Experimental studies of near-surface temperature cycling and surface wetting of stone and its implications for salt weathering


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Abstract

It has long been accepted that thermal and moisture regimes within stonework exert a major influence upon patterns of salt movement and, subsequently, the type and severity of salt-induced decay. For example, it is suggested that slow drying is more likely to bring dissolved salts to the surface, whereas rapid drying could result in the retention of some salt at or near the frequent wetting depth. In reality however, patterns of heating, cooling and surface wetting regimes that drive them – are complex and inconsistent responses to a wide range of environmental controls. As a first step to understanding the complexity of these relationships, this paper reports a series of experiments within a climatic cabinet designed to replicate the effects of short-term temperature fluctuations on the surface and sub-surface temperature regimes of a porous Jurassic limestone, and how they are influenced by surface wetting, ambient temperature and surface airflow. Preliminary results confirm the significance of very steep temperature/stress gradients within the outer centimetre or less of exposed stone under short-duration cycles of heating and cooling. This is important because this is the zone in which many stone decay processes, particularly salt weathering, operate, these processes invariably respond to temperature and moisture fluctuations, and short-term interruptions to insolation could, for example, trigger these fluctuations on numerous occasions over a day. The data also indicate that there are complex patterns of temperature reversal with depth that are influenced in their intensity and location by surface wetting and moisture penetration, airflow across the surface and ambient air temperature. The presence of multiple temperature reversals and their variation over the course of heating and cooling phases belies previous assumptions of smooth, exponential increases and decreases in subsurface temperatures in response, for example to diurnal patterns of heating and cooling.
Keywords
Limestone, thermal regime, moisture regime, simulation, salt weathering

1. Introduction and context

As a consequence of a widespread belief across Europe that physical damage to stone was primarily due to frost action, some of the earliest examples of salt weathering simulations and salt-based durability tests were devised, not to assess the importance of salt weathering per se, but as surrogates for freeze/thaw ((De Thury, 1828 – see also Schaeffer, 1932). It has become apparent, however, that whilst decay of stonework is frequently associated in many environments with severe frosts, these may only act as the final trigger for material loss that comes after a long period during which the integrity of the stone has been compromised by the repeated action of more mundane, ‘everyday’ processes. There are, moreover, strong arguments to suggest that effective ‘frost weathering’ requires the coming together of very precise combinations of saturation, freezing rates and low absolute temperatures that are rarely encountered in urban situations (see Rolls and Bland 1998 for an overview). The development of salt-based durability tests (see Goudie and Viles 1997) did, however, quickly demonstrate the effectiveness of salt weathering in causing stone decay. Not least because the variety of salt weathering mechanisms (solution/crystallization, hydration/dehydration and differential thermal expansion) driven by often subtle combinations of environmental conditions that are encountered on a regular basis by most buildings in response to natural environmental cycles as well as extreme meteorological events. As a consequence, recent years have seen an upsurge of interest in the salt decay of stone (e.g. Steiger and Siegesmund 2007), propelled in no small part by the realisation that the salts in question are widely available from marine, groundwater and atmospheric pollution sources. With this rise in interest it should not be forgotten, however, that whilst salts are the agents of decay, their effectiveness derives primarily from environmentally driven thermal and moisture cycles and associated variations in relative humidity. Without these cycles salt will act largely as a passive pore-filler.

The importance of environmental regimes in controlling salt weathering is, of course, embedded in the design of salt weathering simulations, and Smith et al. (2005) have argued that the temperature regimes employed are crucial to determining their outcomes. This is most obviously through controls exerted on hydration/dehydration and differential thermal expansion of salts precipitated within stone pores. The temperature regime is, however, also crucial in determining the timing and rate of evaporation of salt solutions and, in turn, how far solutions penetrate into a rock and where salt ultimately accumulates. These controls were, for example, investigated by Snethlage and Wendler (1997) who determined that within porous materials moisture concentrates in zones determined by a combination of “the water transport parameters of the material itself and the surrounding drying conditions” (p. 7). From this, they concluded that where this moisture contains dissolved salts, they will precipitate where the maximum moisture zone is located. Under conditions of rapid heating, surface layers could possibly dry out more rapidly than moisture can be drawn from the interior by capillary rise. As a consequence stone will dry slowly through moisture vapour transfer, leaving a salt accumulation at or near the initial wetting depth. Some
consider that this is the eventual cause of breakdown by contour scaling initiated in this zone of subsurface salt accumulation (Smith and McGreevy, 1988). Conversely, slow drying should allow salt in solution to be brought back to accumulate at the surface, where it can result in granular disaggregation or ‘sanding’ (Smith et al., 1987; Snethlage and Wendler 1997).

