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Soft Capping on Ruined Masonry Walls

Chris Wood, Alan Cathersides, Prof Heather Viles

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Chris Wood
Alan Cathersides
Prof Heather Viles

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This is the final report for the Soft Capping project. It has been peer reviewed by three independent reviewers.

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Front cover: Hailes Abbey viewed from the south west, after completion of the soft capping of all the ruined masonry in April 2013. (*Chris Wood, ©Historic England)*

PREFACE

The aim of this research project was quite simply to determine whether or not soft capping is effective as a means of protecting wall tops on historic monuments and whether it is more beneficial than hard capping. Our definition of soft capping is the use of grass and other plants plus soil to cover horizontal masonry surfaces to protect the wall below. Hard capping refers to the use of stone and mortar, designed to shed water as quickly as possible to deter ponding and thereby protect the masonry.

The motivation for initiating this research in the 1990s was to find an answer to the extremely high costs of repairing and maintaining hard caps, a number of which had failed. English Heritage[1] looks after over 400 of the nation's most important historic monuments, many of which are now ruined. The many miles of walls that survive at these castles, monasteries, and priories date back a thousand years; most of them originally carried a roof and the wall tops were never intended to be exposed to the elements. Many lost their roofs during the Dissolution in the mid-16th century, or as a result of the Civil War a century later. Other structures in the care of English Heritage were constructed as defensive walls: some of these are Roman, and these wall tops are extremely important in protecting England's oldest and most significant masonry.

The Building Conservation and Research Team (BCRT) at Historic England (formerly English Heritage) provides technical advice to help those repairing and caring for historic buildings. Where answers are elusive or the problems complex, the Team carries out or commissions research to provide answers. Much time had been spent trying to improve the quality and performance of hard caps but many were unsuccessful, so some of the regional works teams started to experiment with soft caps in the 1980s and 90s, particularly on low walls. However, none of these were monitored or assessed so no conclusions could be drawn on their success or otherwise. This had to be done if soft capping was to prove to be a successful alternative to hard capping.

The research started in the late 1990s and the aim was to keep the objectives straightforward and ensure that the methods used were simple and practical, so if soft capping proved to be effective and beneficial, it could be easily implemented by owners, specifiers and contractors. The research team included Chris Wood (BCRT), Alan Cathersides (Historic England National Landscape Adviser), Professor Heather Viles (University of Oxford, specialist in stone deterioration) and Colin Burns (stonemason formerly with BCRT, with decades of experience working on the English Heritage monuments where hard caps were installed). The team met quarterly to assess the results from the laboratory and ongoing site testing. This proved to be a crucial aspect of the research because this continual critical assessment led to many of the initial questions the research sought to answer being modified; and new objectives identified.

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[1] In 2015 English Heritage became two organisations. The English Heritage Trust looks after the 420 guardianship sites and monuments. Historic England are government advisers on all matters affecting the historic environment, which includes: archaeology, scheduled monument and listed building consents, listing, archiving, and building conservation.

The team have continued to monitor the test sites and now have 14 years of observations and recordings which all help to increase confidence in their results and conclusions. Not all questions were successfully answered, though: probably the biggest gap was obtaining reliable information on moisture levels within the walls, despite all the various monitoring methods tried. This will be no surprise to researchers worldwide who have mostly all been defeated in this quest.

Interest in greening monuments is nothing new. References go back to the 16th century although it is probably the ‘Picturesque’ movement of the late 18th century which really concentrated minds on the presentation of ruins. Much was subsequently written. This research has not added much to this corpus as our emphasis was always on the technical performance of soft capping. Inevitably, though comment was passed on its appearance and indeed towards the end of the active research phase, the opportunity was grasped to fully soft cap a complete monument and to survey the reaction of visitors.

The research project would not have been possible without the help and involvement of a great many people, most of whom are listed in the acknowledgments. In particular, John Ward and Niall Morrissey (formerly Works Managers at English Heritage, Yorkshire and South West Regions respectively) who facilitated our research works and monitoring on the sites and not least, the researchers and students at the University of Oxford who camped out in a snowy mid-winter in North Yorkshire and visited sites throughout England in all weathers in order to download monitoring data. Thanks also to Dr Jeremy Ashbee (Chief Properties Curator at English Heritage), Dr Keith Emerick (Inspector of Ancient Monuments, Yorkshire Region) and Matt Canti (Senior Geoarchaeologist and Soil Scientist at Historic England) for reviewing the research text.

Chris Wood
Head of Building Conservation and Research Team
Historic England

SUMMARY

The Soft Capping Research Project sought to establish the benefits of using turf and grass to protect wall tops and the masonry below on historic ruins. A great many of the most important sites are in the care of English Heritage who together with their predecessors, particularly the Ministry of Works, preferred hard capping (stone and mortar) as the most appropriate conservation treatment. A number of laboratory tests were carried out to compare their performance and this was supplemented by field trials and observations at other sites. The bulk of the testing took place over a four-year period, but all the sites which have experimental hard and soft caps have been regularly monitored for over a decade. This peer-reviewed research report describes the whole project, including the results, and concludes with an assessment of the performance of soft capping.

ACKNOWLEDGEMENTS

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Reviewers

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Ancient Monument Inspectors and Works Managers

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Brian Ridout, Tobit Curteis

Wombwell Arms, Byland

3 generations of 'mine hosts'

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Fountains Abbey: Rory Ogilvie

Godstow Nunnery, Oxford: Dan Bashford, Chris Welch

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Hemyock Castle: Rebecca Child, Francis Kelly

Howbury Manor: Colin Stoneham, Liz Whitbourn

Myross Church and other sites in County Cork, Eire: John Ludlow

North Leigh Roman Villa: David Latham, Roy Porter, Andy Turner

Rievaulx Abbey and Whitby Abbey: Douglas Pickering

Sherborne Old Castle: Elizabeth Vause

Smailholm Tower, Kelso, Scotland: Peter Ransom

St Mary’s Garrison, Isles of Scilly: Robert Laycock

Thirlwall Castle: Robin Kent

Thornton Abbey: Team from Chris Lavington Grounds Maintenance, Mick Wilson

Wytham Woods walls: Nigel Fisher, Gerry Williams

IMAGES

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CONTACT DETAILS

conservation@HistoricEngland.org.uk

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1 INTRODUCTION

1.1 Background and rationale

The presentation of ruins has always been a prime consideration for English Heritage and its predecessors. Many diverse views and solutions have been advocated ranging from significant reconstruction to the idealised notions of the 'picturesque' movement and the romantic ruin. However, in the early 20th century, the Office of Works began to encourage the stripping of all organic growth from ruined sites. In the decades that followed, hard capping became the conventional method for consolidating wall heads on ruined sites. This approach has proved problematic, as a number of factors – severe weather and exposure, poor choice of remedial techniques and materials, visitor footfall on low walls – can cause hard capping to fail. Many of the wall-heads that have been hard-capped are in constant need of repair (see Figure 1.1).

