

Preliminary observations on the impact of complex stress histories on sandstone response to salt weathering: laboratory simulations of process combinations

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Abstract Historic sandstone structures carry an inheritance, or a ‘memory’, of past stresses that the stone has undergone since its placement in a façade. This inheritance, which conditions present day performance, may be made up of long-term exposure to a combination of low magnitude background environmental factors (for example, salt weathering, temperature and moisture cycling) and, superimposed upon these, less frequent but potentially high magnitude events or ‘exceptional’ factors (for example, lime rendering, severe frost events, fire). The impact of complex histories on the decay pathways of historic sandstone is not clearly understood, but this paper seeks to improve that understanding through the use of a laboratory ‘process combination’ study. Blocks of quartz sandstone (Peakmoor, from NW England) were divided into subsets that experienced different histories (lime rendering and removal, fire and freeze–thaw cycles in isolation and combination) that reflected the event timeline of a real medieval sandstone monument in NE Ireland, Bonamargy Friary (McCabe et al. 2006b). These subsets were then subject to salt weathering cycles using a 10% salt solution of NaCl and MgSO₄ that represents the ‘every-day’ stress environment of, for example, sandstone structures in coastal, or polluted urban, location. Block response to salt weathering was monitored by collecting, drying and weighing the debris that was released as blocks were immersed in the salt solution at the beginning of each cycle. The results illustrate the complexity of the

stone decay system, showing that seemingly small variations in stress history can produce divergent response to salt weathering cycles. Applied to real-world historic sandstone structures, this concept may help to explain the spatial and temporal variability of sandstone response to background environmental factors on a single façade, and encourage conservators to include the role of stress inheritance when selecting and implementing conservation strategies.

Keywords Sandstone · Process combinations · Complexity · Inheritance

Introduction

Sandstone is widely used as building stone in the UK and throughout Europe. The decay and conservation of building sandstones is an international problem, as these stones, which are commonly susceptible to deterioration, are often used in buildings and monuments of cultural value. Historic sandstone structures carry an inheritance, or a ‘memory’, of past stresses that the stone has been exposed to since its emplacement (Warke 1996). This inheritance may be made up of the combination of low magnitude/high frequency background environmental factors (for example, salt weathering, diurnal or more frequent temperature and moisture cycling). Many historic structures may be found in locations where salt and moisture are abundant—for example, coastal or polluted urban areas. In these areas salt weathering can be particularly effective, and can be a serious threat to heritage. Superimposed upon these low magnitude/high frequency factors, are low frequency events with the potential to

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have a high magnitude impact. These may be thought of as ‘exceptional’ factors (both human-induced and ‘natural’), diverting a sandstone from a ‘normal’ path of decay. The stress histories of many historic structures also include events that may have a lasting impact on the long-term performance of the stone. Included amongst these ‘exceptional’ events are the application of lime rendering and its subsequent removal—a phenomenon common to medieval and historic structures (McCabe et al. 2006a). Depending on their age and location, many of these structures will also have experienced changes in environmental conditions associated with the Little Ice Age (LIA, c. 1590–1850), when freeze–thaw conditions may have been more intense and frequent (McCabe et al. 2006b). Fire is another major threat to historic buildings. Over the lifetime of an historic sandstone structure exposure to fire damage is likely (Obojes et al. 2006), and it is estimated that one historic building is currently lost to fire each day in the EU (Gomez-Heras et al. 2006; COST C17 2001). The long-term impact of historic fire on the contemporary performance of stone is therefore an important factor worthy of consideration, but one that has not been rigorously investigated with regard to its role in determining the long-term weathering response of sandstone.

The role of these complex stress histories in influencing the decay pathways of historic sandstone is not fully understood, but is an area that requires further detailed research.

One major complicating factor is that each sandstone block within a façade may have a unique stress history and, in addition, a different threshold of change for each process acting on it. These thresholds may be breached by the sudden impact of high magnitude ‘exceptional’ factors, or by the slow convergence of decreasing stone strength with accumulated background environmental stresses. Due to this inherent complexity in stone decay systems, even small variations in stress history can produce significant divergent behaviour in the response of different stone blocks (Smith 1996; Brunsden 2001; McCabe et al. 2006b). Stone response to cumulative stress is not linear, so that variations in system inputs can produce outputs where the initial variations are compounded and exaggerated—changes are multiplicative rather than simply additive. This can commonly be seen in the spatial and temporal variability of the decay of sandstone blocks even on a single façade (Turkington and Smith 2004). This paper seeks to improve understanding in the area of complex stress histories by presenting results from a laboratory ‘process combination’ study, in which “each sample is given a care-

fully designed stress history before it is subject to a new process... [an] area where there has been very limited progress is in the study of process combinations” (Smith et al. 2005, p. 224).

