Chapter 5.3

WEATHERING OF BUILDING STONE: APPROACHES TO ASSESSMENT, PREDICTION AND MODELLING

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Abstract: In the natural environment, weathering and breakdown of stone is an accepted part of long-term landscape development but the same acceptance of change and deterioration is not extended to stone used in construction especially when such deterioration affects historically and/or culturally important structures. The value of an integrative approach to improve understanding of weathering and failure of building stone is examined through review of three investigative approaches. First, condition assessment of the structure is an essential component of any remedial programme as this facilitates identification of the nature, extent and severity of deterioration and provides a measure of the degree of intervention required. Summary data are reported from a Staging System that seeks to impose a more formal structure on condition assessment providing a commonality of methodology, terminology and meaning whilst also providing a procedure for forecasting extent of treatment required and likely outcome in terms of 'life expectancy' of the structure. The second approach to investigation is assessment of the appropriateness of replacement stone. This involves many analytical procedures but gas permeametry in particular is becoming an increasingly useful portable, non-destructive analytical technique for predicting potential durability. Summary data are presented from analysis of Dumfries sandstone and Leinster granite illustrating spatial variability in stone surface permeability and the implications of this for post-emplacement weathering response and long-term durability. The final approach involves modelling potential stone decay pathways. The ability to more accurately model stone behaviour has significant implications for the design of conservation strategies and the avoidance of inappropriate treatments that may, inadvertently, trigger the sequence of decay and failure.

Key words: sandstone; building stone; weathering; condition assessment; staging system; permeametry; modelling.

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1. INTRODUCTION

In terms of mineralogy and structure, stone is an extremely complex material – a complexity that is reflected in its weathering response to both natural and urban environmental conditions. An awareness of the potential complexity of stone weathering response and an understanding of the factors controlling this is essential for successful and long-lasting conservation work. Stone is one of the oldest building materials used by man, selected because of its perceived durability especially when compared to the human lifespan. This perception of durability has given rise to a somewhat flawed assumption on the part of those unfamiliar with its performance in the natural environment that, as a construction material, stone should remain fundamentally unchanged during the lifetime of a building. However, as with any other natural material, change is an inherent characteristic as component minerals degrade through exposure to complex subaerial conditions comprising a combination of frequent low-magnitude weathering episodes (e.g. wetting and drying, heating and cooling) interspersed with the effects of rarer high-magnitude events such as a severe frost or extreme heating as a result of fire in the building. Overtime the combined effects of these processes act to weaken the fabric of the stone with associated physical disruption and loss of material.

Consequently, deterioration in mechanical properties such as stone strength/durability should be expected during the lifetime of a building, especially in historically and archaeologically important structures that have stood for hundreds or possibly thousands of years. The nature and rate of this deterioration is controlled by complex interactions between a variety of intrinsic and extrinsic factors (Table 1) with the significance of each of these varying from building to building and even across different façades on the one building. Further complexity arises from the spatial and temporal variability of the rate, nature and extent of stone deterioration. Rates of deterioration can change overtime in response to changes in conditions of exposure through, for example, an alteration in groundwater conditions or through the use of inappropriate repair techniques such as replacing lime mortar with harder cement-based material during repointing. Spatial variability in the nature and extent of stone deterioration is a common feature affecting outcrops of stone in the natural environment and is primarily a response to differences in structural characteristics and micro-environmental conditions. On buildings similar spatial differences in the condition of stone are common and can make decisions regarding selection of conservation strategies difficult especially with regard to non-selective procedures such as cleaning and application of surface treatments.

Approaches to building stone conservation should be underpinned by an understanding of the potential complexity of stone deterioration and recognition of the controlling variables, the interactions between these and how these interactions change over space and time. In the following sections the value of adopting an integrative approach to improve understanding of weathering and failure of building stone is examined through review of three investigative approaches. The first involves the initial condition assessment of a building. This is an extremely important exercise that forms an essential component of any remedial programme through identification of the nature,

Table 1. Examples of intrinsic and extrinsic factors that may influence the nature, rate and extent of building sandstone deterioration.