As well as contributing to the controls on stone moisture regimes, the thermal regimes experienced by stonework – especially the subsurface temperature gradients established during heating and cooling – are responsible for establishing dynamic patterns of internal stress in their own right. It has been proposed by some, for example, that where temperatures rise more rapidly than heat can be transferred into a stone, and more rapidly than the stresses set up can be accommodated by thermal expansion, a thermal shock is experienced that is capable of fracturing stone (Yatsu 1988). Such effects can clearly be seen when, for example, stone is exposed to fire, but there is little, if any, evidence of such effects resulting from natural environmental cycles (Smith et al. In Press). Instead, greater credence is given to the possibility that near-surface thermal fatigue effects established during repeated low-magnitude environmental cycles are more likely to combine with, complement and in some cases instigate other weathering mechanisms to produce eventual failure.

Of the range of environmental variations experienced on a regular basis by stonework in buildings, diurnal cycles of heating and cooling have traditionally been seen as the most significant, and have certainly formed the basis of the majority of salt weathering simulation studies (Smith et al. 2005). Within these, greatest emphasis is invariably attached to the importance of rapid, early morning heating under ‘summer’ conditions. This is assumed to produce a smooth, exponential increase in temperature from depth to the surface, that in turn is assumed to establish an associated stress gradient. After sunset, rapid surface cooling reverses this temperature/stress gradient. These assumptions have been ‘supported’ by measurements of surface and subsurface temperatures under natural and laboratory conditions (e.g. Warke and Smith 1998; Warke et al 1996). Unfortunately, however, such support has invariably been based on interpolation between surface temperature and often no more than one subsurface temperature several centimetres within the stone (Roth 1965; Smith 1977). Restrictions on data storage have also meant that the recording interval is often quite coarse (15-30 minutes) and that any short-term variability, especially in surface temperatures, is likely to be smoothed out. This is significant because high frequency field measurements from geomorphological studies have shown that surface temperatures can vary significantly over the same 15-30m minute timescale in response to periodic cloud cover and changes in windspeed. These produce short-term rates of surface temperature change that can be in excess of those measured during ‘smoothed’ diurnal cycles (Jenkins and Smith 1990). This is especially the case under cold air conditions when any interruption in insolation can result in a rapid temperature fall (e.g. Hall and Andre 2001), or arguably when the surface is rapidly cooled by, for example, rainfall. These short-term fluctuations have now also been observed on buildings by Gomez-Heras (2006) and Gomez-Heras et al. (2006; In Press), who have acknowledged that their effects are likely to be restricted to the outer few millimetres of a stone. They point out, however, that this is precisely the zone in which much decay by, for example, granular disaggregation occurs, and that they have the advantage that they can occur on numerous occasions within the daytime segment of a
diurnal cycle, thus possibly enhancing near-surface fatigue effects. Gomez-Heras (2006) has also stressed that our knowledge of the rate at which such fluctuations are attenuated with depth and the localised subsurface temperature gradients they establish is little known or understood, thanks to the absence of temperature measurements within the immediate subsurface zone.

It is in an attempt to address this information shortfall, that the current paper reports preliminary results from a laboratory experiment to measure stone response to short-term fluctuations in simulated insolation under different ambient conditions and in response to wetting and drying within a climatic cabinet.

2. Simulation Experiments

2.1 Materials

Experiments to simulate the effects of short-term temperature fluctuations and surface wetting were carried out using an instrumented 15x15x8cm block of Jurassic limestone from the Cotswold region of south central England known locally as Stoke Ground Base Bed. This is a porous (27.1%) sorted oolite that is used in construction across central and southeast England, especially in cities such as Oxford, and is known to be prone to salt weathering in response to pollution-derived salts.

