Geostatistical analysis of multiple correlated variables from salt weathering simulations

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Abstract— **Geostatistical analysis is used to investigate the spatial relationships and quantify the spatial uncertainty between the trigger factors of stone decay in salt weathering and the effect on salt penetration. Interactions between the rock properties of permeability, porosity and mineralogy have implications for moisture movement and salt input, output and storage. The weathering simulation in this study was designed to simulate pre-loading of salt during a wet winter and then complete drying out in summer. Non-destructive (probe permeametry) and destructive techniques were applied to the weathered block. This provided a spatial dataset of several variables for geostatistical analysis and the potential to quantify the degree of spatial correlation between variables to characterise the salt weathered block. The linear model of coregionalisation (LMC) was used to simultaneously model the direct and cross variograms for subsequent kriging and simulation. The results showed strongest spatial cross correlation between permeability data and salt (NaCl) data at a depth of 4-6 cm in the salt loaded sandstone block and suggest that, initially, salt concentration in the near-surface zone decreases permeability. However, continual wetting with salt and alternate heating, increases permeability, enabling the ingress and movement of salt and moisture more effectively through the stone.**

Keywords: salt weathering; spatial cross correlation; cross variograms; permeability

I. INTRODUCTION

This study builds on a long history of previous weathering research that indicated the importance of intrinsic and extrinsic factors as triggers for decay processes and an awareness of the unpredictability of decay dynamics. This research investigates the use of spatial analysis techniques to examine the spatial variability of rock properties as a potential contributing factor to the inconsistent nature of weathering response. This has implications for moisture movement and salt input, output and storage. Unpredictability in stone decay processes can present significant problems when planning conservation and future stone building strategies. Previous research focused on surface modification of building stones has provided a conceptual model of building stone decay (Smith, Warke, McGreevy and Kane, 2005). The aim of this research is to quantitatively test the conceptual model through spatial analysis techniques, comprising geostatistics and GIS, to visualize, simulate and model the dynamics of stone decay. A Carboniferous Peakmoor Sandstone (quarried on Stanton Moor) was used in the salt weathering experiments and is representative of a stone type frequently used in construction and restoration programmes (BRE, 2000). A block of dimensions 20x20x20 cm was used to represent a building stone in the salt weathering experiment.

This research was funded by EPSRC grant EP/E049648/1

II. EXPERIMENTATION

A. *Baseline Assessment of Fresh Stone*

The first stage of the research involved characterisation of a fresh block of the sandstone. This provided a three-dimensional image of the mineralogical and structural properties of the fresh sandstone. The fresh block was analysed using non-destructive probe permeametry (using an unsteady-state Portable Probe Permeameter) and destructive techniques (thin section analysis (TS), scanning electron microscopy (SEM), ion chromatography (IC) and x-ray diffraction (XRD). Non-destructive probe permeametry provided a single measurement (miliDarcies mD) per point using an unsteady-state Portable Probe Permeameter PPP250^{TM} (Core Laboratories Instruments, 2001).The representative block of fresh sandstone was cut horizontally at 2cm intervals to produce slices through the block. A grid pattern of non-destructive measurements was used for each slice followed by destructive sampling for analysis. Measurement of the fresh rock enabled a baseline assessment of the sandstone: an integral step for modelling and analysis of subsequent deterioration and decay pathways.

B. *Rapid Salt Weathering Simulation*

The second stage of the study comprised the use of a rapid salt weathering regime, designed with the experience of established weathering studies (Goudie, 1974; Smith and McGreevy, 1988; Warke, McKinley and Smith, 2006; McCabe, Smith and Warke, 2007), to replicate experimentally the retreat of individual building stones. Climate change studies on NW British Isles have projected increased seasonality with winters expected to become warmer and wetter. The salt weathering experiment employed in the research was designed to account for the implications of increased seasonality on building stones. To simulate the complete wetting of a building block during a damp winter, the weathering experimentation involved pre-loading a block of Peakmoor sandstone with salt. The block was placed in a bath of solution of equal parts NaCl and MgSO4 (salts commonly associated with temperate maritime climates) for 48 hours, with heat applied to the top surface. This encouraged capillary rise of the solution to the 'back' face of the block. Data were recorded at a series of stages through the weathering simulation to explore changes in trigger factors such as porosity, permeability, mineralogy and to examine the effect of salt surface concentration, salt penetration and accumulation at depth. This enabled interactions between rock properties and salts to be quantified to predict and model the dynamics of stone decay. Permeability measurements (mD) were made on a 10x10 cm grid for each block slice. Following probe permeametry on the exposed surfaces, the blocks were then dry cut horizontally at 2 cm intervals as described for the fresh sandstone block. The sampling scheme and complete block analysis was designed to characterize the permeability of sandstone blocks subjected to a rapid salt weathering regime in three dimensions. IC analysis proved to be extremely effective in providing quantitative data of the concentration of salt at the surface of the blocks along with the amount of salt penetration and accumulation at depth.