The simulations implemented in this research are thus designed to provide insights into the impact, and investigate the significance, of ‘exceptional’ pre-treatment factors (lime render, fire and freeze–thaw cycles) in combination with exposure to low magnitude background environmental factors (temperature and moisture/salt weathering cycles) on the decay of sandstone. The simulation experiments investigate the effects of process combinations on sandstone weathering, and seek to provide a better understanding of the combination and cumulative impact of the above stresses. Only through improved understanding can event sequences (Brunsden 2001) in sandstone monument decay be identified and their potential influence on contemporary conservation practices be considered as an important element in building management.

Methods

The stone type used in the simulation experiments is Peakmoor Sandstone, a Carboniferous quartz sandstone quarried in Derbyshire and commonly deployed in monument restoration in the UK. The characteristics of this stone are shown in Table 1 (data taken from the BRE Stone List, apart from permeability measurements, taken using a gas permeameter).

Sample blocks of Peakmoor Sandstone (10 cm × cm × 10 cm) were divided into different stress history groups (16 blocks in each subset) that would undergo ‘exceptional’ pre-treatments (lime rendering, simulation of heating experienced during a fire using a furnace, and repeated freeze–thaw cycles) and low magnitude/high frequency background stresses represented by salt weathering cycles. Blocks were unconfined throughout the experiment, with the exception of

Table 1 Characteristics of Peakmoor Sandstone

	Peakmoor Sandstone
Colour	Buff
Porosity	16.46%
Average permeability	31.67 mD (range 9.42–88.2 mD)
Saturation coefficient	0.68
Absorption	5.07% (by weight)
Compressive strength	72.5 MPa
Bulk specific gravity	2,210 kg/m ³
Sodium sulphate crystallization test	1.07% mean weight loss

the impact of lime rendering. Thus, different groups would experience different stress histories both in isolation and combination. A summary of the different stress histories experienced is shown in Table 2, which also shows the total amount of debris released from selected blocks in each group after 75 cycles. The stress histories experienced are based on the event timeline of a real medieval sandstone structure in NE Ireland, Bonamargy Friary (McCabe et al. 2006b). The experimental procedure is illustrated in Fig. 1, which highlights the concept of a ‘normal’ path of decay (due to background environmental stresses) and the various ‘exceptional’ decay pathways that may be taken during the lifetime of an historic sandstone structure. A brief discussion of each of the laboratory pre-treatments follows.

‘Exceptional’ pre-treatments

Lime render pre-treatment

Lime rendering of building sandstones has been shown to have significant implications on subsequent decay (particularly for non-calcareous stones), carrying both chemical (in terms of potential sulphation due to calcium loading) and physical (in terms of surface roughness and pore blocking) consequences (Smith et al. 2001; McCabe et al. 2006a). It has been hypothesized that, while lime render may initially increase the integrity of a stone surface, after the render has been removed or has deteriorated over time, the exposed stone may experience accelerated decay through the action of calcium salts (for example, gypsum). Furthermore, salts have been shown to concentrate more at depth (up to 3 cm) in blocks that have previously been rendered than in unrendered blocks. This may be due to the blocking of surface pores by the surface rendering which effectively prevents salts being drawn back to the surface upon drying (McCabe et al. 2006a).