2.2 Instrumentation

To monitor internal temperature and moisture levels, sensors were embedded by drilling into one 15x8cm face and placing them so that they were at different depths below the opposing face. Once the sensors were in place the holes were re-filled with compacted dust produced during the drilling. Temperatures were measured using commercially available bead thermistors (Grant Instruments) attached to a data logger, at depths of 0.5, 1.0, 2.0, 5.0 and 10.0cm below what was to become the exposed surface in the simulation experiments. Care was taken to calibrate each thermistor prior to insertion and on removal at the end of the experiment for any drift or faults. In this way their initial and continuing accuracy to 0.1 °C was confirmed. Moisture sensors were placed in another set of holes drilled to the same depths. Each sensor comprises two parallel steel electrodes 1.6 mm in diameter and 10 mm apart sheathed in shrink heat plastic to leave a length of 5 mm of exposed steel at the tip. By passing a current through the electrodes and measuring changes in the resistance between the exposed tips it is possible to obtain a measure of the moisture content within the stone. This technique was developed for the measurement of moisture and chloride ingress into concrete by McCarter et al. 1995 and has subsequently been used to monitor moisture movement in concrete structures (Basheer et al. 2005). In the experiments reported here, the electrodes were used specifically to monitor the movement of the wetting front into the dry stone after the exposed surface was wetted.

2.3 Experimental setup

To simulate the effects of short-term variations in incident insolation on the exposed surface of a stone block set into a building, the test block was insulated with expanded
polystyrene. The block was then set into an ‘artificial wall’ of expanded polystyrene within a large climatic cabinet as shown in Figure 1.

![Figure 1: Schematic diagram illustrating the laboratory set-up designed to simulate the surface heating and wetting of a limestone block within a controlled ambient environment (climatic cabinet).](image)

Within the cabinet the ambient air temperature could be controlled and the surface of the test block could be heated using an infra-red heat lamp inclined at 20° to the horizontal and placed at a distance of 50cm from the test block. A less sophisticated version of this apparatus (outside of a climatic cabinet) has previously been used to replicate surface heating and cooling of quartz sandstones (Turkington et al. 2002), and heating with lamps in this way has been shown to closely replicate temperature regimes experienced under direct insolation in nature, and to very effectively reflect controls exerted by the thermal characteristics of different stone types (Warke and Smith 1998; Gomez-Heras et al. 2006). In addition to the lamp, the cabinet contained an infra-red thermometer to measure the surface temperature of the block, air temperature and relative humidity probes to monitor ambient conditions and a small fan that could simulate airflow across the block surface as required. Finally, a spray nozzle connected to a pressurized water reservoir (held at 20° C) outside of the cabinet allowed the simulation of driven rain on to the exposed surface of the test block.

2.4 Experimental regimes

Before each experimental run, the test block was dried at 50° C until resistivity readings in the electrodes stabilized at original levels. The block was then placed in the climatic cabinet and allowed to equilibrate to the ambient temperature to be used in the experiment. Two ambient air temperatures (20° and 5° C) were chosen that are considered to approximate to summer and winter daytime conditions respectively in south central England. Under each of these conditions relative humidity was held at 50% and short-term variations in insolation were replicated by alternately switching the lamp on for 15 minutes and off for 30 minutes. Stone temperatures under dry
conditions for each experiment were collected over the fourth cycle after the internal temperature regimes had developed into a stable response pattern. This procedure was followed to establish the heating and cooling regimes under winter and summer conditions. To examine the effects of surface wetting on these thermal regimes, the experimental runs were repeated with the surface of the block being sprayed with water for 5 minutes prior to switching on the lamp, with and without a forced airflow across the surface.

3. Results and discussion

3.1 Overall results

Results of temperature measurements from the various experimental runs are shown in Figures 3 and 4. They are portrayed specifically to give an impression of the dynamics of heat flow into and out of the surface of the test block and for purposes of clarity are divided into heating (15 minutes) and cooling (30 minutes) phases. Although temperatures were measured at one-minute intervals, they have only been plotted for every three minutes during heating and five minutes during cooling so that the plots with depth can be distinguished at the scale of the diagrams. The data have also been smoothed in Excel to identify temperature trends with depth. It is acknowledged that between data points this could lead to some slight distortion in the curvature of the plots, but in terms of interpretation it is important to note that all lines continue to pass through the measurement points. Results from the resistivity probes showing the inward progression of the wetting front are presented in Table 1.

<table>
<thead>
<tr>
<th>Wind conditions</th>
<th>Arrival of wetting front (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5cm 1cm 2cm 5cm 10cm</td>
</tr>
<tr>
<td>Summer (20°C)</td>
<td></td>
</tr>
<tr>
<td>Without wind</td>
<td>5 20 63 - -</td>
</tr>
<tr>
<td>With wind</td>
<td>4 19 62 - -</td>
</tr>
<tr>
<td>Winter (5°C)</td>
<td></td>
</tr>
<tr>
<td>Without wind</td>
<td>4 11 167 - -</td>
</tr>
<tr>
<td>With wind</td>
<td>9 54 139 - -</td>
</tr>
</tbody>
</table>