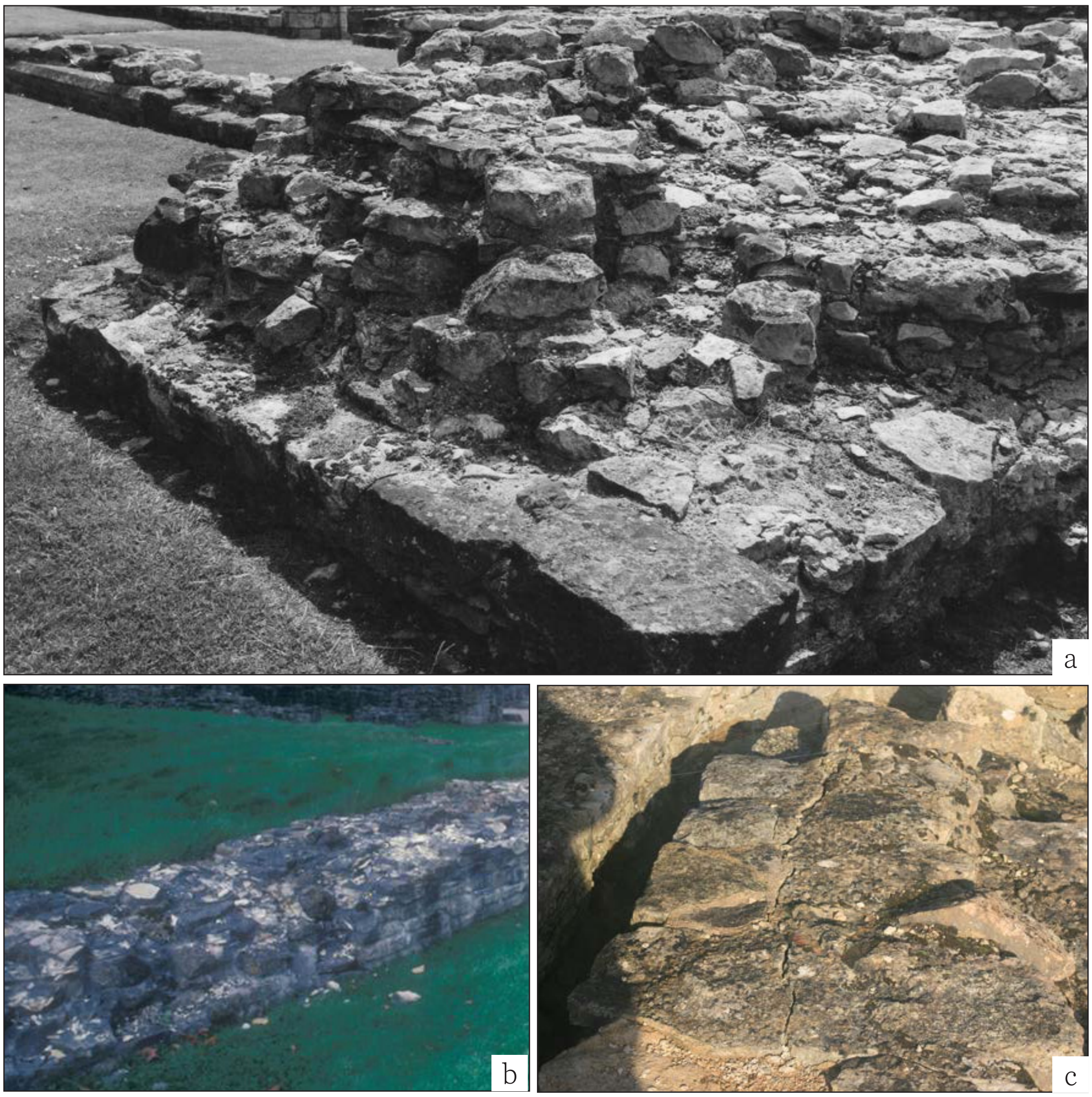

Figure 1.1 Failures in hard capping from (a) Thornton Abbey, (b) Hailes Abbey *(both Chris Wood ©Historic England)* and (c) North Leigh Roman villa *(© Alan Cathersides)*.

In 1994, members of the Architectural Conservation Team (now the Building Conservation and Research Team, or BCRT) at English Heritage, together with its former Head of Team, John Ashurst, carried out a condition survey of all properties in care. It was clear that a considerable amount of time and resource was being spent to maintain wall-tops and their mortared cappings. This problem was confirmed in conversations with local works teams. It was concluded that the cementitious mixes that were normally used tended to shrink and crack, allowing more water into the wall head, thereby increasing the risk of frost damage. Open joints also resulted in more water percolating into the core of the wall, with consequential washing out of core mortar (see Figure 1.2 showing frost damage at Okehampton and Launceston Castles). Lime-based mortars were tried as an alternative to cements for hard capping. But they presented their own problems. Despite the great care taken over their preparation, they were not durable enough to combat damage caused by wind, sun and frost.

