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SPATIAL DISTRIBUTION OF SALT PENETRATION IN WEATHERED SANDSTONE

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Abstract: This research investigates the importance of the spatial distribution of salts in the weathering process of stone decay. The relationship between salt penetration and the intrinsic rock property, permeability, is examined to elucidate the ingress and egress of salt solution in masonry sandstone. The accelerated weathering trial simulates pre-loading a sandstone block with a 10% salt solution (equal parts NaCl and $MgSO_4$) during a wet winter followed by dried out in summer. Permeability data measured from horizontal slices through the block are correlated with salt data from IC analysis. Results indicate relatively high surface permeability values and salt crystallization on exposure to air. The effect of salts blocking pores and reducing permeability is evident in a reduction in permeability in the near surface zone where permeability and (sulphate and chloride) salt data are correlated. At greater depth, continual wetting with salt and subsequent heating increases permeability and pore connectivity of the sandstone block. Salt crystallization enlarges and fractures pores, enabling the ingress and movement of soluble chloride salts. The stone's intrinsic properties (permeability and porosity) have been changed by salt weathering, ultimately leading to deterioration and accelerated stone decay.

Keywords: Salt weathering, sulphate, chloride, probe permeametry, sandstones, correlation matrix.

1. Introduction

The breakdown of masonry sandstone has been extensively researched due to its significance in architectural and archaeological conservation (e.g. Mottershead, 1994; Smith and Warke, 1996; Smith et al., 2002). Mechanical decay in sandstones in polluted urban environments is attributed to salt concentration through crystallization, thermal expansion/concentration, and hydration/dehydration (Warke and Smith, 2000; Turkington and Smith, 2000). Previous work has alluded to an oversimplification in current modeling of salt solution fluctuation that fails to address moisture movement from within masonry stone (Bluck and Porter, 1991; Warke and Smith, 2000) and stresses the importance of modeling building stones as three-dimensional features (Turkington and Smith, 2000). The decay of natural masonry materials such as sandstone can be unpredictable and is related to the variability of the intrinsic properties of the stone, such as permeability, porosity and mineralogy (McKinley et al., 2006), and the mobility of the salts in the weathering process (Warke and Smith, 2000). The interaction between these properties has implications for moisture movement and salt input, output and storage. Any attempt to model the decay dynamics of natural building stone must take into account the impact of the spatial variability of the stone properties on the ingress and egress of salt solution. In this paper the spatial distribution of salts in weathered sandstones is investigated and the relationship between salt penetration and permeability, a key trigger factor of stone decay.

2. Materials and Methods

Sandstone blocks of dimensions 20x20x20 cm were used to represent building stones in accelerated weathering trials. Peakmoor Sandstone, a medium-grained sandstone of Carboniferous age, was used which is representative of a stone type used frequently in construction and restoration programmes (BRE, 2000). Predictions for future temperate climates envisage warmer and wetter winters (Crawford, 2007, Viles, 2002). The implications for building stones are that blocks will remain damp for long periods of time during winter months. As a result soluble salts may migrate through a block, and entire building stones potentially could be contaminated with damaging salts in a relatively short time (Smith et al., 2004). The weathering simulation used in this paper was designed to simulate the scenario where a masonry building stone is ‘loaded’ with salt during a wet winter and then completely dried out in summer. The weathering simulation involved pre-loading a sandstone block with a 10% salt solution (equal parts NaCl and $MgSO_4$) by capillary rise through one face, and subsequent drying out with a heat lamp from the same face. The block was placed in a salt solution (2 cm deep and topped up as necessary) for 48 hours. Following removal from the salt solution the block was dried for 6 hours by a heat lamp directed at the block face which had been immersed in the solution. This encouraged capillary rise of the solution to the ‘back’ face of the block. Limited ingress and egress of moisture and salts to one exposed face more closely simulates the situation of a building stone (Smith and McGreevy, 1988).

Following the weathering simulation, the block was cut horizontally at 2 cm intervals resulting in 10 slices through the block to characterize the rock properties and salt distribution of the sandstone block in three dimensions. Non-destructive and destructive techniques were applied to the weathered block. Probe permeametry is a non-destructive technique that measures pressure decay as a function of time, enabling the determination of gas permeability. An unsteady-state Portable Probe Permeameter PPP250^{TM} (Core Laboratories Instruments, 2001) was performed on the block before each slice was cut. In the technique, initial flow pressure declines as gas flows into the stone surface and the decay versus time is recorded and used to calculate permeability from the pressure decay curve (Jones, 1992). The PPP250 has an aperture radius of 8 mm producing an approximate effective penetration depth at each position of between 17.6 mm and 32 mm (2.2-4 times the radius; Goggin et al., 1986; Goggin et al., 1988; Jensen et al., 1994; Tidwell and Wilson, 1999).