Intrinsic Factors	**Examples**
Mineralogy	Calcareous sandstones may be susceptible to long-term chemical dissolution resulting in changes in pore dimensions and generalised disintegration through removal of inter-granular calcite cement. The presence of clay minerals may increase deterioration as clays can adsorb moisture and act as loci for salts.
Structural characteristics	Structures such as bedding planes and soft seams provide access points for moisture increasing weathering. Porosity characteristics have a major control on ingress and subsequent mobility of moisture and pollutants in stone.
Pollution legacy	Particulate pollutants absorbed into the stone prior to introduction of 'Clean Air' legislation can continue to influence stone deterioration despite improvements in air quality.
Legacy of previous conservation	Accelerated degrading of susceptible minerals due to inappropriate chemical cleaning and changes in surface porosity through over-aggressive mechanical cleaning such as grit blasting with possible removal of protective case-hardened outer layers of stone.
Extrinsic Factors	
Micro-environmental conditions	Aspect related differences in micro-environmental conditions at the rock/air interface influence the nature and effectiveness of weathering processes. Stone in shaded areas can remain damp for longer periods after wetting thus facilitating chemical weathering and increasing mobility of agents such as salt within the fabric of the stone.
Exposure history	Change in exposure conditions since original construction can alter receipt of atmospheric pollutants and change micro-environmental conditions. A building originally standing as an isolated structure but subsequently surrounded by urban development will have a comparatively complex exposure history. Also relevant is exposure to extreme events such as fire, earthquake and bomb blasts.
Availability of weathering agents	Proximity of building to the coast and the associated availability of marine aerosols. Also the proximity of buildings to industrial complexes, busy roads and junctions may increase concentrations of gaseous and particulate pollutants within the local environment.
Groundwater characteristics	A rise in groundwater can result in accelerated deterioration of stone in the lower few metres of a building with an increased risk of salt penetration especially in locations close to the coast where marine water incursion may be a problem.
Quality of original workmanship	Inappropriate mortar replacement, inaccurate positioning of subsurface cramps and face-bedding of blocks.

degree and type of intervention required. The second involves assessment of the appropriateness of replacement stone with particular emphasis on the benefits of gas permeametry, a portable, non-destructive analytical technique. Summary data are presented from analysis of Dumfries sandstone and Leinster granite illustrating spatial variability in surface permeability and the implications of this for post-emplacement weathering response and long-term durability. The final investigative approach involves creating models of stone behaviour which build upon a better understanding of the factors that trigger deterioration to provide an overview of potential decay pathways. The ability to more accurately model stone behaviour has significant implications for the design of conservation strategies and the avoidance of inappropriate treatments that may, inadvertently, trigger the sequence of decay and failure.

The methodologies outlined primarily focus on the weathering response of sandstones but the issues raised are equally applicable to other types of dimension stone.