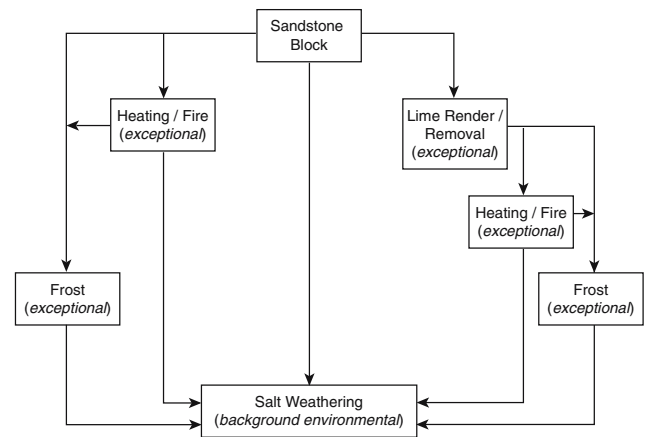


Fig. 1 Experimental procedure, showing different ‘exceptional’ decay pathways that may be experienced by sandstone

For this experiment, a wall of Peakmoor Sandstone was constructed in the laboratory and rendered with lime putty in an attempt to simulate a simple medieval lime mortar. The wall was sprayed regularly for the first week with a fine mist of water to stop the render drying out too quickly and cracking. After 1 month, the wall was demolished and the render was chipped and scraped off blocks, before proceeding to the next pre-treatment appropriate to each stress history group (Table 2).

Heating pre-treatment

Research on fire damage to stone has taken the form of anecdotal field observations (Blackwelder 1926; Emery 1944), or, more recently, laboratory simulation (Allison and Goudie 1994; Allison and Bristow 1999). Recent studies have demonstrated that extreme heat (provided by placing blocks in a furnace) can have a significant impact on the character and performance of sandstone (Gomez-Heras et al. 2004; Hajpal and Török 2004). These studies have shown that the length of time over which extreme heat is maintained, and the speed with which high temperatures are reached, are key

Table 2 Summary of different stress histories experienced by Peakmoor Sandstone in laboratory simulation

	Lime putty (one-off pre-treatment)	Furnace (one-off pre-treatment)	Freeze–thaw cycles (pre-treatment)	Salt and temperature/ moisture cycles	Debris released after 75 cycles (% of total weight in g)
Group A				★	0.29
Group B			★	★	1.13
Group C		★		★	1.29
Group D		★	★	★	1.47
Group E	★		★	★	0.73
Group F	★	★	★	★	0.20

factors in determining stone response (Goudie et al. 1992). Extreme high temperatures have the potential to cause catastrophic damage to stone because thermal surface/substrate stresses are set up within the stone relatively rapidly, giving the stone no time to physically absorb the change (thermal shock). Physically, quartz sandstones can be especially susceptible to extreme heat (Goudie et al. 1992), with temperatures in excess of 573°C usually resulting in the internal fracturing of quartz grains (Chakrabarti et al. 1996). Chemically, the extreme heat produced by fires can bring about changes in the mineral matrix or cement of a sandstone, creating lines of weakness for subsequent exploitation by physical processes including salt weathering and environmental heating and cooling leading to the establishment of near-surface thermal gradients that could result in the formation and development of microfractures.

To simulate the effects of heating, 48 blocks of Peakmoor Sandstone (16 of which had undergone the lime render pre-treatment) were placed in a furnace at a temperature of 500°C for 30 min. This temperature is considered to be the approximate average temperature experienced by a burning structure (Gomez-Heras 2006). After this time in the furnace, blocks showed a significant colour change related to the oxidation of iron within blocks. Average ultrasonic pulse velocity was measured by a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) before and after heating in the furnace. It should be noted that the uniform heating experienced by sandstone blocks in a furnace cannot simulate the blackening (caused by soot) and the temporal and spatial variability of heating caused by a real fire.

Freeze–thaw pre-treatment

Freeze–thaw weathering is a well-documented stone decay process (Schaffer 1932; McGreevy 1982), and recent work has illustrated the synergistic relationship of frost and salt weathering (Williams and Robinson 2001; Warke et al. 2006). As well as experiencing environmental cycles over daily and seasonal time-scales, structures may also experience a change in local climate during their lifetime—it is well-documented that climate has varied significantly over the last 1,000 years (Viles 2002; McCabe et al. 2006b), with periods such as the LIA marking significant changes in environmental conditions, especially in freeze–thaw activity, when compared to present-day regimes. Confirming this idea, recent research from central England has illustrated the increased frequency and intensity of frost events during the LIA (Nesje and Olaf Dahl

2003). The consideration of severe frosts should not, however, be limited to past climatic conditions as they may still occur as high magnitude/low frequency events in the present day.