Figure 1.2 Frost damage at (a) Okehampton castle and (b) Launceston Castle.
(both Chris Wood ©Historic England)

Figure 1.3 Luxuriant natural soft capping growing at Wigmore Castle.
(Chris Wood ©Historic England)

Figure 1.4 (a-d) Natural soft capping and deliberate planting at Jervaulx Abbey.
(a,c Chris Wood ©Historic England; b, d ©Heather Viles University of Oxford)

Clearly another solution was needed. Soft capping potentially offered one. It has long been observed that ruins with natural soft caps are often in remarkably good condition. At Wigmore Castle in Herefordshire, for instance, some of the walls survive after several centuries of neglect, even though the castle was built of a relatively poor local mudstone and had lost all its render. It is thought that the luxuriant growth covering these walls enabled them to survive. In Yorkshire, the private owners of Jervaulx Abbey let nature predominate when the ruins were consolidated in the 1980s (Figure 1.4). The walls were covered by a natural soft capping that had seemingly provided protection for centuries (see Figure 1.4 and Figure 1.3). In Ireland, a number of 16th-century ruins with natural soft caps survive. An example of this is the late medieval church of Myross in County Cork. Although it has lost most of its mortar and joints, the walls still remain standing, with little sign of bowing under a thick canopy of grass (Figure 1.5).

Figure 1.5 (a-d) Natural soft capping at Myross Church, County Cork, Ireland.
(a-b © Alan Cathersides, c-d Chris Wood ©Historic England)

Biodiversity was also a consideration, as English Nature (now Natural England) had implemented the 1992 European Habitats directive. Oliver Gilbert's seminal guidance document, Rooted in Stone (Gilbert 1992), emphasised the importance of historic walls as natural habitats, and how most plant species caused little harm to the fabric. In fact, far from damaging a stone or mortar surface, lichens, for example, usually indicate a very stable environment. They do not colonise surfaces that are rapidly decaying, and although their hyphae penetrate into the surface, the damage this causes is usually relatively minor in comparison with the major agents of frost, pollution, temperature changes and inappropriate repair. Furthermore, recent research has demonstrated that lichens on walls have an important bioprotective role (Carter and Viles, 2003; Pinna, 2014).

Figure 1.6 (a-b) Soft capping trialled at (a) Kirkham Priory, 1993 and
(b) Fountains Abbey in the late 1980s. *(a Chris Wood ©Historic England; b ©Rory Ogilvie)*

English Heritage started consolidating a variety of ruined sites with soft capping as early as the 1980s. Abbeys, priories, castles and walls have all been repaired in this way. The results have been encouraging. For instance, at Kirkham Priory in North Yorkshire, water percolation was causing significant staining with lime and even large stalactites forming above the vaults. Locally cut turfs were placed above an opening on the cloister side of the western range and above the vaults (at the north end of the western range adjoining the nave, Figure 1.6a). The problems stopped quickly, presumably because the turfs absorbed rain, which would then evaporate.

In 1986, a local team working at Fountains Abbey in North Yorkshire noticed that important medieval facework on the lower part of the west wall of the Lay Brothers' Dormitory was deteriorating rapidly (Rory Ogilvie, pers. comm.). They decided to remove this newly installed hard capping that was intended to speed the shedding of water. Unfortunately, it concentrated rainwater down distinct pathways, causing excessive wetting of certain areas of the wall and consequently decayed medieval masonry that had previously survived in good condition for hundreds of years. When the hard capping was removed and replaced with soil and turfs, it seemed to markedly reduce the harmful run-off (Figure 1.6b).

All of these observations pointed to the need for research to properly understand the benefits and possible harm soft capping could cause to the performance and longevity of ruined masonry walls. Funding was found for BCRT to commission pilot testing at University of Oxford's School of Geography and the Environment in 2000 to see if a successful methodology could be developed for subsequent larger-scale testing.

1.2 Wall capping and the conservation of ruined walls – theoretical background

1.2.1 Deterioration processes acting on ruined walls

Ruined walls have by definition suffered significant structural damage, which over time has made them susceptible to a range of decay processes: freeze-thaw, salt crystallisation, wetting and drying, heating and cooling, biodeterioration and a range of chemical reactions. Removing protective roofs exposes the wall tops and their cores to these damaging agents of decay. These forces act upon all elements of the wall (stones, bricks, plaster, mortar, rubble core) and may cause all kinds of deterioration, from the detachment of small fragments of stone to a partial collapse.

Ruins can also be harmed by inappropriate repairs . Using hard cementitious mortars, grouts and concrete restricts their normal thermal and moisture movements, which leads to stone and brickwork cracking and water penetration. Wall faces have also been adversely affected by the design of wall top repairs where the aim was to shed water as quickly as possible. This kind of repair can concentrate the flow down distinctive pathways over the face, creating 'runoff streaking'. In addition, the concentration of moisture can encourage the growth of algae and other microorganisms, producing dark streaks. Concentrated runoff can also increase wetting/drying cycles, which in turn can speed the decay of masonry.

In the following sections the major potential impacts of soft capping are considered, as well as its impact on the upper and lower parts of walls (both core and face). This is based on a theoretical understanding of moisture flow and the thermal behaviour of ruined walls. Comparison is then made with hard capping.

1.2.2 Hydrological and thermal behaviour of ruined walls

One of the major causes of decay in ruined walls is moisture. Most historic walls were built with two skins of facing stones and mortar with a rubble core. This structure makes water ingress easy. If moisture enters frequently, or does not evaporate quickly, deterioration can occur (Figure 1.7).

Thermal behaviour can also cause deterioration in ruined walls and exacerbate the problems created by moisture (as illustrated in Figure 1.8). For instance, when sun heats the external face of a wall, water will evaporate at and near the surface, influencing relative humidity and facilitating salt crystallisation damage. When the wall cools at night, freeze-thaw damage can occur, especially near the surface, where day and night temperature differences will be more pronounced. Furthermore, differential heating of surface and inner parts of stones, or of those partly constrained within mortar, will set up stresses and may result in cracking of susceptible materials.