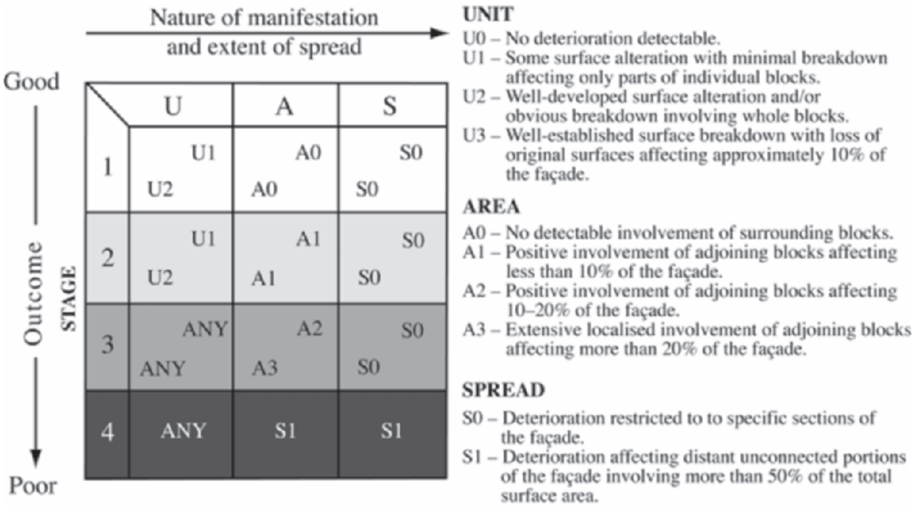
2. CONDITION ASSESSMENT

Condition assessment of building stone is an essential component of any conservation programme. A number of descriptive schemes have been developed to provide a framework for determining the nature and extent of stone deterioration through reference to a pre-defined list of decay and alteration features. Such schemes emphasize a block-by-block classification that requires considerable operator time and expertise[1,2]. Although such schemes have been successfully applied to internationally important archaeological and historical sites where each building block is a valued part of the whole[3], they are not generally appropriate for the less historically significant but more common structures that comprise the urban fabric of many towns and cities. In such instances, there are usually financial and manpower constraints that necessitate a more rapid and less detailed form of condition assessment usually undertaken by individual project managers who, in the absence of a formal methodology, are guided by their own experience. This lack of a common condition assessment scheme has contributed to an often, confusing mix of terminology used by different “experts” and the absence of meaningful long-term records against which to compare the condition of other buildings and the success or failure of different conservation strategies[4].

System assessment and classification are essential tools in many disciplines such as medicine where reliable condition assessment schemes have been developed as a necessary means of conveying clinical information in an unambiguous way. One of the most widely used of these schemes is the TNM Staging System developed for assessment and treatment planning for patients with cancer[5]. This is a deceptively simple system that “…provides an indication of prognosis and the extent of medical intervention required with the latter seen in the context of ‘life expectancy’ set against treatment cost, the probability of cure or disease recurrence and the presence and potential influence of predisposing factors”[4].

The apparent simplicity of this scheme belies the many decades of research that have informed the selection of classification categories and weighting of notation values. The principles that underpin the TNM Staging System are similar in many respects to those that govern the weathering response of stone. For example, in both cases, system response and outcome is determined by complex interactions between system components with many different factors influencing the dynamics of deterioration. In addition, the ‘prognosis’ and extent of remedial intervention required is normally closely associated with the nature and extent of ‘malignant’ change. In the case of the cancer patient, the larger the tumour and the greater the evidence of spread, the poorer the long-term prognosis whilst on a building, the greater the extent of damage to individual blocks and the greater the area affected on a façade, the more invasive and costly the conservation treatment required to prolong the ‘life’ of the building.

There are limits to the parallels that can be drawn between these two systems but because of the many common elements the TNM Staging System was adopted as the basis for the development of a similarly robust scheme for condition assessment of stonework – a scheme that goes beyond purely descriptive classification to include a forecast of likely long-term outcome with classification criteria and notation weightings based on current understanding of the decay dynamics of sandstone.



	U	A	S
1	U1 U2	A0 A0	S0 S0
2	U1 U2	A1 A1	S0 S0
3	ANY ANY	A2 A3	S0 S0
4	ANY	S1	S1

UNIT

U0 – No deterioration detectable.
U1 – Some surface alteration with minimal breakdown affecting only parts of individual blocks.
U2 – Well-developed surface alteration and/or obvious breakdown involving whole blocks.
U3 – Well-established surface breakdown with loss of original surfaces affecting approximately 10% of the façade.

AREA

A0 – No detectable involvement of surrounding blocks.
A1 – Positive involvement of adjoining blocks affecting less than 10% of the façade.
A2 – Positive involvement of adjoining blocks affecting 10–20% of the façade.
A3 – Extensive localised involvement of adjoining blocks affecting more than 20% of the façade.