To simulate the effects of freeze–thaw, 64 blocks of Peakmoor Sandstone (including blocks that had previously undergone lime rendering and furnace pre-treatments in isolation and combination) experienced 50 freeze–thaw cycles. At the beginning of each alternate cycle, blocks were immersed in de-ionized water for approximately 10 s to provide moisture. Temperatures cycled between 10 and –10°C (see Fig. 2). Surface and subsurface temperatures were monitored by drilling holes in blocks and embedding bead thermistors at different distances below the upper surface. Ultrasonic pulse velocities were again measured by a PUNDIT, with blocks being monitored after every ten cycles.

Low magnitude, background stressing of stone

Salt weathering

Salt weathering and temperature cycles were designed to simulate the background environmental factors that historic sandstone structures continually experience on a daily basis. It is this context in which the one-off pre-treatments should be viewed. Salt weathering may exploit weaknesses in the stone brought about by the effects of lime rendering, fire and freeze–thaw weathering.

When pre-treatments were completed, the 16 blocks from each stress history group (A–F, Table 2) were subjected to repeated wetting and drying with a 10% salt solution (equal parts NaCl and MgSO₄), simulating a present day temperate maritime environment. A 2-

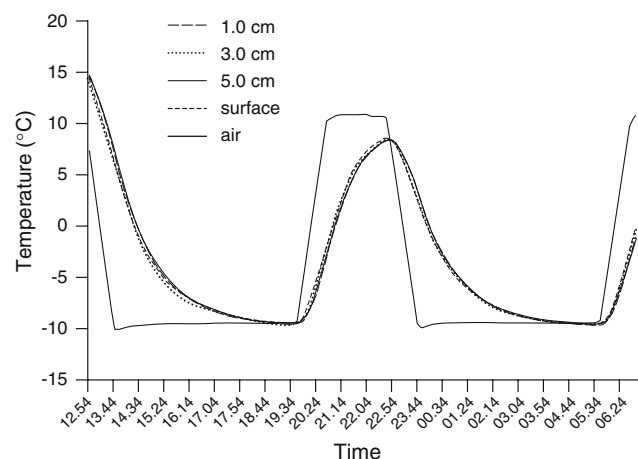


Fig. 2 The temperature regime (ambient air and stone surface/subsurface) experienced by blocks during freeze–thaw cycles

day temperature cycle was used because it allowed the complete drying out of blocks, attempting to replicate natural conditions of regular temperature cycling combined with periodic wetting. The temperature regime for the 2-day cycle is shown in Fig. 3, and is based on observations from the North Antrim Coast during the month of May. Temperatures were again recorded by embedding bead thermistors within blocks at different distances from the block surface. The top temperature of 40°C is commensurate with surface temperatures achieved on clear, sunny days. It is also within the range of temperature cycles previously used in simulation experiments. At the start of each cycle blocks were immersed in a 10% salt solution (equal parts NaCl and MgSO₄). These salts were chosen for the study because they are often associated with maritime environments, and have commonly been used in previous salt weathering simulation studies (Smith et al. 2005; Goudie and Viles 1997). It should be stressed that the aim of the study was not simply to achieve the rapid breakdown of Peakmoor Sandstone blocks, but rather, to monitor (in high resolution) the slow (realistic) deterioration of blocks, and to investigate subtleties in the decay sequence of the sandstone.

Recording and monitoring the decay of blocks was achieved qualitatively, by photographing the blocks at

regular intervals, and quantitatively, by monitoring weight loss. Each time blocks were immersed in solution the debris released was collected, dried and weighed.

Results and discussion

Table 3 shows ultrasonic pulse velocity values for blocks of Peakmoor Sandstone with different stress histories. Each axis through a block was measured and an average was calculated. Results show that 50 freeze–thaw cycles may have a greater cumulative impact than the one-off furnace treatment, but that, in combination, these two pre-treatments bring about a significant decrease in the pulse velocity measurements, suggesting that blocks developed discontinuities as a result of undergoing pre-treatments. The impact of these inherited weaknesses can be seen in stone response of salt weathering.

Figure 4 shows the cumulative weight loss of representative blocks from each stress history group (expressed as a percentage of the total weight of the block). The experimental design encourages the salts to behave in a certain way. The cooling to 2°C may cause a drop in solubility of MgSO₄, which rapidly decreases in solubility with nocturnal temperatures (Goudie and Viles 1997), causing crystallization. As temperatures rise again crystals may go back into solution until evaporation occurs, encouraging crystallization of both MgSO₄ and NaCl.