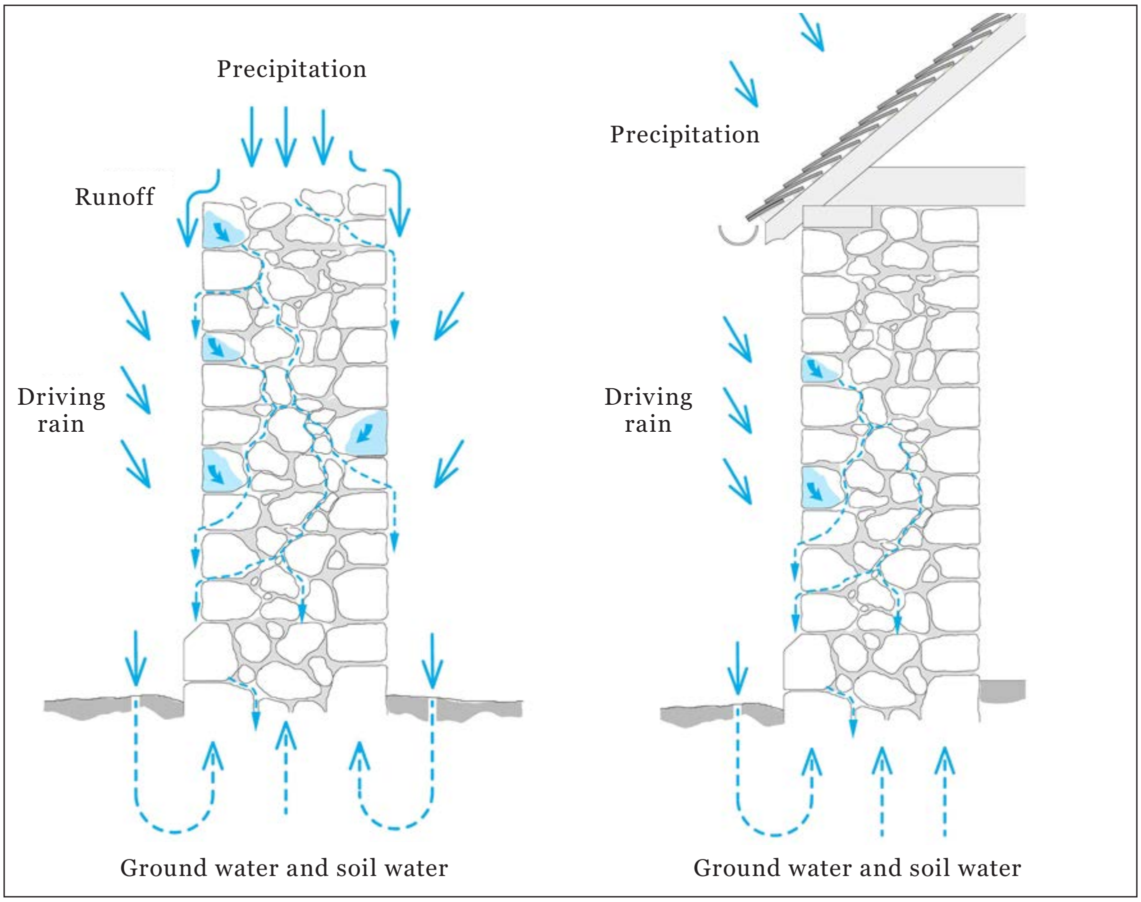

Figure 1.7 Hydrological pathways on (a) ruined and (b) intact walls.
Iain McCaig © Historic England

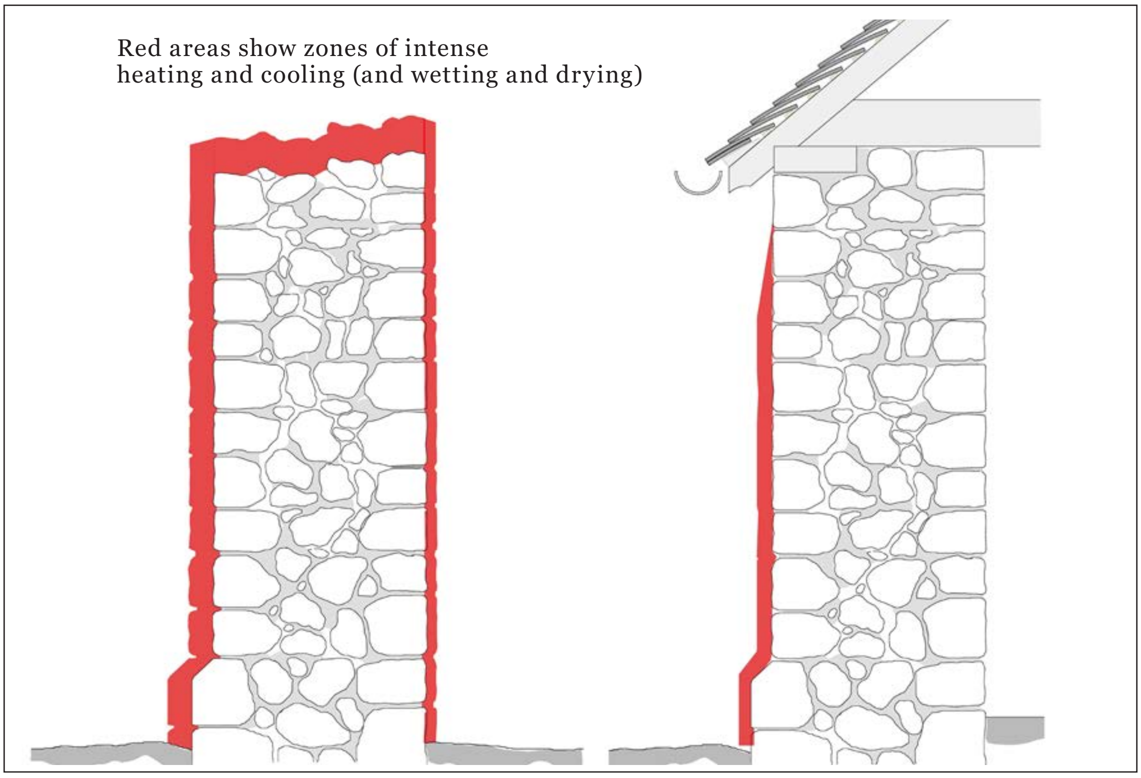

Figure 1.8 Thermal behaviour of (a) ruined and (b) intact walls.
Iain McCaig © Historic England

1.2.3 Hydrological and thermal behaviour of soft capping

There are a number of ways water interacts with soil. Rain falling onto grass can evaporate, or it can be absorbed by plants, and transpire back to the atmosphere. (Figure 1.9). It can run off over the surface downslope or infiltrate the soil. Once in the soil, water may move downward through interconnected small pores by matrix flow, through larger pore spaces by macropore flow, or along preferential pathways (such as root traces, animal burrows or shrinkage cracks) by pipeflow.