SPREAD

S0 – Deterioration restricted to to specific sections of the façade.
S1 – Deterioration affecting distant unconnected portions of the façade involving more than 50% of the total surface area.

Figure 1. UAS Staging System developed for condition assessment of stone buildings from the TNM Staging model[4].

A necessary part of adapting the TNM Staging System was a change of terminology and revision of the definition of each of the Stage categories. For example, the original TNM notation, which is shorthand for 'Tumour' (T), 'Node' (N) and 'Metasteses' (M), was changed to UAS representing 'Unit' (U), 'Area' (A) and 'Spread' (S). 'Unit' refers to individual blocks of stone, 'Area' refers to sections of stonework where blocks are adjoining and 'Spread' refers to the extent of façade affected by deteriorating stonework. Once an assessment of which value is most appropriate for each of the U, A and S categories has been made one of 4 Stage classifications can be assigned (Table 2). For example, a façade showing evidence of well-developed surface alteration involving whole blocks of stone (U2) with connecting blocks affected over more than 20% of the façade (A2) but with deterioration restricted to specific parts of the façade (S0) would be classified as being Stage 3. Although Stage 3 indicates the necessity for significant remedial intervention (Table 2) it also notes that such intervention should prolong the serviceable life of the structure. Stage classification can be done for the building as a whole or for individual facades.

The benefits of developing a formal condition assessment scheme that is quick and easy to use like the UAS Staging System are fourfold:

- The criteria for condition assessment used in the Staging System method are deliberately limited in number and extremely generalised placing emphasis on identifying the presence or absence of obvious surface deterioration/alteration features coupled with an estimate of the percentage area of façade affected thereby enabling a more rapid evaluation of the condition of the building as a whole.
- Because the UAS Staging System is less detailed it should provide a relatively uncomplicated assessment tool for everyday use that is quick and easy to use with consequently less demands placed on operator time. Consequently it should be a valuable tool for condition assessment of the less exceptional but much more common stone buildings.
- Use of such a system would also provide the basis for a common condition assessment terminology providing an easily understood record of original condition against which the success or failure of conservation treatments could be assessed. Alternatively, if no treatment is considered necessary, the Stage classification of each façade would provide baseline data against which to compare subsequent assessments in a long-term monitoring program.
- The Staging System approach goes beyond the basic descriptive form of classification to provide an indication of likely outcome and the degree of intervention required based on current understanding of the decay dynamics of sandstone.

Detailed discussion and preliminary data from initial field trials of the UAS Staging System are reported in a paper by Warke et al.[4] but the system

Table 2. Summary guidelines for the extent of remedial treatment indicated by each of the four condition stages identified[4]

Stage	Summary of required intervention
Stage 1	A façade in this condition would require only localised remedial treatment concentrating on individual stone blocks. A staging classification of 1 may also indicate that no active intervention is required with only periodic reassessment of the façade advised.
Stage 2	Section specific remedial action would be required in this case but the extent of intervention should be relatively limited because of the lack of distant involvement within the façade boundaries.
Stage 3	Significant intervention will be required with up to 40% of the total façade surface showing evidence of deterioration. Although the extent of deterioration is severe, appropriate conservation treatment should prolong the life expectancy of the structure.
Stage 4	Serious deterioration affecting more than 50% of the total façade surface with stone decay detected on unconnected, distant portions of the façade. On a stage 4 category of façade, considerable intervention will be required to restore the stonework. If the structure is of limited historic and/or architectural merit then consideration should be given to the provision of palliative rather than restorative treatment.

still requires considerable refinement and field-testing especially with regard to the 'certainty' status of initial stage classifications and to the development of classification criteria for other stone types such as limestone and granite.