The weight loss graph (Fig. 4) shows that Peakmoor response was fairly uniform over the first 20 cycles. Even at this stage, however, group D (furnace, frost and salt) released noticeably more debris than other groups. After cycle 20, debris release increases from groups B–E (see Table 2 for stress history summary) (though at different rates), while groups A (salt) and F (lime render, furnace, frost and salt) remained low and relatively constant. In the following points, observations from the weight loss graphs are discussed, with relevant groups being compared.

– Weight loss plots for groups A (salt) and B (frost and salt) show clearly that freezing had a significant

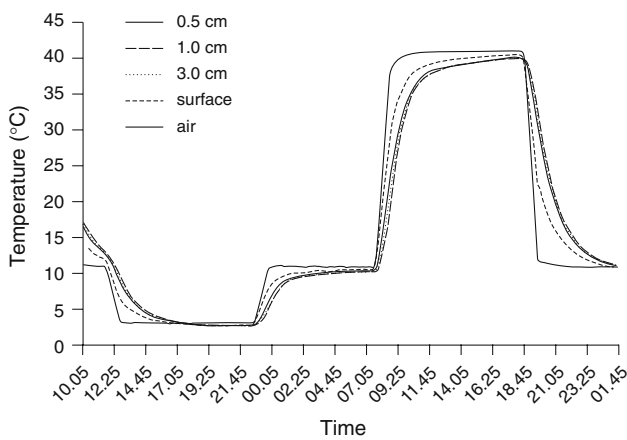


Fig. 3 The temperature regime (ambient air and stone surface/subsurface) experienced by experimental blocks after wetting with salt solution

Table 3 Ultrasonic pulse velocity measurements for Peakmoor Sandstone blocks with different stress histories

Pre-treatment	A–B axis	C–D axis	E–F axis	Average pulse velocity (m/s)
Unweathered	3,125	3,125	2,702	2,984
After furnace	2,941	2,941	2,564	2,815
After 50 freeze–thaw cycles	2,777	2,702	2,272	2,583
After furnace and 50 freeze–thaw cycles	2,439	2,380	2,325	2,381

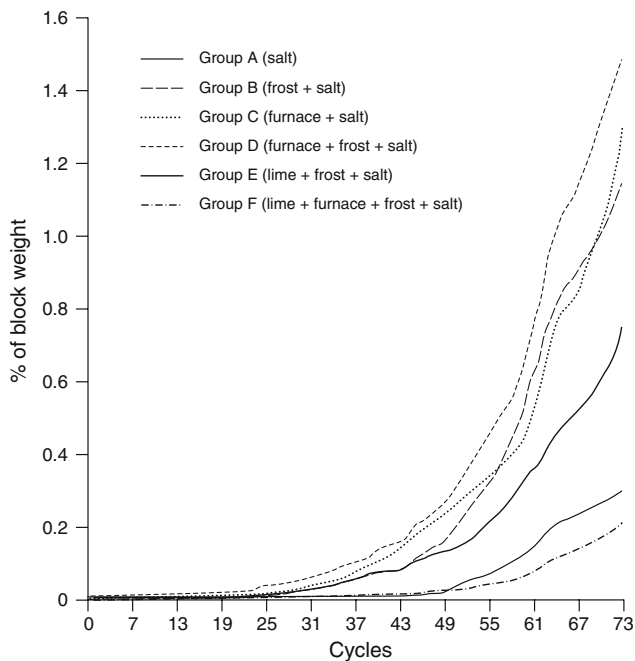


Fig. 4 Sandstone response to salt weathering (by weight) after experiencing stress histories A–F (Table 2)

impact on the response of Peakmoor Sandstone—perhaps more than was suggested by the gradual change in ultrasonic pulse velocity during freezing cycles (similar to results reported by Warke 1994). Ultrasonic pulse velocity did decrease, though, suggesting that discontinuities had developed in blocks as a result of the freeze–thaw cycles. Sandstones that have experienced a harsher environment in the past (for example, the LIA) may carry a ‘memory’ of these past regimes that can manifest itself in present day performance. Salt weathering is exploitative, requiring pre-existing lines of weakness and access to pore spaces to operate most effectively. Experimental data indicate that the legacy of structural change arising from exposure to freeze–thaw cycles in the Peakmoor Sandstone blocks influenced stone response to subsequent salt weathering cycles. Around cycle 20 the two weight loss paths separate, with group B debris release becoming more pronounced, especially after 50 cycles. After 50 cycles group A begins to show deterioration similar to that experienced by group B after cycle 20.

