: Detached surface blister on granular building limestone coupled with the generation of a hollow due to a weakened subsurface.](image)

The second sector of the graphs corresponds to the more aggressive ‘Negev-type’ cycles. In these sections of the graphs, the general trends are similar to those observed in the first sector but with a steeper rate of change. It is worth noting the similarity between the pattern of the weight loss for the block SG-B (figure 3) and the volume above the fixed datum for the SG-NB block. In particular, weight loss seems to provide a strong indication of a more rapid change during the aggressive cycles. It could be argued that this only occurs because of ‘pre-weathering’ during the preceding ‘milder’ cycle, but this argument is undermined by the decrease in rate of weight loss once the experiment returns to ‘mild’ conditions. It is also noteworthy that the slopes of the graphs in this sector are the same for both blocks. In contrast, the results from brushing of block SG-B after the second set of cycles show dramatic differences compared to results following the first brushing. The same decrease in volume above the fixed datum is observed, this time with a steeper rate of change. Surface area and roughness show opposite trends to those observed after the first episode of brushing.
While the results from brushing after the first set of cycles are interpreted as the results of the generation of swelling and flaking in the surface during the first set of cycles without subsurface detachment, results from second brushing after the more aggressive cycles is interpreted as the result of the generation of blisters that also affect the subsurface of the block. This is clearly seen in figure 1 in the images from the SG-B block after cycle 60 in which the areas with more positive relief before brushing (corresponding to blisters) transform into pits after brushing. This explains the increase of roughness generated as a consequence of the second episode of brushing. This is in agreement with the observations of this phenomenon in real cases of building stones, in which the detachment of a surface blister promotes the generation of a hollow (figure 4).

The third sector of the graphs corresponds again to the ‘mild’ environmental cycles. In the data from the SG-NB block, the rates of change of the volume above the datum and the roughness return to rates similar to those observed in the first sector. The exception to this is a decrease in the surface area for the SG-NB block. However, in the case of the brushed SG-B block the trends change completely from the first to the second set of ‘mild’ cycles, suggesting an increasingly complex weathering regime as a result of the combination of environmental conditions and the repeated removal of debris from the surface. The causes for these changes are as yet unclear and highlight the need for repeat experiments to assess not just surface change but also to study more closely linked process responses.

4. Conclusions

These preliminary results show the HD laser scan is a very sensitive non-destructive technique that detects subtle changes produced during simulated weathering experiments, especially when changing the experimental conditions. In interpreting these results it must be remembered that the experiment was restricted to one stone type and a limited range of environmental conditions. Its purpose was not to understand the salt weathering of Stoke Ground, but to ascertain whether meaningful and ‘useful’ measures of surface change could be obtained from HD laser survey. Within this context, it has demonstrated that the technique can be used effectively for repeated re-survey with a high degree of precision. The results further demonstrate that in many instances trends and discontinuities in the time series produces can be linked to physical changes in the surface that are explicable in terms of the processes acting. In other cases, however, changes are noted that are either ambiguous or require further explanation. In some ways the uncertainties and ‘unknowns’ are similar to developments that took place in the field of geomorphology in the 1950’s and 60’s in attempts to characterize the morphometry of landscape change. Whilst the landscapes of the block surfaces are of a vastly different scale, they highlight the fact that the same morphometric responses can derive from a variety of pathways – so-called equifinality. To understand the ambiguities, geomorphologists attempted to link morphological change to a detailed study and understanding of the processes operating. The same requirement is clearly needed if we are to take the morphometric analysis of test blocks to the next level of understanding.
Results for this study suggest that efforts could initially concentrate on, for example, refining the characterization of the surface area parameter, as the inability of distinguishing between stone and salts in the scan make it difficult to interpret the results obtained. Further work is also necessary in relation to the use of H, as heterogeneous stone surfaces may not be purely random and, as discussed by Broustea et al. (2007) for the case of stylolites, the combination of H with other indices may be necessary to fully characterize a rough heterogeneous surface.

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References