The Staging System model is an attempt to provide a rapid, relatively simple to use, assessment scheme that provides a formalised recording method for everyday use and is not intended to replace or devalue other existing but more detailed descriptive classification schemes. Both approaches have their place, the former for the stone structures that make up much of the historic urban fabric of contemporary towns and cities and the latter, for assessment and monitoring of internationally important stone built structures.

3. RESPONSE PREDICTION

Deterioration and failure of building stone can result from the action of many different weathering processes operating both sequentially and cumulatively. For example, salt weathering is primarily a mechanical process that disrupts the physical integrity of stone whereas chemical weathering processes degrade specific chemical elements within the crystal lattice of constituent minerals. Although disparate, nearly all weathering processes rely on the presence of moisture to transport salts or other contaminants into stone and to enable chemical reactions to occur with subsequent removal or relocation of solutes.

Whilst the presence of moisture is important, the ease with which it can penetrate the fabric of stone is a critical factor in determining the susceptibility of stone to the action of weathering processes. The movement of moisture into and within stone reflects its porosity and permeability characteristics. It is important to note that porosity and permeability are fundamentally different properties with the former describing the fractional space between solid particles in a given volume while the latter is a measure of how easily a fluid flows through stone under a pressure gradient[6, 7].

Many studies have identified a link between porosity characteristics and susceptibility of stone to weathering related damage with particular emphasis on 'effective' porosity whereby the abundance of interconnected pore spaces increases moisture penetration and movement within substrate material[8–11]. Although porosity characteristics have been used as a means of predicting resistance of stone to weathering[9,12] there are limitations associated with this property because of the problems of identifying 'effective' as opposed to 'total' porosity and the different rates of moisture loss associated with different sizes of pores. McGreevy[8] notes that there are just too many anomalies associated with porosity that limit the extent to which generalisations can be made between porosity characteristics and predicted weathering response.

Small-scale spatial variations in effective porosity can have a significant influence on permeability leading over time to differential surface weathering and loss of material[11,13]. Recognition of the importance of permeability and the implications of this for long-term weathering response and the uptake of stone surface treatments such as consolidants and biocides has only come to the fore in recent years because of the transfer of technology developed for the oil industry which allows detailed measurement of permeability under both field and laboratory conditions[7].

The ability to quantify permeability may prove to be a more reliable means of predicting long-term weathering response of stone because it can provide a more accurate representation of the potential for moisture movement in stone. However, as with any stone property it is important to recognise that permeability characteristics can change over time in response to the blocking of some pores through salt accumulation or by the creation of a secondary porosity through mechanical breakdown and microfracture development[14]. To illustrate the role of permeability as a potential indicator of the likely weathering response of stone, summary data are presented from a laboratory study in which the durability of five stone types (Table 3) was tested using a complex weathering simulation experiment comprising salt weathering and freeze/thaw cycles. A total of sixty-six 75mm^3 blocks of each stone type were used in this study and a full explanation of the experimental procedure and detailed discussion of Stanton Moor sandstone data is given in Warke et al.[11].

At the end of the simulated weathering experiment weight-loss data indicated that Dumfries sandstone sample blocks had undergone the greatest amount of breakdown and Leinster granite, the least with the other three stone types falling between these two end points (Table 4). Dumfries sandstone samples lost on average over one third of their initial weight but given the combination of a comparatively high porosity and permeability and the abundance of clay minerals (smectites) that form interstitial clay laminae, this was not unexpected. More significant was the existence of a clear association between the range of permeability values for each of the five stone types and the extent to which samples failed under experimental conditions. Data indicate that the smaller the range of permeability values the less susceptible this stone was to weathering under the experimental conditions used in this study (Table 4). It is also evident that the lower the mean permeability the more durable the stone type although the reliability of this relationship breaks down when comparisons are made between the response of Stanton Moor A, Stanton Moor B and Portland limestone (Table 4).

Table 3. General description of stone types used in the experimental study.