- Group D (furnace, frost and salt) yields consistently more debris than group C (furnace and salt), again showing that extreme freeze–thaw events are a factor in deterioration. The two groups follow a similar pattern of weight loss over the 75 cycles, but in the case of group D, overall debris release is greater. Groups C and D released the largest amount

of debris over the 75 cycles (1.29 and 1.49% of the total block weight, respectively), suggesting that the furnace pre-treatment had the highest impact on Peakmoor Sandstone response. The impact of freeze–thaw appears less significant in comparison to groups A and B. A possible explanation for this is that the furnace pre-treatment may have accomplished so much ‘work’, or change, that the freeze–thaw cycles were not severe enough to result in an appreciable stone response (as seen in groups A and B)—“if a harsh regime precedes a gentle process domain, then all the possible work may have been done and no change is possible until there is a further change in the controls” (Brunsden 2001, p. 103). This statement is true when an individual low magnitude event follows a harsh regime, but it should be acknowledged that the cumulative impact of repeated low magnitude events (for example, salt weathering cycles) can cause further change stone strength/stress thresholds are breached.

- Groups B (frost and salt) and E (lime render, frost and salt)—initially, a slightly larger amount of debris was released from Peakmoor blocks in group E which may be associated with the greater surface roughness produced by the residual lime render layer. The rate of weight loss for this group then slows down considerably, following a similar path to group B. However, at approximately cycle 45, group B weight loss noticeably increases and the response paths of the two groups diverge. Lime render appears to slow down the weight loss at this stage because of two effects. First, it increases the intergranular cohesive integrity of the near-surface zone of Peakmoor blocks and second, through the sealing of surface pores, it restricts, to some extent, the ingress of salt and moisture. There is no such hindrance in group B so salt and moisture are able to infiltrate the surface zone, leading to more extensive granular disaggregation. However, although the remnant lime render appears to retard salt and moisture penetration, over time this may lead to the concentration of salts at depth, as demonstrated by McCabe et al. (2006a). This may cause exaggerated rapid decay in the future, perhaps fuelled by deposits of calcium (from the render) within the stone.
- Group F (lime render, furnace, frost and salt) exhibits one of the most interesting responses to salt weathering, with decay appearing to be suppressed by the stress history within the period of the experimental run. Though group F experienced the most complex stress history, over 75 cycles these blocks yielded the least debris (0.20% of the total weight). A likely reason for this is the order in which

the pre-treatments were applied. After lime rendering, the blocks were exposed to heating in the furnace. This seems to have baked and hardened the remnant surface lime render layer (and whatever lime water had infiltrated the blocks). This, ostensibly, has led to an apparent increase in durability in the group F blocks. However, as has been highlighted, it is likely that this is a short-term effect as salts that concentrate at depth may have significant implications for future deterioration. Consequently, a short-term increase in durability does not preclude the future rapid catastrophic decay of these blocks. Another consideration to take into account is that this experiment used unconfined Peakmoor blocks. If the same baking and hardening of lime mortar occurred in the context of a real-world façade, stone response may be quite different. With rigid mortar joints comes increased compressive loading of stone (if mortar is more rigid than the blocks it surrounds), and an increased likelihood of ‘boxwork’ occurring—rapid retreat of block surfaces, leaving rigid mortar to protrude from the façade.