Ion chromatography (IC), thin section and scanning electron microscopy (SEM) facilitated the structural and mineralogical characterization of the weathered sandstone. The use of a 10 x 10 cm sampling grid, giving 100 sample points for each slice, resulted in permeability measurements at the same relative positions as samples taken for destructive analysis. This provided a spatial dataset and the potential to quantify the relationship between permeability and salt distribution of the weathered block.

3. Results and Discussion

Quartz formed the predominant detrital framework mineral in the fresh Peakmoor sandstone. Feldspars formed the second most volumetrically important detrital framework mineral. The major feldspar type present was albite with subordinate microcline (as determined by XRD analysis). XRD analysis, thin-section petrography and SEM analysis confirmed the presence of illite and kaolinite as diagenetic clay phases. Kaolinite was the most volumetrically significant diagenetic clay. Results from the weathering simulation show variable permeability at different depths in the salt-loaded block. Figure 1 shows mean permeability values (Fig. 1a) and mean salt (SO_4 and Cl) concentration (Fig. 1b) at increasing depths in the sandstone block. The inset figure (Fig. 1c) provides greater detail for mean concentrations of SO_4 and Cl (ppm) below the surface layer of the block.

High permeability was observed for the surface slice (range 62 -120 mD; mean 84 mD) but permeability values were reduced at 2 and 6 cm depth (Fig. 1a; mean 56 and 57 mD for 2 and 6 cm depth respectively). Permeability increased at greater depth in the block with a maximum mean value of 90 mD at 18 cm depth. IC analysis indicated extensive salt concentration in the surface layer of the salt-loaded block. High concentrations of sulphate (SO_4) and chloride (NaCl) were indicated in the surface slice following salt-loading (Fig. 2). Results showed concentrations of 8515 ppm and 1018 ppm for Cl and SO_4 respectively (Fig. 1b). The large quantity of salts rapidly diminished at 2 cm depth where a mean concentration of 445ppm and 449 ppm was recorded for Cl and SO_4 respectively. The amount of SO_4 observed in the block remained relatively constant from a depth of 4 cm (range 530 to 460 ppm) to 12 cm when the concentration is reduced to 362 ppm. Lowest concentration of sulphate was recorded at depth in the salt-loaded block (Fig. 1c; 181 ppm at 18-20 cm depth). This pattern of salt concentration through the block is not replicated by chloride in that although IC results indicate a decrease in chloride concentration immediately under the surface layer (Fig. 1c; 445 ppm), the quantity of chloride remains relatively constant with increasing block depth (range 507 to 428 ppm) until at depth of 16 cm when an increase in chloride is observed. A concentration of 1018 ppm is recorded at a depth of 18 cm in the salt-loaded block.

The correlation matrix between salts indicate a correlation between salt concentration in the surface layer of the block where high quantities of both salts were found (Tab. 1; correlation coefficient = 0.68.) However strongest correlation is found at a depth of 4 – 6 cm in the salt-loaded block (correlation coefficient = 0.7 to 0.91). This coincides with the observed decrease in salt quantities (Fig.1c) and shows that the salts are acting in a similar way between 4 and 6 cm depth in the block. After this depth the salts act in different ways and show weaker correlations and an inverse relationship as sulphate salts decrease through the block but chloride salts were found to increase towards the base of the block (Tab. 1). The correlation between permeability and salts data show strongest spatial cross correlation at a depth of 4-6 cm in the salt loaded sandstone block (correlation coefficient = 0.35 and 0.37 for SO_4 and Cl respectively).

The block weathered in the accelerated salt simulation trial provided detail on the three dimensional changes in the sandstone. Once the block was loaded with salt solution to simulate the complete wetting of a building block during a damp winter, a heat lamp was directed at the block face which had been immersed in the solution. Permeability measured from the horizontal slices was used to correlate with salt data. Results from permeability measurement and salt data indicate relatively high surface permeability values (84mD) and high salt

