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INVESTIGATIONS INTO DECAY MECHANISMS OF MAGNESIAN LIMESTONE AT CHAPTER HOUSE, HOWDEN MINSTER

David Odgers[1], Sarah Pinchin[2], Bill Martin[2], Chris Wood[2], Tobit Curteis[3], Eric Doehne[4] Giacomo Chiari[4], Jeanne Marie Teutonico[4,] Ann Bourges[5]
[1]*Odgers Conservation Consultants, Somerset, UK*
[2]*Building Conservation Research Team, English Heritage, London, UK*
[3]*Tobit Curteis Associates, Cambridge, UK*
[4]*Getty Conservation Institute, Los Angeles, CA, U.S.A*
[5]*LRMH, Historical Monuments Research Laboratory, Paris, France*

Abstract
Constructed entirely of magnesian limestone, the Chapter House at Howden Minster, East Yorkshire, dates from 1380 and has been in the care of English Heritage since 1971. For two hundred and fifty years, it was a roofless ruin; the elaborately carved stone interior subject to significant on-going decay. The acute stone degradation on this site prompted English Heritage and the Getty Conservation Institute to establish a joint project in 2003 to understand the mechanism of magnesian limestone decay. The aim of this project is to understand the causes and mechanism of the deterioration at Howden Minster and devise a conservation strategy for the site that would help our general understanding of how to conserve deteriorating dolomitic limestone structures.

Results from decay mechanism studies in the laboratory show that flaking of Magnesian Limestone can be achieved in three months using magnesium sulfate salts and fluctuating moisture levels. Petrographic investigations have included characterisation of the properties of magnesian limestone samples from Howden compared to freshly cut stone from local quarries and stone from other historic sites.

On site, the patterns and rate of decay have been mapped and documented. The condition of the stone is recorded and compared to the existing historic photographic record. Methods of recording active decay are being compared, including condition survey, photogrammetry, laser scanning, repeat photography, and field-time lapse photography.

Changing environmental conditions are monitored, including relative humidity, ambient temperature, radiant temperature, and surface temperature. A weather station also measures external temperature, humidity, rainfall, wind speed and direction at the site. Atmospheric pollutant levels are also recorded. Changing moisture levels and placement of moisture, at heights and at depth within the wall, are monitored. The type, concentration, and location of salts have been examined before and after large-scale desalination trials.

There are a number of issues driving the stone decay, including concentration and mobility of magnesium sulphate, activity of salts instigated by humidity fluctuations, periodic condensation on the stone, historic pollution levels and site-specific physical factors.

Keywords: Magnesian limestone, Magnesian Sulfate salts, monitoring deterioration

1. Introduction

1.1 Minster History

Howden Minster was established as a collegiate church in the 13th century. The Chapter House on the south side of the Choir, which seated thirty, was built in the 14th century (Pevsner 1972). The Chapter House is arranged on an octagonal plan and constructed entirely of magnesian limestone. Intricately carved stonework, spanning two stylistic periods, dominates the interior. The structure has colossal Perpendicular windows and below the windows, Decorated crocketed ogee arcades, with four bays to each elevation. Each bay has a panel of quatrefoils.

The Reformation of the Church in England took its toll on Howden Minster. A lack of funds necessitated partial use of the church. By the 17th century, the disused East end was closed off from the functioning nave and transepts. The roofs on the Choir and the Chapter House collapsed in the subsequent one hundred and fifty years and these areas were left in ruins. The ruins were taken into the guardianship of the Government's Department of the Environment in 1971, and are now managed by its successor body English Heritage.

Concerns for the state of the exposed exceptional carved stonework have been recorded for some time. Stone consolidation trials took place as early as 1981. A new roof was put on the Chapter House in 1984, and proposals were made at that time to enclose the structure by glazing the open windows, although this was never carried out. In 1988, the level of the ground abutting the exterior walls was lowered, and gravel covered 'air drains' collecting water at the wall base were installed to address water dispersed from the roof and down pipes.

1.2 Deterioration of the stone

The stone displays many different patterns of degradation. Some stones exhibit extensive interlocking cracks while other stones have poor cohesion. Much of the surface is spalling with flakes becoming detached and then the process being repeated. A large amount of the decorative detail is now eroded. A thick black crust which once covered much of the surface was substantially removed during cleaning which occurred in 1988, and now exists only in some protected areas.

Figure 1: Detail of the flaking stone on the Northwest wall.