Stone Type	**General Description**
Leinster granite	Tertiary feldspar-rich granite with interlocking crystalline structure. Feldspars comprise 42.5% (plagioclase 31.5%), quartz 26.7%, mica 19.7% and clays 11%.
Portland limestone	Jurassic oolitic limestone with bimodal pore size distribution (30–8μm and 0.3–0.08μm). Calcite comprises 57.8%; quartz 2.3% and clays 13.5%. Porosity can be extremely variable especially with regard to larger pores.
Dumfries sandstone	Permian quartz and iron-rich red sandstone with well defined bedding and a unimodal pore size distribution of approximately 100μm diameter. Quartz comprises 52%, feldspars 10.5%, clays 18% (smectites) and mica 1%.
Stanton Moor A (fine to medium-grained)	Carboniferous fine–medium grained (<300μm) quartz-rich sandstone (Millstone Grit series) with well-developed interlocking quartz and feldspar overgrowths. Quartz comprises 62%, feldspars 14.25%, mica 0.75% and clays (chlorite) 11.25%.
Stanton Moor B (medium to coarse-grained)	Carboniferous medium–coarse grained (>300μm) quartz-rich sandstone (Millstone Grit series) with well-developed interlocking quartz and feldspar overgrowths. Quartz comprises 62.25%, feldspars 21.5%, mica 2% and clays (chlorite) 7.5%.

*Table 4***.** Durability ranking results based on mean weight change data from weathering simulation experimentation with the most durable stone type being Leinster granite and the least durable Dumfries sandstone.

Stone type	**Initial Porosity (%)**	**Mean weight change (%)**	**Permeability range (mD)**	**Mean permeability (mD)**
Leinster granite	0–3	-0.93	3.7 (0.4–4.1)	1.75
Stanton Moor sandstone B	13.5	-10.26	109.3 (4.7–114)	58
Portland limestone	13–26	-22.63	149 (1–150)	15
Stanton Moor sandstone A	17	-27.02	198.3 (7.7–206)	61
Dumfries sandstone	18–25	-33.46	800 (200–1000)	600

While general permeability data were collected from each of the five different sets of 66 blocks used in the simulation study, a more detailed investigation of the spatial variability of permeability was undertaken for each of the five stone types used in this study. Space restrictions preclude the discussion of all five stone types but an overview of data from Dumfries sandstone and Leinster granite is given.

Detailed analysis of permeability was made using an unsteady-state portable gas permeameter following a regular grid scheme with 10 mm sample spacing applied to one face of a block of Dumfries sandstone and one face of a block of Leinster granite. The dimensions of each of the two blocks were 75x75x75mm. A total of 49 measurements were obtained from each block face. Sequential Gaussian Simulations (SGS) were performed using the grids of permeability data to produce representations of permeability variation for each of the two block faces (Figure 2). The SGS method is a form of conditional simulation in which simulated values are conditional on the original data and previously simulated values. The simulated realisations of permeability were made to 1mm grid-point spacing. SGS was conducted using algorithms supplied as a part of the Geostatistical Software Library[15] and further detail regarding the geostatistical procedure can be found in[7,15-17].

The simulations clearly illustrate marked differences in the permeability characteristics of both stone types with the Dumfries sandstone showing a much greater range of values in comparison to the Leinster granite (Table 5). Whilst permeability of Dumfries sandstone is an order of magnitude greater than that of the Leinster granite, the patterns of spatial variability across each block also exhibit significant differences.

Permeability data from Dumfries sandstone show several clearly identifiable areas of higher values (Figure 2a) that may be associated with the surface expression of clay laminations that are characteristic features of this sandstone. Data from Leinster granite show that areas of higher permeability tend to be less well defined and are possibly related to the presence of mica and feldspar minerals that comprise significant proportions of this stone (*c*.19% and *c*.42%, respectively) (Figure 2b). It is important to note that because of the specialised software used to produce the permeability grids, the shading scales shown in Figure 2 are block-specific and therefore the same degree of shading will not indicate the same permeability value.