Table 1. Time of arrival of the wetting front

3.2 Temperature regimes under dry conditions

Under ambient conditions of 20°C, the periodic surface heating has raised the surface temperature of the block to just above 22°C at the beginning of the heating cycle (Figure 2, A1). Once heating commences, there is, as expected, a rapid rise in surface temperature, especially within the first three minutes to approximately 27°C, thereafter it rises more slowly to peak just below 29°C after 15 minutes. This is some 7°C above ambient. The effect of this rapid surface temperature rise is to establish a very steep subsurface temperature/stress gradient between the surface and 1cm depth. The most striking feature of the temperature curves is, however, that at the start of the heating cycle the subsurface temperature regime is very complex. Because overall block temperature is above ambient, at the end of the previous cooling phase surface temperature is, as one would expect, lower than that at 0.5cm. Below 0.5cm however, temperature falls again at 1cm, before rising again at 2cm and then decreasing with increased depth. This produces a wave like effect of multiple inflections that are
progressively simplified as the surface rapidly heats. Once the lamp is switched off (Figure 2, A2), a rapid drop in surface temperature from 29°C to 24°C over the first 4 minutes quickly establishes a new, but reversed subsurface temperature/stress gradient now largely restricted to the outer 0.5cm. It also rapidly reasserts the complex wave pattern this extreme gradient is.

![Figure 2](image)

**Figure 2**: Surface and internal stone temperatures for ambient air temperature of 20°C.

The origins of this wave-form pattern of subsurface temperatures remains, as of yet unclear. One possibility is that the data clearly indicate, despite the brevity of the simulated insolation, that its effects are felt, albeit in an attenuated and delayed form well below 5cm. Because of this difference in response time with depth it is possible, especially nearer the surface, that an outgoing thermal wave triggered by surface cooling does not dissipate before it encounters the next incoming thermal wave. In this way, especially if more than one pair of thermal waves are superimposed on each other, to envisage the establishment of interference patterns stabilized at particular depths. It is understood that such patterns could also possibly be an artifact of temperature measurement at a limited number of fixed depths. The changes in the relationships through cycles of heating and cooling suggests however that they are
real and that if intervening measurements were taken their only possible effect could be to identify further complexity. One way in which this hypothesis could be tested is to vary the lengths of the heating and cooling phases to see if the interference patterns shift, and work is currently underway to do this. What is clear, however, is that the cycles of short-term heating and cooling are very effective in rapidly establishing steep subsurface temperature/stress gradients and that, whilst they may be transient they are established during both heating and cooling and are disproportionately effective within the first 1cm of the stone. The data also reveal that the temperature regime with depth is far more complex than that surmised from previous studies that used only a limited number of sampling depths. This means that whilst overall temperature gradients may decrease with depth, their frequent reversal at more than one depth is likely to establish a complex stress pattern that could influence a range of weathering mechanisms from thermal fatigue, to the behaviour of any salts contained in pores at these depths.

![Figure 3](image)

**Figure 3**: Surface and internal stone temperatures for ambient air temperature of 5°C.

When the dry block was subjected to the same regime of surface heating and cooling at an ambient temperature of 5°C (Figures 3, D1 and D2), the most obvious feature is
retention of similar wave-form patterns of subsurface temperatures with depth – especially when the block has ‘relaxed’ at the end of the cooling phase. Whilst the periodic heating of the block raises overall block temperature above ambient, absolute temperatures are reduced compared to those during the 20°C cycle, as is the surface temperature range across the cycles – c. 4.5°C, from 7.5°C to 12°C. As with the measurements at 20°C however, the most rapid changes/temperature gradients are associated with the first 3-4 minutes of heating and cooling, although in this case the steepest gradients are more clearly within the outer 0.5cm. Lowering the ambient temperature did not, however, appear to steepen the cooling gradient. This is most probably because of the shortness of the heating phase, and it is envisaged that by changing the ratio of heating to cooling it should be possible to raise surface temperatures beyond those observed here. In which case it might be expected that initial surface and immediate subsurface cooling could be much more rapid. What these data do suggest is that under cool air conditions the heating phase does not generate an exceptional rate of surface temperature increase.