Figure 2: Detail of the surface blistering on the East wall.

Figure 3: Detail of soft erosion on the North wall.

There are clearly multiple factors causing such extensive and variable damage.

1.3 English Heritage/Getty Conservation Institute project

It was necessary to examine the decay, to avoid subjecting the stone to irrelevant treatments. Such treatments would be both a costly misuse of resources, or worse still, might exacerbate or cause additional damage. It was essential to ascertain the rate, degree, and causes of deterioration, before finding ways of addressing the problems. Full documentation and real-time monitoring reveal the activity of decay, and allow the affects of trial remedial measures, or measures to slow the decay processes, to be accessed.

In order to understand the decay processes that are occurring at Howden Minster, a six-year collaborative project between English Heritage and the Getty Conservation Institute was initiated in 2003, to investigate in detail the deterioration occurring in the Chapter House. The project includes on site and laboratory inspection, monitoring, and analysis: to assess the environmental conditions, stone composition and contaminants, physical placement variables, documentation, salt analysis and desalination. Investigating these mechanisms will inform the conservation strategy for the site and will add to the understanding of the effectiveness of treatments for other magnesian limestone structures.

2. Magnesian Limestone

Magnesian limestone in England comes from an outcrop that extends North-to-South from Newcastle upon Tyne to Nottingham (Hart 1988). The stone is light cream coloured with iron oxide inclusions. The mineral composition of magnesian limestone is dolomite. It is a sedimentary carbonate rock with the principal chemical composition: $CaMg(CO_3)_2$.

2.1 Characterisation of the stone

Stone samples taken from the Chapter House at Howden were compared with freshly quarried stone from three local quarries by analysis of thin sections with a polarising microscope and elemental analysis with an environmental scanning electron microscope (ESEM). The chapterhouse stone samples revealed hollow spheres with dolomite crystals in the size range of 50 µm and though the pore walls were weathered, this stone closely resembled stone from Cadeby quarry. Cadeby stone was found in trials to be more susceptible to decay than other magnesian limestone types tested.

The stone has a high free porosity with a high connectivity of the pores. This pore network facilitates water absorption, storage, and transport (Bourges, 1995). Pore sizes measured by mercury intrusion range from 5mm to below 0.1mm; this variation can be associated with increased potential for damage (Everett 1961, Rossi-Manaresi *et al.* 1991). Artificial weathering of samples from Cadeby quarry by freeze-thaw cycling tests in the laboratory at the Getty Conservation Institute revealed this as a structural weakness in this stone.

3. Mechanism of Decay

The flakes at Howden detach in layers, or 'skins' of stone. This type of flaking could relate to a number of different mechanisms such as: the growth of salts which break the stone apart at specific distances from the surface due to evaporation, differential expansion of the surface of the stone and the interior, differential thermal expansion of specific components of the stone, or a combination of these (Laycock 1997).

3.1 Salts

The salts in samples from Howden were analysed with ion chromatography and found to contain a mixture of magnesium sulphate, calcium sulfate, sodium chloride and potassium nitrate salts. Direct evidence that the salts are associated with the damage to the stone has been shown by comparing sound stone samples with flaking stone samples using ESEM. Magnesium sulfate crystals were found on the underside of the flakes on the flaking stone samples.

Magnesium sulfate salts are very prevalent in the stone and may be largely responsible for the damage. Magnesium sulfate is present in very high concentrations in the first centimetre in depth from the interior surface and much lower beyond 2 cm. Magnesium sulfate salts are formed from magnesium from the limestone, and sulphate from deposition left from sulphur dioxide, from historic air pollution (Sanjeev et al. 1991). Magnesium sulfate is an extremely hygroscopic salt; it readily converts ambient moisture into liquid water so that it can deliquesce. Magnesium sulfate is about 300 times more soluble than calcium sulfate which makes it more mobile and capable of penetrating deeper into the stone leading to more aggressive damage (Cooke et al. 1993.). Similar damage to the cathedral of York Minster has been summarized by Saiz-Jimenez & Brimblecombe (2004).

4. Physical Examination in situ

The decoratively carved walls below the windows in the Chapterhouse are constructed of large masonry blocks; the walls are 450 mm in thickness at the top and 580 mm at the base.