III. Geostatistical Analysis

The use of geostatistical analysis in this research provided a quantitative basis for quantifying and visualising the effects on building stones of weathering in temperate maritime climates (McKinley, McCabe and Smith, 2008). Research on the vast data base generated from the study is ongoing but current findings of the study elucidate weathering processes at the different stages of the conceptual model. Results from the salt-loaded block of Peakmoor sandstone designed to simulate complete wetting of a building block during a damp winter indicate that surface pores can block very quickly in response to salt weathering (only pore throats need to block to inhibit subsequent ingress of moisture and salts). Salt crystallization on the surface may establish a period of stability (in the form of a salt crust) because surface pores are blocked and permeability is reduced minimizing the ingress of moisture and salts.

The results indicate, however, that stability is temporary and at greater depth permeability begins to increase resulting in pore stresses due to crystal expansion. This acts as a positive feedback mechanism developing a zone of transition that enables the inward migration of salt. Continual wetting with salt and alternate heating enables the ingress and movement of salt and moisture through sandstone building stones (McKinley and McCabe, 2010). This study addresses the importance of the spatial distribution of salts in the weathering process of stone decay. The sampling grid used, facilitated permeability measurements and salt at the same relative positions for each rock slice. This enabled permeability, porosity and mineralogy data to be cross correlated with dynamic data (such as salt movement) to test the spatial relationship between rock slices and salt accumulation and any subsequent decay of the stone block.

A. Spatial Cross Correlation

The linear model of coregionalisation (LMC) was used to simultaneously model the direct and cross-variograms for subsequent kriging and simulation. In the LMC, the cross- and auto-variograms for the individual variables are modeled at the same time. The same number and type of structures must be fitted to the cross- and auto-variograms, and these must all have the same range. The strength of the cross correlation is indicated by the proximity of the cross variogram to the hull of perfect correlation (Wackernagel, 2003); if the two are close the cross correlation is strong and vice versa (Webster and Oliver, 2007). For the fresh sandstone highest correlation between permeability measured on rock slices was recorded at a depth of 10-12 cm in the sandstone. Highest correlation between permeability data for the salt weathered block was found at a depth of 8-10 cm and 14-16 cm in the sandstone block. Fig. 1 shows the cross-variograms for permeability data between rock slices for the fresh (A) and salt-loaded (B) sandstone blocks of Peakmoor sandstone.

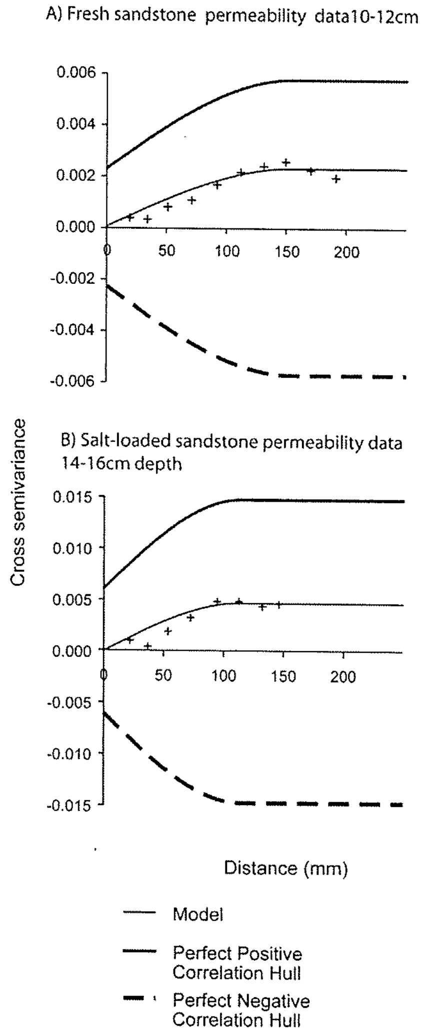

Figure 1. Cross variograms of permeability for (A) fresh and (B) salt-loaded sandstone blocks

The cross-variograms were selected based on the strength of the correlation coefficients. Correlations between the selected rock slices are all positive and the cross-variograms are positive. The graphs show the hulls of perfect correlation for the cross-variograms. For both the fresh and salt-loaded blocks the models are some way from the hulls. This indicates moderate spatial cross correlation between these rock slices as also indicated by the correlation coefficients (0.28 and 0.24 for the fresh and salt-loaded sandstone respectively). The coregionalisation analysis indicates spatial variability in the degree of connectivity in permeability between rock slices which would enable the movement of moisture and salts through the stone. The movement of salt was found to be dependent on the composition and mobility of the salt solution with both sulphate and chloride salts accumulating in the near surface zone (Fig. 2).