Table 5. Permeability statistics for single unweathered block faces of Dumfries sandstone and Leinster granite used in durability testing (values are expressed as MilliDarcys (mD)).

Permeability Statistics	**Dumfries sandstone**	**Leinster granite**
Maximum	298.0	34.8
Median	103.0	22.0
Minimum	49.7	7.2
Mean	127.2	22.1
Range of Values	248.3	27.6
Standard Deviation	61.0	7.9

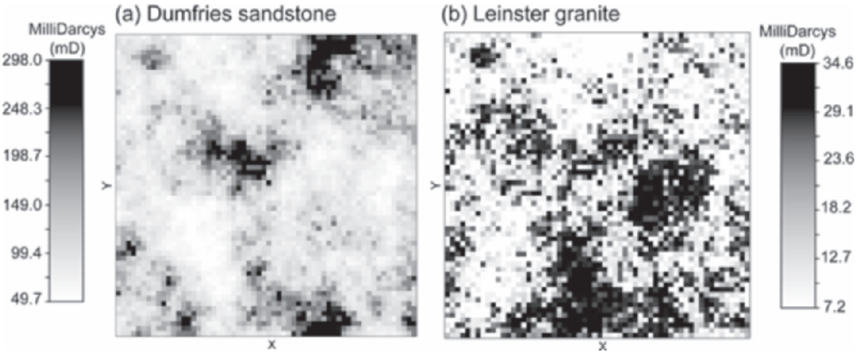


Figure 2. Sequential Gaussian Simulations (SGS) of single block faces of (a) Dumfries sandstone and, (b) Leinster granite, highlighting the spatial variability of surface permeability. Note the differences in shading scales for each block.

These data demonstrate that under laboratory conditions stone types with a large range of permeability values, where greater spatial uncertainty occurs in (simulated) permeabilities, tend to be less durable. These data also suggest that the spatial distribution and variability of permeability is more important in predicting the overall strength and weathering properties of stone than mean permeability and absolute minimum and maximum values. However, much more research is required to better understand the factors that control permeability and how these may change overtime as stone 'ages' in response to long-term weathering.

4. MODELLING DECAY PATHWAYS

The final investigative strand in an integrative approach to improved understanding of the weathering and failure of building sandstones is the modelling of decay dynamics. The importance of this aspect cannot be over-emphasized as it is only through development of such models that research is made effective. Price[18] notes that although the number of papers relating to aspects of building stone deterioration has increased markedly in the last few decades, many authors fail to follow-up on the significance of their data or to set their research in context. Consequently, despite an ever-increasing knowledge base, its actual effectiveness in dealing with 'real-world' stone conservation issues is somewhat limited. It is only through using these data to inform development of conceptual models that the relevance of research is assured and meaningful advances in understanding made.

Research has shown that sandstone deterioration in particular, is characterised by threshold decay phenomena such as granular disintegration, scaling and flaking – features that are triggered by the crossing of intrinsic and/or extrinsic stress/strength thresholds[19,20]. In order to identify the most appropriate and cost effective conservation treatment a sound understanding of the factors that can trigger the development of such features, and the conditions that promote continuation of deterioration and failure through establishment of positive feedback conditions, is essential so that every effort can be made to avoid them[21].

Our understanding of the factors that control sandstone deterioration has rapidly advanced in the last two decades primarily through the combination of laboratory-based experimental work linked with field site studies with considerable progress made and insights gained through the adoption of an interdisciplinary approach to investigation. For example, there is now a much improved understanding of the complexity of factors that contribute directly to the weathering and surface retreat of sandstone. In particular, research regarding the formation, mobilisation and accumulation of salts within stone demonstrates their spatial variability on the surface and at depth and the implications of this for differential surface retreat and the long-term success of conservation treatments[19,22]. For example, the concentration of salts at depth in 'hot-spots' has been shown to have significant implications for the continuation of deterioration once failure has been initiated because these 'hot-spots' act as reservoirs of salt that continue to 'fuel' the decay process[21,22].