The structure was examined in 2005 with non-destructive survey techniques: impulse radar and dynamic impedance to evaluate how water might enter the core of the wall. The resulting interpretation of the interior wall structure was that the outer and inner faces were linked by a course of bonding stones which extend the full span of the wall at 2.5m from the ground. Such a stone course could collect water entering the wall through the cill of the window above or from rising damp below. It was conjectured that such a through stone course might be responsible for the significant deterioration at the central portion of the wall face.

To gain a better understanding of the structure and the route of moisture ingress, an invasive excavation was carried out in 2007. A wide joint was removed from both sides of a wall at this course level enabling a good view of the internal composition of the wall and stones were removed from the lower and upper parts of the wall. It was found that some stones do run through the wall at this level but adjacent stones do not. A mortar and rubble core fills the space between the blocks.

5. Monitoring the Decay

5.1 Rate of decay

When the rate of flaking was examined from 1999-2001, by 'surface rationalisation' i.e. brushing off large flakes from the surface and observing changes in the same location, it was found that within a year the area had formed new flakes of the same proportion.

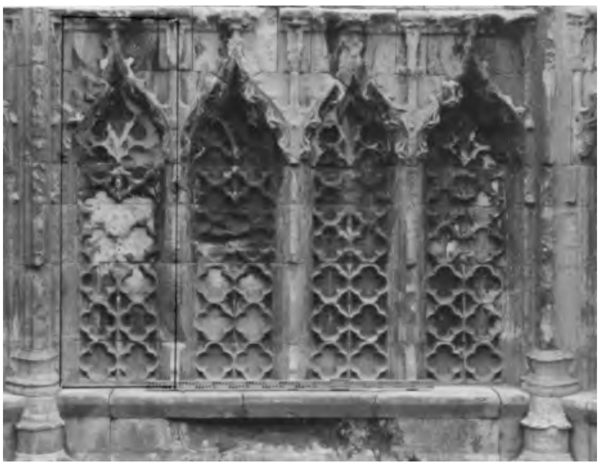
Macro photographs of the highlighted areas are taken at six-month intervals, recording when new flakes occur. A field time-lapse camera records damage as it is occurring. Stone loss events and the creation of new flakes appear to correlate with environmental changes such as high winds and condensation. The time-lapse sequence records the creation of new flakes and the loss of existing flakes which do not occur uniformly over the stone surface but rather in precise locations.

Figure 4: Macro photograph of flaking column on West wall.

Stereo photographs and photogrammetry of the interior have been periodically taken since 1980. These measured images allow us to ascertain the level of ongoing surface loss over time. However, areas examined in minute detail are unrepresentative of the loss as a whole because of the non-incremental nature of the decay. In 2006 a laser scan of the building produced a 3-dimensional model of the interior and exterior surfaces of the building. The model will allow future surface scans to be compared to the current model and also the evaluation of factors including air movement and solar radiation.

5.2 Patterns of decay

The patterns and progression of decay can be traced with photographic evidence. Photographs taken prior to the reroofing in 1984 show that extensive damage to the surface topography has occurred in the last twenty-four years. Photographs from 1980 reveal that the surface has undergone significant damage following this intervention.



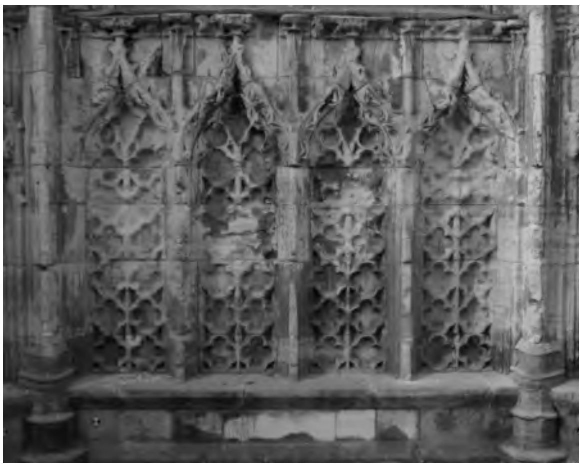


Figure 5: Photograph showing the extent of deterioration on the interior Northwest wall in June 1980.
Figure 6: Photograph showing the extent of deterioration on the same wall in June 2007.

The condition of the stones has been recorded for future reference, noting the patterns of deterioration such as flaking, lack of cohesion and microbiological growth and their placement throughout the interior.