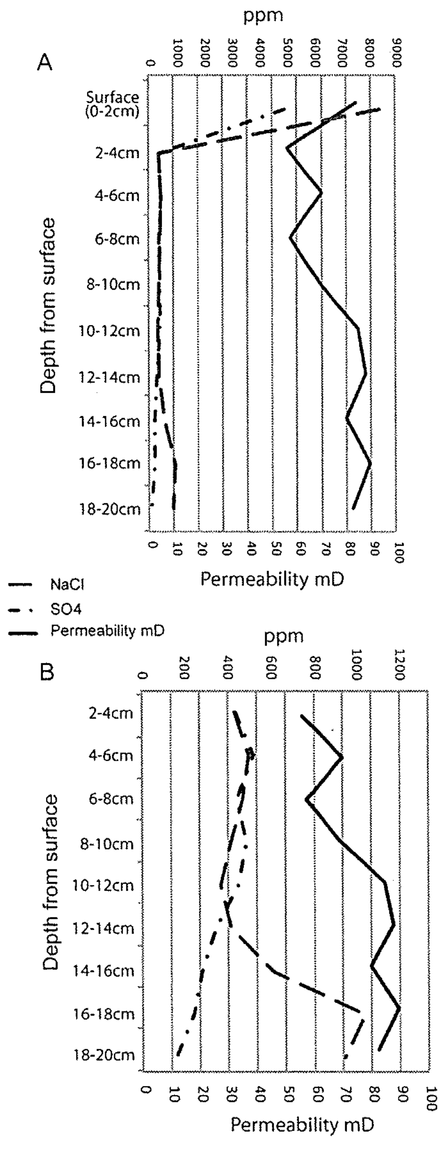

Figure 2. Cross correlation between permeability, chloride and sulphate salts

The results indicate strongest cross correlation between high permeability values and salts (chlorides and sulphates) at a depth of 4-6 cm in the salt loaded sandstone block (Fig. 2). At 6-8 cm depth in the block a decrease in permeability correlates with high salt concentration.

Fig. 3 shows the modelled variograms of (log) permeability (A), chloride (B) and sulphate (C) salt concentrations for 4-6cm depth in the Peakmoor sandstone salt-loaded block. The modelled variograms estimated for the salts indicate spatial structure in the concentration of salts across the block at this depth. The variogram of permeability has a large nugget value (nugget:sill ratio = 76%). This suggests a more spatially variable distribution of permeability values across the block at a depth of 4-6cm.