Snow also influences soil hydrology. It is stored in the soil when the air temperatures are below freezing, then released in the various hydrological pathways upon melting. The roots of plants play a part, as they continually take up water to feed the process of transpiration from leaves, especially on hot, dry, windy days (see Box 1.1). Stones within the soil are also a factor, as they may act as barriers to evaporation and encourage water retention in the soil. Organic acids produced by vegetation and animals within the soil can acidify water flowing through it. Longer residence times will lead to longer time available for chemical reactions, and thus increase the impact of soils on water quality.

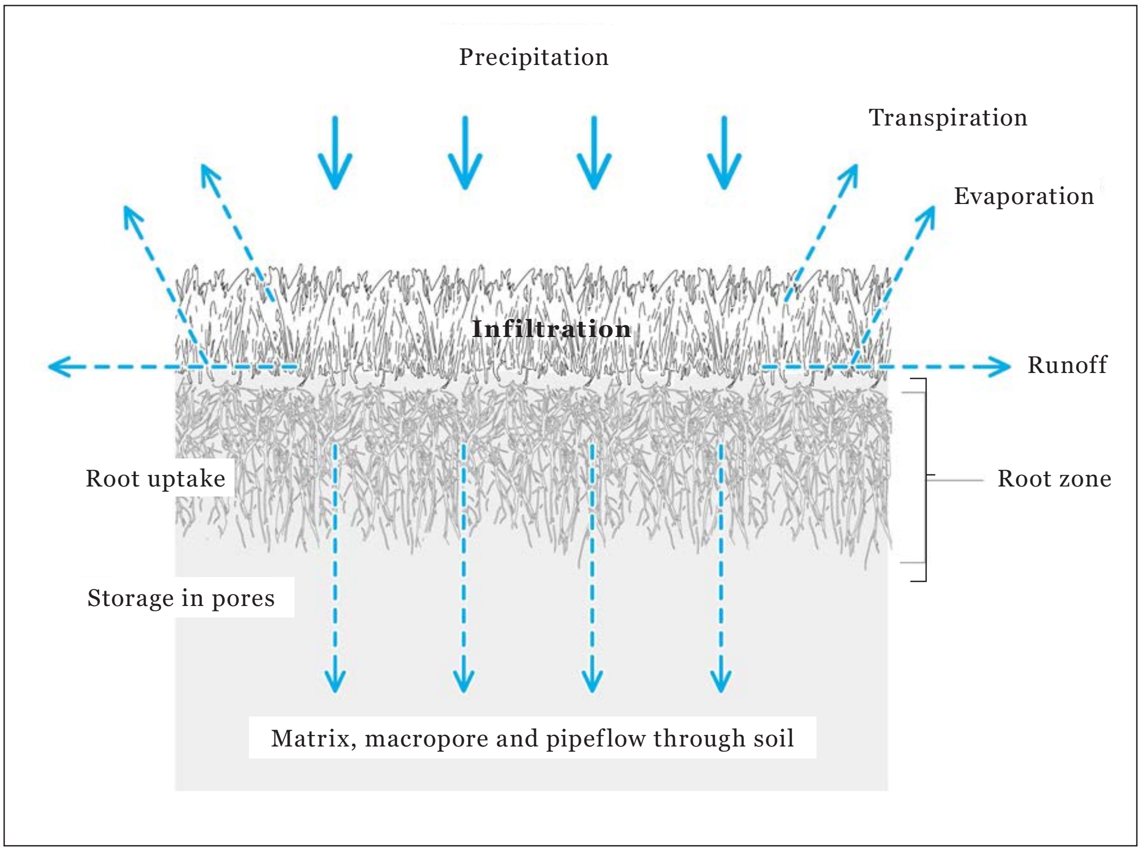

Figure 1.9 Simplified diagram of hydrological pathways in soil. *Iain McCaig © Historic England*

When rainfall is extremely heavy, the runoff rate will be much greater than the infiltration rate for many soil types, thereby encouraging surface runoff over infiltration (called Hortonian overland flow). For many years it was assumed that this occurred mainly in semi-arid areas that experience sporadic, intense rainfalls. However, recent research has revealed that temperate zone climates such as England can also experience heavy runoff. Where soil has already received much rainfall and thus its infiltration capacity has been reduced (and also where vegetation is present), saturated overland flow can occur, especially in winter. All these hydrological pathways can potentially occur in soft capping as well, although the thin depth (5-15cm) and small extent of most caps will reduce the potential of some water movements.

Porous soils have a relatively high heat capacity, and store heat effectively. This also has a bearing on their performance as a soft capping.

Box 1.1 Photosynthesis and Transpiration

Photosynthesis is the basis of almost all life on earth. It is the process by which plants, using the energy of the sun and a specialised catalyst molecule called chlorophyll, convert carbon dioxide and water into sugar, with oxygen as a waste product. Transpiration is another important process. It enables the plant to extract nutrients from the soil and keep cool in overheated conditions.

Transpiration plays an important role in the health of a plant. Water taken up by the roots moves to the leaves through the specialised xylem cells, which are part of the plant's vascular system. On reaching the leaves, some water is used in photosynthesis, but the majority is lost by evaporation via holes called stomata. This process is termed transpiration. Transpiration helps maintain water flow pulling water through the plant as some is lost from the leaves. This movement of water is termed the 'transpirational flow'.