6. Monitoring the Environment

The environmental conditions are being monitored to establish to what extent microclimatic factors are contributing to the deterioration of the stone. In July 2007 relative humidity and ambient temperature sensors, surface temperature sensors and radiant thermistors and a weather station were installed. The weather station is powered by a solar panel; it monitors wind speed and direction, rainfall, relative humidity, temperature, radiant temperature. The Eltek monitoring system is radio telemetric and has a Global System for Mobile communications (GSM) modem for remote access to data. Passive diffusion tubes are used to record the levels of air-borne nitrogen dioxide, sulphur dioxide, and ozone but the levels are found to be low. Moisture levels in the walls are being recorded with gravimetric analysis of wooden dowels inserted in purpose drilled holes at various heights in the wall, calcium carbide moisture meter readings, and electronic profile probes attached to the monitoring system.

The data demonstrates that the stone is undergoing severe phases of wetting and drying. Comparing the surface temperature of the internal walls with the dewpoint temperature of the air reveals that condensation events occur regularly. The hygroscopic nature of the salts in the stone will promote condensation in addition to the instances where the data indicate that condensation is occurring. In addition, it is likely that interstitial condensation is occurring more regularly than superficial events. In winter condensation is recorded on a daily basis. Because of the regularity of condensation occurring during this period, the stone will remain wet, due to the inability of the liquid condensate to evaporate between condensation cycles.

7. Remedial measures

Tests for remedial measures to minimize decay are being carried out. The results of durability laboratory testing at the Getty Conservation Institute reveal stone samples from the Highmoor quarry had a greater longevity than Cadeby (Bourges, 2005). However, stone variability within existing Magnesian Limestone quarries is significant, complicating the selection of replacement stone. Criteria for replacement stone may include saturation index, amount of swelling, microtexture and strength.

Since much of the damage to the structure can be attributed to salts, treatments to reduce the salt concentration and the capacity for the salt to crystallise have been tested both on site and in the laboratory.

7.1 Desalination trials

Desalination is a large, time consuming treatment, not practical for large structures. However, if periodic desalination results in the reduction of salts levels and their damaging effect then it should not be discounted. Appropriate times of contact, method, materials and schedule for re-treatment, need to be established. Testing to this end was carried out on site in conjunction with an EU desalination project designed to optimise the selection and performance of poultices for the purpose of creating guidelines for conservators for poulticing different substrates.

The poultice tested at Howden was half cellulose pulp and half sepiolite clay. Different contact times were observed from 20 hours-15 days. Powdered samples of the stone, taken before and after treatment, analyzed using ion chromatography, revealed that although the salt levels were initially reduced by the poulticing, the salts came back in the same quantities after 2 weeks. The samples taken at depth revealed that the wet poultice drove some of the salts deeper within the stone instead of removing them.

The negative results obtained from these desalination tests highlight the inconsistencies in the technique and reaffirm the need to better understand the mechanism of desalination so that conservators can carry out effective treatments. Controlling the introduction rate of water and allowing a longer time for extraction are two approaches that appear promising.

8. Conclusions

We are piecing together what is occurring on site on multiple levels: through full scale, macro, and micro investigations. The area directly above the height of rising damp (approximately 1.5 m above ground level) is the location where the largest quantities of salts have accumulated, and the area most vulnerable to decay due to persistent changes in temperature and moisture conditions. The stone is undergoing regular superficial and interstitial condensation; the wetting of the stone is leading to deliquescence of very soluble salts. These have accumulated in the 10 mm closest to the surface of the stone. The stresses at the surface of the stone from crystallization pressure of salts and differential wetting are leading to the stone detaching in thin layers. Following the loss of surface material, the process continues on the newly exposed stone surface. This new understanding helps to explain why previous consolidation treatments were not successful and provides an opportunity to intervene to reduce the effects of this cycle through removal of salts, now that air pollution at the site has been reduced.

This understanding of the process of decay in the Chapter House at Howden will instruct in the choice of remedial measures. The detrimental environmental conditions can be influenced by adjustments to the structure, for example to temper air movement or condensation events. We have now established a means for monitoring the condition of the stone, the rate of decay, and external conditions, which we can use to monitor the success or failure of interventions and treatment trials. Our results will be considered in the wider framework of magnesian limestone buildings – e.g. York Minster and Selby Abbey and will influence further investigations at other sites.

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10. Materials

Eltek Limited
35 Barton Road
Haslingfield
Cambridge CB23 1LL
U.K.
Tel: +44 (0)1223 872111
Fax: +44 (0)1223 872521