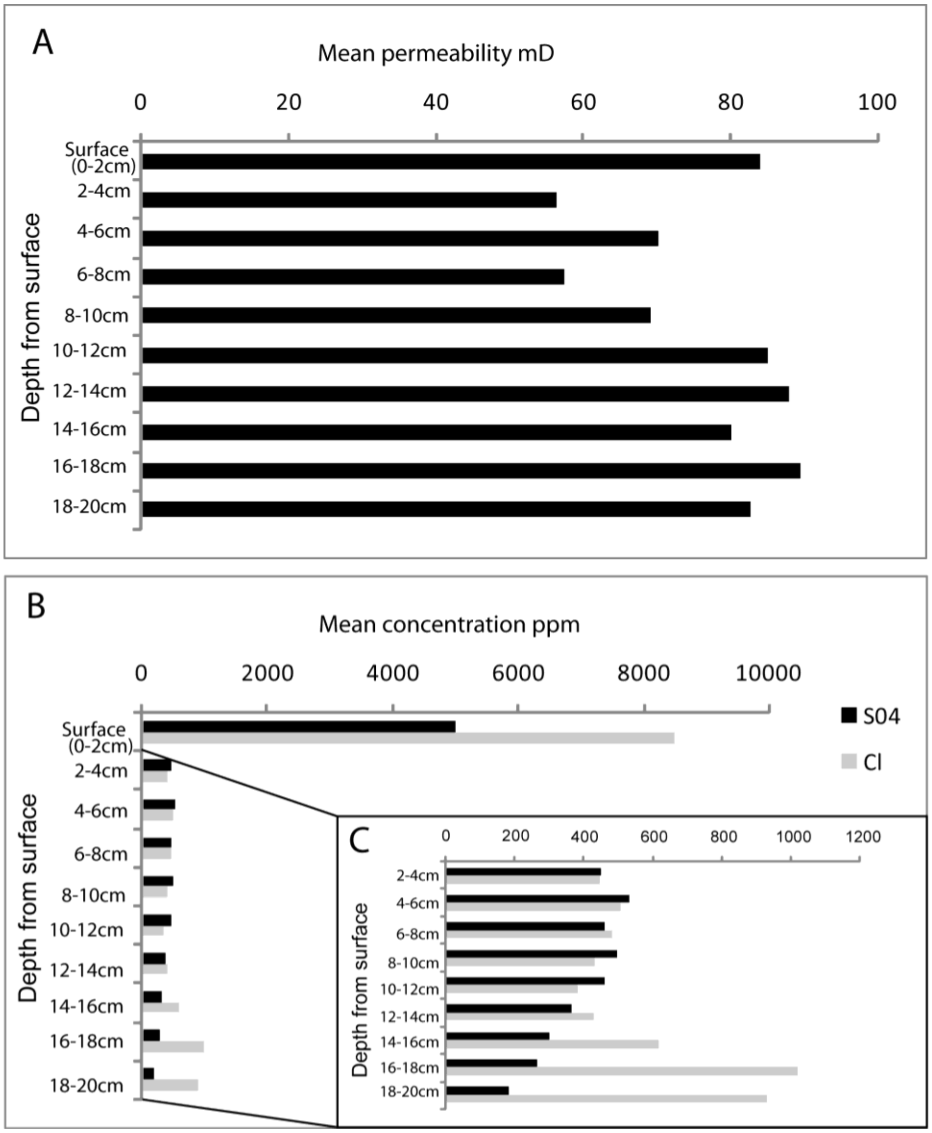

Fig. 1. Graphs showing A) permeability mD; B) salt (SO_4 and Cl) concentration at different depths in the sandstone block. Inset C) shows (SO_4 and Cl) concentration at different depths below the surface of the block.

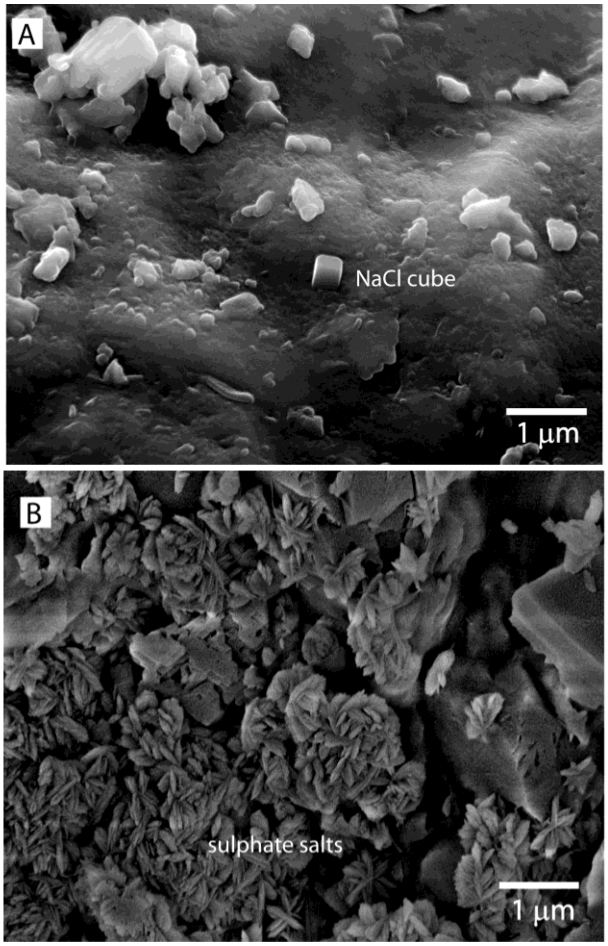

Fig. 2 SEM micrographs of salt-loaded block showing A) NaCl cube and B) sulphate salts.