Transpiration is lowest when the weather is cold and cloudy, and highest when the weather is hot and sunny with a gentle breeze. When there is no breeze, transpiration slows slightly, because the microclimate around the leaves becomes saturated with water vapour, reducing evaporation. Air movement prevents the build-up of this saturated microclimate. If air movement becomes too strong, transpiration reduces, because the stomata close to prevent damage to the leaf.

Plants have a certain amount of control over transpiration. The stomata can close and leaves can wilt if the roots cannot supply sufficient water. This will reduce both the surface area heated by the sun and air movement around the stomata. However, if transpiration flow is not restored quickly, plants can die from overheating or lack of water.

1.2.4 Potential benefits of soft capping

Soil and turf possess distinctive properties of moisture flow and thermal response to heating and cooling. Soil physicists have studied these properties for many years. The basic principles of moisture flow and thermal response in soil and turf can also be easily applied to soft capping.

For the wall head

The most obvious benefit from soft capping is the thermal blanket effect. Soil and turf have a higher heat storage capacity than air. When used in soft capping, they provide thermal buffering on a wall top, reducing the amount of temperature change. This thermal blanket effect is particularly useful when protecting ruined walls from heating, cooling and freeze-thaw weathering.

The soft cap also has a high water absorption capacity (much higher than the masonry itself) and thus acts as an effective moisture control, reducing the ingress of water from rainfall into the wall top. A soft cap should reduce the amount of rainfall entering the wall head to almost zero, although the amount of rainfall stored in soft capping will vary according to antecedent moisture conditions and rainfall intensity.

The thermal blanket and moisture retention effects of soft capping (as depicted in Figure 1.10) act to reduce damaging ingress of water and create a less variable thermal and humidity regime. Together they should dramatically reduce the likelihood of damage to the wall head from freeze-thaw, heating and cooling, chemical reactions and salt crystallisation.

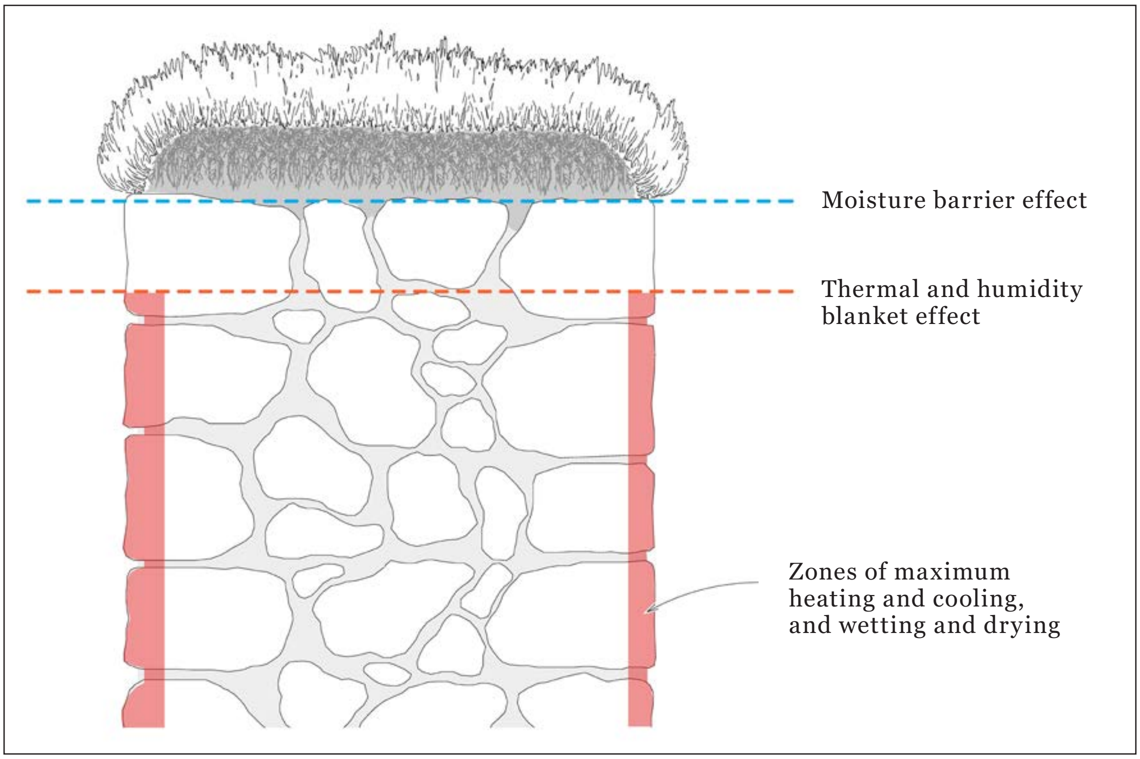

Figure 1.10 Proposed thermal and moisture barrier effects of soft wall capping.
Iain McCaig © Historic England