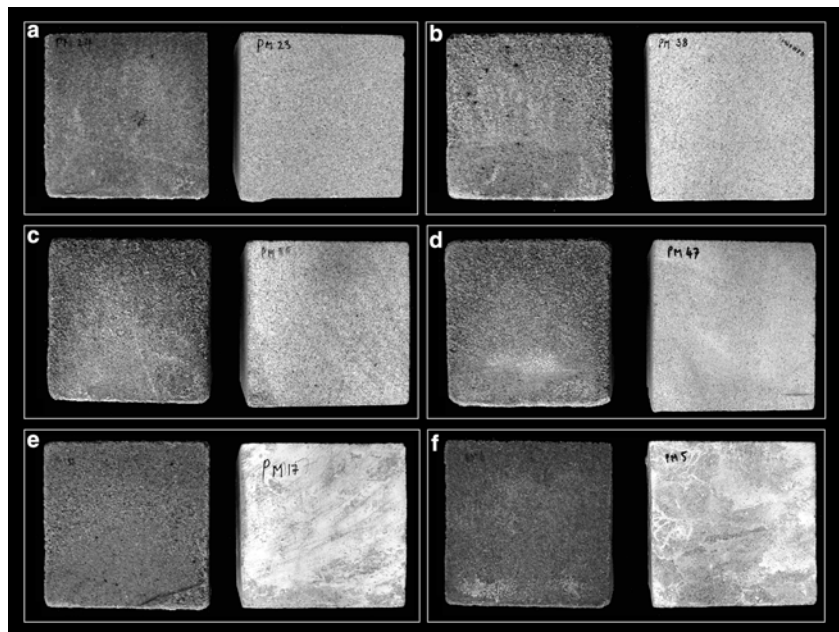
Figure 5 shows photographs of a block from each stress history group alongside a control block from the same group.

Conclusions

This brief, preliminary analysis of the impact of complex stress histories on sandstone decay has shown that:

- There are clear relationships between the stress histories experienced by different groups and the amount of debris that they released in breakdown during salt weathering cycles. Differences in stress history produce (sometimes unexpected) divergent sandstone response to salt weathering.
- Stone response to stress histories is not linear, and the order in which pre-treatments took place appears to have had a significant impact on the results (though this order was based on a real event timeline for a historic stone structure). For example, it has been shown that, after extreme heating, the impact of freeze–thaw cycles appears to be diminished—possibly because a ‘harsh’ high magnitude regime has preceded a gentler low magnitude one, with the amount of change accomplished by the furnace pre-treatment negating much of the impact of the subsequent freeze–thaw cycles. Furthermore, the group with the most extensive stress history (lime, furnace, frost, salt) yielded the least debris, probably due to the lime render residue being baked and hardened by the furnace pre-treatment.
- Debris release seems to be suppressed in blocks that had been previously lime rendered. However, previous research has shown that salts tend to concentrate more at depth in such blocks (because pore blocking interferes with drying, when salts would usually be drawn back to the surface) suggesting that future catastrophic decay may become more likely.
- Pre-treatments (simulating one-off ‘exceptional’ events) have been placed in the context of background environmental factors. Data reported illus-

Fig. 5 Photographs of blocks from groups A–F after 75 cycles (beside control block from each group on the *right*). A salt; B frost and salt; C furnace and salt; D furnace, frost and salt; E lime render, frost and salt; F lime render, furnace, frost and salt



trate the impact of structural weaknesses inherited from exposure to ‘exceptional’ events that can be subsequently exploited by more frequent, less extreme daily factors like salt weathering. Decay occurs when strength thresholds are breached by high magnitude one-off ‘exceptional’ events, or by the slow accumulation of stresses caused by background environmental factors converging with decreasing stone strength.

Work on the impact of complex stress histories on the decay of historic sandstone structures is continuing, with studies on different stone types being undertaken and the effects of a real wood fire on sandstone being explored experimentally.