concentrations related to salt crystallization on exposure to air. At this stage salt concentration is not strongly related to permeability. High salt concentration can be related to an efflorescence observed on the block surface produced as salt was drawn back to the surface on heating with the heat lamp. This would be expected to block surface pores and reduce permeability. The effect of this is not obvious in surface permeability but is more evident in the reduction in permeability below the rock surface where both salt solutions and permeability data are more strongly correlated. The results suggest that, initially high permeability values are reduced with the build up of salt concentration in the near-surface zone (2 – 6 cm depth). At greater depth in the block (at 12cm depth) continual wetting with salt and heating appears to be effective in increasing permeability and consequently pore connectivity, enabling the ingress and movement of salt and moisture more effectively through the stone. The findings indicate that chloride salts are more abundant than sulphates at this depth in the block.

The findings from this study concur with and build on previous research (e.g. Warke and Smith, 2000; Turkington and Smith, 2000) in that the research aims to elucidate the importance of the spatial distribution of salts in the weathering process of stone decay. The results indicate that continual wetting with salt laden rain followed by drying out produces a salt residue in the form of a zone of accumulation of chloride and sulphate salts in the surface zone. Salt crystallization on the surface may re-establish stability because surface pores are blocked (surface efflorescence blocks pores). Permeability is reduced in the near surface zone minimizing the ingress of moisture and salts. At this depth salt crystallization is controlling permeability. The results of this study indicate, however, that this stability is temporary and at greater depth (10 - 12 cm depth) permeability begins to increase due to crystal expansion. Salt crystallization enlarges and fractures pores, increasing the mobility potential of moisture and salts. This acts as a

Table 1: Correlation matrix for sulphate (SO_4) and chloride (Cl) salts.

Salts		Sulphate (SO_4)									
	Depth from surface	Surface 0-2 cm	2-4 cm	4-6 cm	6-8 cm	8-10 cm	10-12 cm	12-14 cm	14-16 cm	16-18 cm	18-20 cm
Chloride (Cl)	Surface 0-2 cm	.68*	.39*	.42*	.35*	.31	-.23	-.24	.04	-.11	-.29*
	2-4 cm	.06	.91*	.80*	.80*	.69*	.08	-.03	.29	-.08	-.72*
	4-6 cm	.06	.84*	.85*	.74*	.68*	.14	.05	.36	-.09	-.72*
	6-8 cm	.04	.77*	.67*	.70*	.67*	.22	-.01	.33	.08	-.61*
	8-10 cm	.01	.75*	.71*	.61*	.66*	.34	.08	.28	.12	-.54*
	10-12 cm	-.06	.79*	.73*	.64*	.57*	.37*	.18	.17	.12	-.56*
	12-14 cm	-.08	.75*	.69*	.63*	.60*	.27	.27	.31	.15	-.53*
	14-16 cm	-.03	.61*	.61*	.50*	.55*	.24	.13	.44	.04	-.49*
	16-18 cm	.03	.42*	.41*	.22	.27	.33	.37*	.24	.64*	-.17
	18-20 cm	-.18	.58*	.50*	.42*	.45*	.13	-.03	.15	.02	-.45*

Symbol * indicates correlation is significant at the 0.05 probability level.

zone of transition that enables the inward migration of salt. At depth in the weathered block, there is an observed increase in permeability and a zone of accumulation of chloride salts (18 – 20 cm depth). Stresses exerted by the expansion of salt crystals in confined pore spaces, and subsequent hydration during periods of drying, have increased pore connectivity and hence permeability enabling the ingress of soluble chloride salts. The stone's intrinsic properties (permeability and porosity) have been changed by the salt weathering, ultimately leading to deterioration and accelerated stone decay.

4. Conclusion

This paper presents a three-dimensional examination of a sandstone block following a salt weathering trial to investigate the spatial distribution of salts in zones of accumulation, transition and concentration. The implications of the study are that continual wetting with salt solution and drying enables the ingress and movement of salt and moisture through the stone. The movement of salt depends on the composition and mobility of the salt solution; both sulphate and chloride salts accumulate in the near surface zone. At greater depth chloride salts are effective in changing the intrinsic properties (permeability and porosity) of the stone and concentrate at much deeper levels in the stone. Ultimately this may result in accelerated stone decay. The results from this study are currently being validated against weathered stone masonry provided by an ongoing building restoration programme.

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