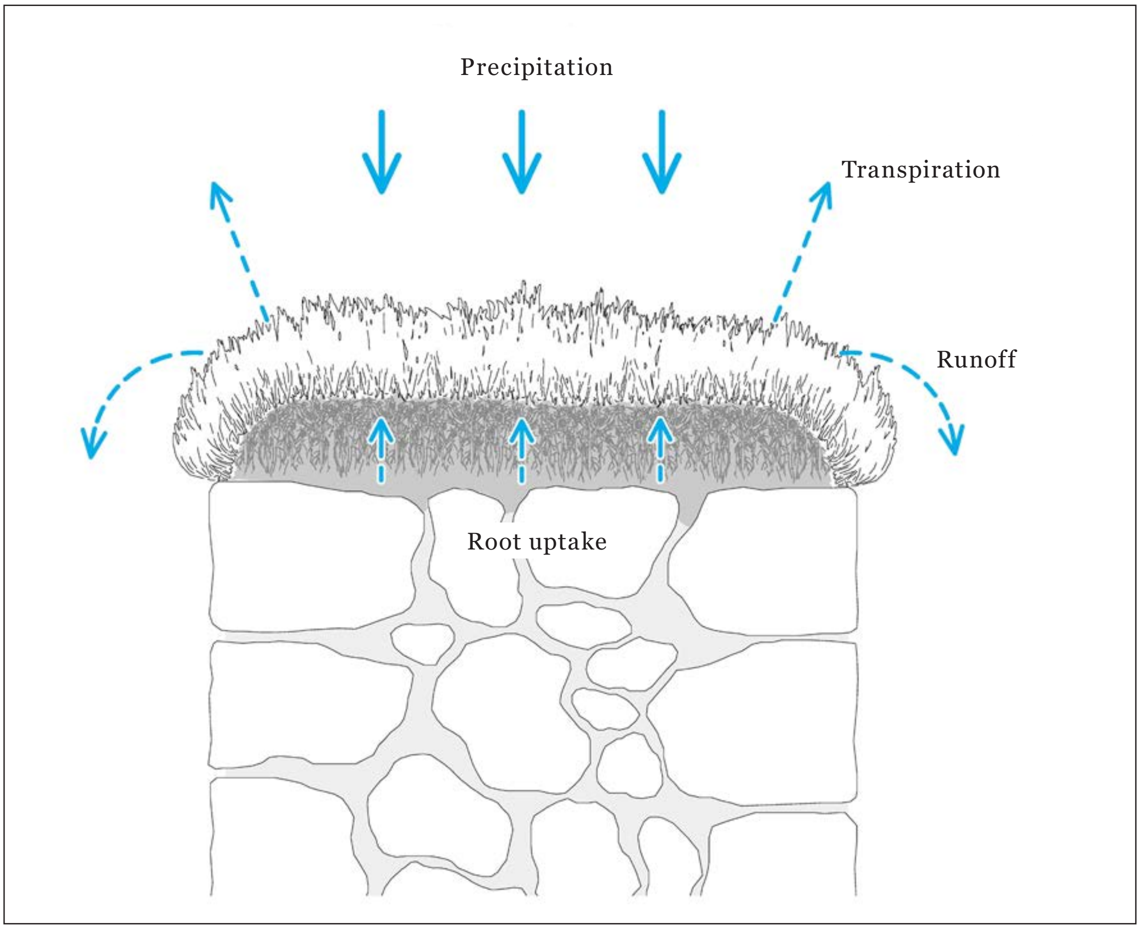

Figure 1.11 Ways in which grass reduces water runoff down the wall face.
Iain McCaig © Historic England

For upper wall face and core

Soft capping on a wall head reduces water runoff down the underlying wall faces. This may occur as a result of two processes (as shown in Figure 1.11). Firstly, grass will absorb and then transpire back into the atmosphere much of the incident rainfall, whilst a significant remaining proportion will be stored within the soils. Secondly, where water runs off over the grass surface, it will tend to be shed away from the wall face (because of the shape of the grass tussocks; see Figure 1.11) rather than running down the face, as is the case with hard capping. Soft capping will not stop driving rain from hitting wall faces (except for the uppermost areas where overhanging grass may buffer the rainfall). However, it usually reduces water runoff and subsequent soiling caused by runoff streaking. As well, by impeding water ingress through the wall head, it can reduce the wetting of the upper corework of ruined walls.

For lower wall face and core

Moisture ingress from groundwater may have a greater impact on the lower parts of ruined walls than rainfall. Soft capping generally provides little protection from moisture ingress at the base. However, in situations where the ruined walls are very low (less than 1–1.5m) and subjected to capillary rise of water, the impact of soft capping might be more complicated. We hypothesize that the presence of a moist, semi-permeable soil and turf layer on the top of low walls reduces capillary rise. The controlled relative humidity and temperature conditions under the capping reduce evaporation potential at the wall top, thus depressing the height to which capillary movements will occur. Although not directly tested in this project, soft capping should act to reduce moisture-induced deterioration on low walls, even where a significant source of moisture is from the ground.

1.2.5 Potential harm caused by soft capping

Potentially damaging or negative aspects of soft capping need to be considered and tested in the same way as any purported beneficial impacts.

For the wall head

Water stored and acidified in the soft cap can potentially seep down into the top of the wall, causing accelerated chemical damage to acid-susceptible stones (such as limestone). Furthermore, roots penetrating through the relatively thin soils can also cause biochemical and biomechanical deterioration of the underlying stone and mortar. There is some evidence to show that acids produced by plant roots can cause small scale etching of acid-sensitive minerals, such as calcite (Mottershead and Viles, 2004), and also that the growth of roots into crevices within stonework may produce pressure which can cause cracking – although such mechanical effects are only seen in large, woody species. However, grass roots are highly unlikely to cause any damage through secondary thickening (see Box 1.2). Finally, under some circumstances we might hypothesize that soft caps can encourage water ingress into the wall top. For example, animals living in soft cap soils can create burrow systems that might facilitate fast-moving pipeflow down through the soil. Alternatively, drying out of soils in the summer may lead to the development of cracking, which would provide preferential pathways for fast pipeflow during an intense rain event. Once water ponds on the wall top, it can easily enter through cracks. The presence of the soft cap can then slow evaporation of water from the top of the wall.

Box 1.2 Secondary thickening of roots and stems

Most plants have a vascular system consisting of two types of cells, xylem and phloem, which perform different functions. Xylem cells transport water and nutrients from the roots to the leaves. Phloem cells transport the sugars produced in the leaves (mostly) by photosynthesis inside the plant to provide energy for respiration in its cells, with any surplus going to its storage organs. Secondary thickening is the usual process by which many plants increase the size of their vascular system to sustain continued growth.

Seedlings have distinct individual vascular bundles with xylem and phloem cells separated by a strip of cambium cells that divide and grow, producing more xylem and phloem on each side. As plants grow, the vascular bundles coalesce to form a complete circle of vascular tissue, which then continues to grow outward. In the stems of many trees and woody shrubs this produces clear growth rings). This process also occurs in roots, in some cases leading to roots of a metre or more in diameter. This type of growth in stems or roots can cause serious structural damage to buildings.

However, plants such as the soft herbaceous plants found in soft caps do not grow to a size where secondary thickening would cause damage. More significantly, most grasses (Monocotyledons, or monocots) lost their ability to secondarily thicken early in their evolutionary history, and most still remain unable to do so. A few specialised monocots can enlarge their stem and root diameter by producing various types of 'anomalous secondary growth' – for example, palm trees increase diameter by division and enlargement of non-vascular parenchyma cells – but these are exceptions.