3.3 Temperature regimes modified by surface wetting

Wetting the surface of the test block at an ambient temperature of 20°C (Figures 2, B1 and B2) produces an overall similarity in the pattern of temperature change over depth and time that is, nonetheless, distinguished from the dry block by a number of detailed differences. The same wave-form is produced and the rate of surface/near-surface change is most rapid and internal temperature gradients steepest during the first 3-4 minutes after heating and cooling commences. Absolute temperatures, but not the temperature range at the surface are suppressed, presumably by evaporation, and the increased thermal conductivity consequent on the presence of the moisture means that the thermal wave penetrates more deeply and rapidly into the block. Resistivity data (Table 1) indicates that moisture penetrates very rapidly to 0.5cm whilst it is still ‘raining’, and that within the heating phase it has penetrated to at least 1cm. Although it takes considerably longer for the wetting front to penetrate more deeply, it appears that enhanced surface heat transfer facilitates overall heat transfer to depth and results in a greater temperature variation over the heating/cooling cycle. The effect of this is to accentuate not only the temperature range but also the degree and rapidity of the temperature reversals at each of the inflection points. This could further accentuate any physical stress in these zones, especially if salts and moisture are now both present.

When the test block is wetted and subject to a surface airflow (Figures 2, C1 and C2) at 20°C, the effects, presumably, of increased surface evaporation are to suppress both the absolute surface maximum temperature and the temperature range. In doing so, it is inevitable that the average internal temperature gradients are reduced, although they remain steep for the first few minutes after heating and cooling commence. Resistivity measurements suggest that the rate of moisture penetration, at least over the first 1cm remains approximately the same, and whilst it is apparent that heat transfer to depth is enhanced compared to dry conditions, the reduction in temperature range subdues the overall variability. This is especially the case at the inflection points where, in comparison to wetting with no airflow, that at 2cm virtually disappears.
At an ambient temperature of 5°C, surface wetting with water at 20°C (Figures 3, E1 and E2) appears to make little noticeable difference to absolute surface temperature or temperature range, apart from possibly a slight suppression of surface temperature at the end of the cooling phase. As with wetting at 20°C, however, moisture penetration appears to enhance temperature variability at depth, i.e. penetration of the heat wave, and accentuate temperature reversals and temperature/stress gradients across the inflection points. With an airflow across the wetted block (Figures 3, F1 and F2), the most significant result is a marked reduction in surface and subsurface temperatures at the end of the first cooling phase, which effectively destroys any internal temperature gradient with depth. The reduction in surface temperature is most probably a response to enhanced surface evaporation, a suggestion that is supported by data on water penetration (Table 1), which shows a much slower movement of the wetting front. Any enhanced evaporation could be similar to that observed from warm water bodies during winter months when, in accordance with Dalton’s Law, evaporation from the surface is proportional to the difference between the saturation vapour pressure at the surface temperature and the actual vapour pressure of the overlying air (Ward and Robinson 1999). Smith and Kennedy (1999) noted a similar effect when measuring weight loss from salt loaded blocks by surface evaporation and they suggested that this could in turn possibly lead to enhanced salt crystallization at or near the surface. Clearly, not only ambient and rock surface temperatures should influence these effects, but also the temperature of the ‘rain’. Thus, whilst this experimental run provides an insight into possible effects, work is under way to investigate the impacts of different air, rock and water temperature combinations.

4. Conclusions

In the context of traditional views on stone temperature variations, the data presented here indicate that in response to rapid, short-term changes in insolation it is possible for surface and subsurface temperature regimes to develop that are much more complex than the smooth, exponential increases and decreases that are assumed to characterize, for example, diurnal patterns of heating and cooling. The data confirm the significance of very steep temperature/stress gradients within the outer 1cm or less of exposed stone under short-duration cycles of heating and cooling. The importance of this was hinted at by, for example, Gomez-Heras et al. (2006), who argued that this is the zone in which many stone decay processes (particularly salt weathering) operate, these processes invariably respond to temperature and moisture fluctuations, and short-term interruptions to insolation could, for example, trigger these fluctuations on numerous occasions over a day. The data also indicate that there are complex patterns of temperature reversal with depth that are influenced in their intensity and location by surface wetting and moisture penetration, airflow across the surface and ambient air temperature. Surface wetting is seen, for example, to enhance internal heat transfer and to generally enhance the range of temperature variability at depth and the intensity of temperature reversals at inflection points within the temperature profile. It must be emphasized that these are preliminary results and that work is continuing to characterize and quantify different combinations of the variables mentioned above. In particular, there is a need to explore the origins of the complex wave-forms that were consistently identified within the subsurface temperature profiles. What is clear, however, even at this early stage, is that the
thermal response of stone to complex environmental conditions can be equally as complex, and that this complexity has major implications for all stone decay processes that are in turn driven by moisture and temperature changes – especially salt weathering.

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