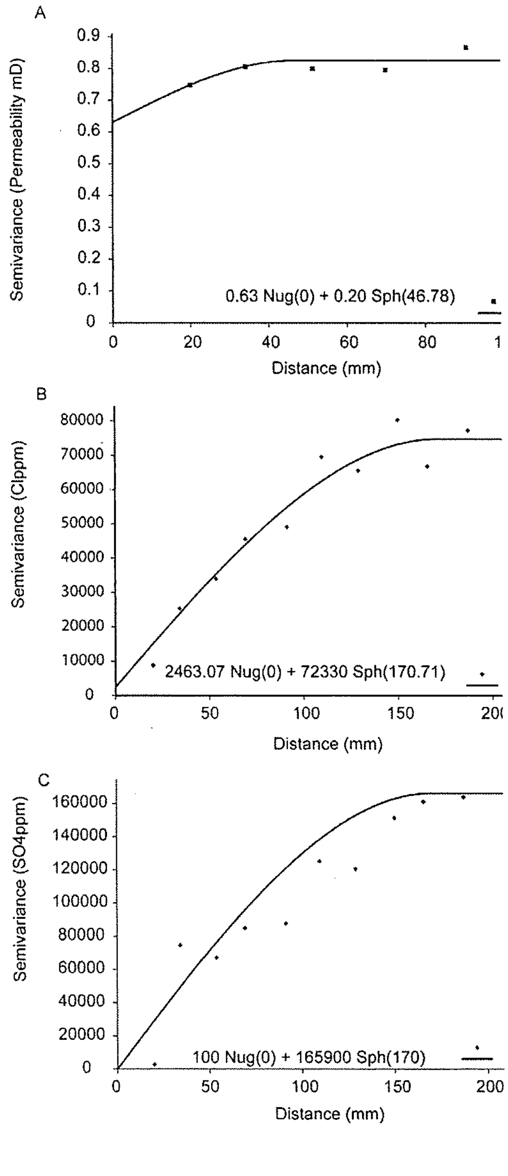

Figure 3. Modelled variograms of (A) permeability, (B) chloride and (C) sulphate salts.

Fig. 4 shows the kriged maps of permeability (A), chloride (B) and sulphate (C) salt concentrations for 4-6 cm depth in the Peakmoor sandstone salt-loaded block. An 'edge effect' is observed where highest salt concentration occurs at the edges of the block. This concurs with high permeability values on two outer edges of the block but there is spatial variability of permeability values across the block. This suggests the combination of salts is effective in changing the intrinsic properties (permeability and porosity) of the stone and may result in accelerated stone decay. The moderate spatial cross correlation at a depth of 14-16 cm in the salt-loaded block demonstrated, by the coregionalisation analysis, corresponds to an observed decrease in permeability and an increase in chloride salts. Chloride salts were found to concentrate at much deeper levels in the stone. The moderate connectivity demonstrated in permeability at this depth may have enabled the movement of the more mobile chloride salts to the 'back' of the block.

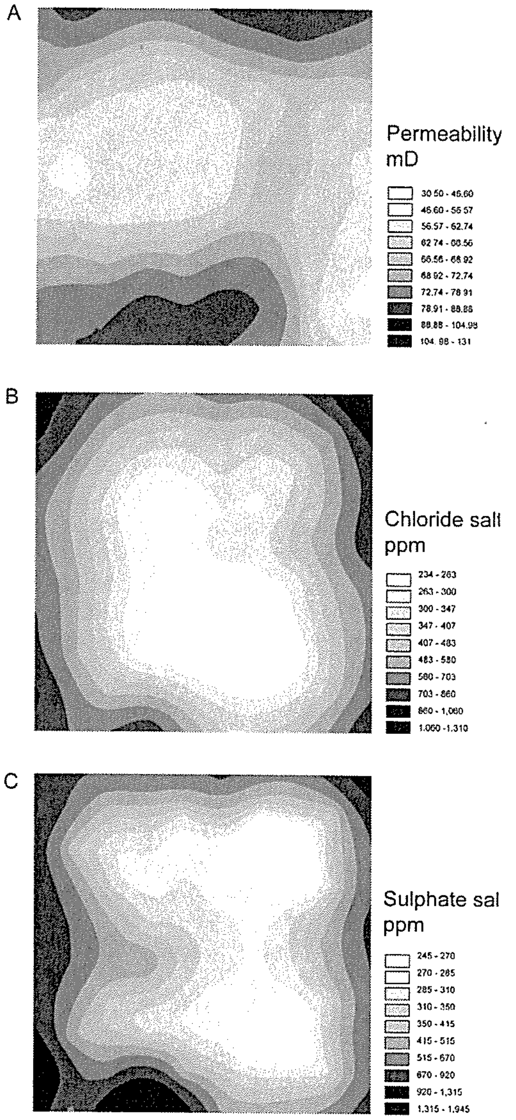

Figure 4. Kriged maps of (A) permeability, (B) Chloride and (C) Sulphate salts at a depth of 12-14 cm in the salt-loaded sandstone block.

IV. Conclusions

The research underlines the role of spatial analysis in modelling the decay dynamics of stone masonry. The results indicate that initially, permeability decreases with an associated build up of salt concentration in the near-surface zone. Following continual wetting with salt and alternate heating however permeability is increased, enabling the ingress and movement of salt and moisture more effectively through the stone. This has significant implications for stone conservation strategies.

The salt-loading weathering simulation produced multiple variables (including permeability, porosity and mineralogy) to investigate the trigger factors of stone decay. As the number of variables increase fitting the direct and cross variograms simultaneously becomes increasingly difficult. The ongoing study examines the use of collocated cokriging in Gaussian simulation to study the interaction between rock properties and salts.

V. Acknowledgements

Thanks to the laboratory staff of the Weathering Group at Queen's University Belfast for assistance with the preparation and analysis of samples.

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