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References

- Allison RJ, Bristow GE (1999) The effects of fire on rock weathering: some further considerations of laboratory experimental simulation. *Earth Surf Processes Landforms* 24:707–713
- Allison RJ, Goudie AS (1994) The effects of fire on rock weathering: an experimental study. In: Robinson DA, Williams RBG (eds) *Rock weathering and landform evolution*. Wiley, Chichester, pp. 41–56
- Blackwelder E (1926) Fire as an agent in rock weathering. *J Geol* 35:134–140
- Brunsdon D (2001) A critical assessment of the sensitivity concept in geomorphology. *Catena* 42:99–123
- Chakrabarti B, Yates T, Lewry A (1996) Effects of fire damage on natural stonework in buildings. *Construction Build Mater* 10(7):539–544
- COST C17 (2001) Memorandum of understanding for the implementation of a European Concerted Research Action designated as COST C17 Built Heritage: fire loss to historic buildings
- Emery K (1944) Brush fires and rock exfoliation. *Am J Sci* 242:506–508
- Gomez-Heras M (2006) *Procesos y formas de deterioro termico en piedra natural del patrimonio arquitectonico*. Editorial Complutense, Madrid. ISBN 84-669-2801-4
- Gomez-Heras M, Varas MJ, Alvarez de Buergo M, Fort R (2004) Characterization of changes in matrix of sandstones affected by historical fires. In: Kwiatkowski D, Lofvendahl R (eds) *Proceedings of the 10th International congress on deterioration and conservation of stone*, Stockholm, 2004, pp. 561–568. ICOMOS, Sweden
- Gomez-Heras M, Alvarez de Buergo M, Fort R, Hajpal M, Török A, Varas MJ (2006) Evolution of porosity in Hungarian building stones after simulated burning. In: Fort R, Alvarez de Buergo M, Gomez-Heras M, Vazquez-Calvo C (eds) *Heritage, weathering and conservation*. Taylor Francis Group, London, pp. 513–519
- Goudie AS, Viles HA (1997) *Salt weathering hazards*. Wiley, Chichester
- Goudie AS, Allison RJ, McLaren SJ (1992) The relations between modulus of elasticity and temperature in the context of the experimental simulation of rock weathering by fire. *Earth Surf Processes Landforms* 17:605–615
- Hajpal M, Török A (2004) Mineralogical and colour changes of quartz sandstones by heat. *Environ Geol* 46:311–322
- McCabe S, Smith BJ, Warke PA (2006a) Calcium loading of building sandstones by lime rendering: implications for decay. In: Fort R, Alvarez de Buergo M, Gomez-Heras M, Vazquez-Calvo C (eds) *Heritage, weathering and conservation*. Taylor Francis Group, London, pp. 177–182
- McCabe S, Smith BJ, Warke PA (2006b) A legacy of mistreatment: understanding the decay of medieval sandstones in NE Ireland. *Build Environ* (in press)
- McGreevy JP (1982) Some field and laboratory investigations of rock weathering, with particular reference to frost shattering and salt weathering. PhD thesis, Queen’s University Belfast, Belfast
- Nesje A, Olaf Dahl S (2003) The ‘Little Ice Age’—only temperature? *Holocene* 13(1):139–145
- Obojes U, Tropper P, Mirwald PW, Saxer A (2006) The effects of fire and heat on natural building stones: first results from the Groden Sandstone. In: Fort R, Alvarez de Buergo M, Gomez-Heras M, Vazquez-Calvo C (eds) *Heritage, weathering and conservation*. Taylor Francis Group, London, pp. 521–524
- Schaffer RJ (1932) *The weathering of natural building stones*. Donhead, London (facsimile)
- Smith BJ (1996) Scale problems in the interpretation of urban stone decay. In: Smith BJ, Warke PA (eds) *Processes of urban stone decay*. Donhead, London, pp. 3–18
- Smith BJ, Turkington AV, Curran JM (2001) Calcium loading of quartz sandstones during construction: implications for future decay. *Earth Surf Processes Landforms* 26:877–883
- Smith BJ, Warke PA, McGreevy JP, Kane HL (2005) Salt-weathering simulations under hot desert conditions: agents of enlightenment or perpetuators of preconceptions? *Geomorphology* 67:211–227
- Turkington AV, Smith BJ (2004) Interpreting spatial complexity of decay features on a sandstone wall: St. Matthews Church, Belfast. In: Smith BJ, Turkington AV (eds) *Stone decay: its causes and controls*. Donhead, London, pp. 149–166
- Viles HA (2002) Implications of future climate change for stone deterioration. In: Seigesmund S, Weiss T, Vollbrecht A (eds) *Natural stone, weathering phenomenon, conservation strategies and case studies*. Special Publications 205. Geological Society, London, pp. 407–418
- Warke PA (1994) *Inheritance effects in the weathering of debris under hot arid conditions*. PhD thesis, Queen’s University Belfast, Belfast
- Warke PA (1996) *Inheritance effects in building stone decay*. In: Smith BJ, Warke PA (eds) *Processes of urban stone decay*. Donhead, London, pp. 32–43
- Warke PA, McKinley J, Smith BJ (2006) Variable weathering response in sandstone: factors controlling decay sequences. *Earth Surf Processes Landforms* 31:715–735
- Williams RBG, Robinson DA (2001) Experimental frost weathering of sandstone by various combinations of salts. *Earth Surf Processes Landforms* 26:811–818