Advances in technology have also enabled more detailed short and long-term characterisation of micro-environmental conditions at the rock/air interface. These data are important because they illustrate the complexity of conditions and enable identification of the weathering processes that operate and how these in turn can change overtime in response to differential surface weathering[23]. Micro-environmental data (e.g. air and stone temperature and atmospheric humidity) have also been used to create laboratory-based weathering experiments that more accurately simulate 'real-world' conditions thus producing results that have a direct relevance for predicting the performance of stone on buildings.

These advances in understanding, together with progress in many other areas have enabled the development of conceptual models of stone breakdown that identify potential decay pathways (Figure 3). The model shown in Figure 3 illustrates the episodic nature of failure in sandstone where, for example, failure through the initiation of surface scaling of a block with an apparently stable crusted surface but with a weakened substrate may be triggered by an extreme event such as a severe frost acting on previously wetted stone. Following this loss of surface material the sandstone can take one of two decay pathways. First, the newly exposed surface may stabilise sufficiently to allow development of a secondary crust with associated substrate weakening until some point in the future when the cycle of failure and stabilization is repeated. Alternatively, the newly exposed but weakened substrate may continue to degrade through development of multiple flaking and granular disintegration with accelerated surface retreat. These two different responses can be seen on many sandstone buildings and demonstrate the complexity of interactions between factors such as moisture and salt avail-

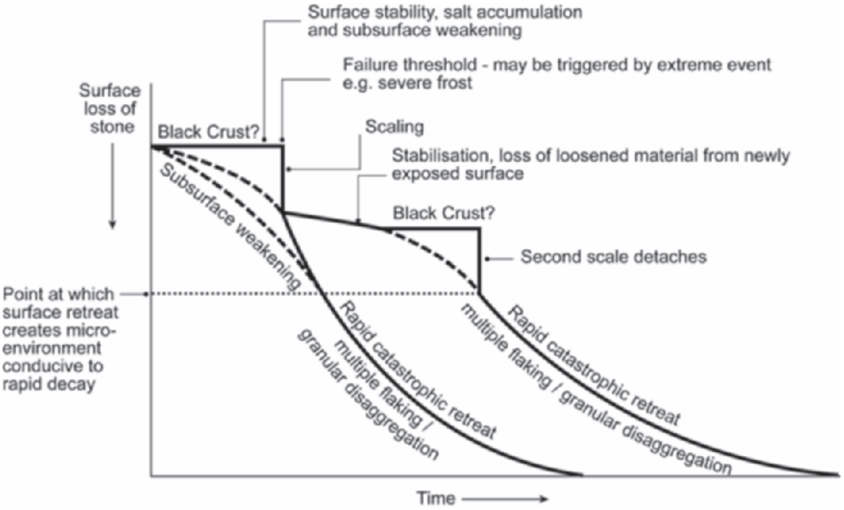


Figure 3. Schematic diagram modelling the possible decay pathways associated with sandstone building blocks exposed to the effects of salt weathering[21]. (Reproduced with permission from the Geological Society, London).

ability, permeability, porosity and mineralogy. These interactions can vary from block to block and will determine whether conditions of positive or negative feedback become established.

It is this improved understanding of the factors that control the decay dynamics of sandstone that enables informed decisions to be made regarding the selection of conservation treatments and will hopefully help prevent the use of inappropriate techniques that have resulted in so much damage in the past.

5. CONCLUSION

This brief overview of three investigative approaches to the problem of the weathering and failure of building sandstones highlights the value of an integrative strategy and the importance of linking laboratory-based study with ‘real-world’ conditions. However, there are still many gaps in our understanding and much work still to be done especially with regard to testing and refining predictive models and condition assessment methodologies.

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