1.2.6 The effect of different seasons on the performance of soft capping

The impact of soft capping varies with the seasons. In winter, grass growth is minimal and precipitation is high (both in the form of rainfall and snow). Thus, more water is likely to flow into and through soft capping in winter than any other time of year. Under very cold conditions, the whole thin cap can freeze, potentially leading to damage (although it is hard to see that this would be any more damaging than the freezing of an uncapped wall-head). In summer, grass growth and air temperatures are generally high and precipitation is low, sometimes causing soft caps to dry out completely. Incorporating porous stone fragments into the soft capping may help retain moisture, even during summer droughts. This will prevent excessive dieback of the grass and maintain a more equable climate at the wall top.

1.2.7 Longer term development of soft capping

Vegetation and soil communities evolve and change over time. The protective role of soft capping may also change over years or decades.

Natural soft capping – establishment and development over time

Under entirely natural conditions, ruined walls develop natural soft capping through the process of ecological succession. Algae, lichens and moss, which can all grow without the need for soil, establish first. They then trap wind-borne material (dust, pollen and spores), which contributes to the development of a 'proto-soil' through its own biomass and, to a lesser degree, biodeterioration of the underlying stonework (Figure 1.12). Over time, higher plants colonise the newly developing thin soils. In turn, the litter they produce, such as leaves, contributes to further soil deposition. Observations at several ruined monuments in England and Ireland illustrate that given enough time such natural capping can develop, even on quite steeply sloping wall heads. Such communities are typically self-regulating, as the wall top environment is harsh (lacking in moisture, limited in surface area, covered by only thin soils, often buffeted by high winds) and many plants could not tolerate these conditions. Grass and herbs appear to dominate and outcompete woody species in naturally developed soft capping.

Figure 1.12   Natural growth of lichens and mosses on wall heads.
(a-b) Kirkham Priory, (c-d) Hailes Abbey and (e) Wigmore Castle. *(a-d © Alan Cathersides, (e Chris Wood ©Historic England))*

Development of planted soft capping over time

'Manufactured' soft caps might develop very differently from natural ones over the first few years, but they are also subject to similar constraints. We hypothesize that over the first few years the roots penetrate from the turf layer into the underlying soil, forming a coherent well-bound mass. We also suggest that grass growth should soon 'knit' the edges of the turfs together, further stabilising the whole cap. In terms of plant composition, we anticipate other species that are particularly tolerant of the wall top environment will establish alongside the grasses, but that the grasses will remain the dominant species. These predictions are based on growth under usual climatic conditions (i.e., mild winter and variable summers). However, where climatic conditions are harsher during the first few years of establishment of the soft cap (very dry summers), we anticipate different outcomes. For example, during very dry summers, grass will die completely or substantially. As long as the turf remains a coherent unit and is not eroded away, we anticipate that the seed bank within the soft cap and other wind- and bird-dispersed plants might be expected to re-establish the dead turf, and produce a diverse community of vegetation that can thrive on wall tops.

As both natural and planted soft capping develops over time, the benefits of thermal blanketing and better moisture control may also change. We hypothesize, for example, that as the soft capping matures, a thicker root mass will develop, providing a more efficient control of water movement. However, longer-term observations are needed before any more confident statements can be made. In summary, soft caps are dynamic and developing natural systems with complex hydrological, thermal and biological characteristics. Understanding their potentially protective role on ruined walls is therefore complicated, and many different aspects of their performance require testing.

1.2.8 Hydrological and thermal behaviour of hard capping

Hard capping is designed to protect wall heads by reducing water ingress, but it also affects the thermal regime at the top of ruined walls. Hard capping usually varies in thickness from 10 cm or so to 2 metres or more, depending on the degree of consolidation needed. It reduces water flow into the wall-head by creating a homogenous surface with minimal cracks or voids. The mortar should be permeable, but as it is built up in the middle, its sloping surface will discharge rainwater rapidly down wall faces. As long as this surface layer remains intact, hard capping is assumed to limit water penetration into the core. However, by channelling water directly down the wall faces, hard capping can increase runoff streaking. Furthermore, if any part of the hard cap fails, water flow may be channelled directly into the core, and any protective function lost. Even the most successful hard caps will, of course, be permeable just like any masonry wall. Thus water will still move through the joints to some degree unless very hard cement mortar is used. The use in England of hard capping and allied hard engineering methods as a way of stabilising ruins is summarised in Box 1.3.

Box 1.3 Past hard engineering of ruins in England

During most of the 20th century, ruins under the care of the Ministry of Works were subject to structural stabilisation at the wall head with hard cement mortars. This was considered to be essential if the walls were to maintain their appearance and leans without the need for new buttressing or ties. Reinforced concrete wall head beams were commonly used along with precast lintels. So-called 'rough racking' became a favoured technique for wall-head consolidation: A new wall top was created by lifting the top course and reconstructing it with high points near the centre line, allowing the mortar and stones in the core to be shaped downwards to discharge water quickly. The original profile of the wall head was seldom recorded. These days, however, a planning frame is used to record the position of facing stones before work is begun so they can be reinstated in the same position.

Hard caps can also moderate temperature fluctuations under the existing top of the wall, through the same basic mechanism as soft caps. However, as they are rigid and mortared on to the stonework below, problems caused by the differential thermal expansion of different stones and mortars can be exacerbated. For example, using a hard mortar to bind together stones with variable thermal expansion characteristics will produce a heterogeneous mass in which different sections will respond differently to heating and cooling. Since they are all firmly bound together, individual stones cannot react individually to heating and cooling without affecting the others. Stresses can easily build up, leading to cracking. Extensive cracking can lead to serious water ingress. Using softer mortars will allow stones to expand and contract individually, which will alleviate this problem, as they will be able to absorb the stresses generated. However, these softer mortars may not withstand exposure to harsh weather.

Development of hard capping over time

Hard capping will gradually fail over time. In many circumstances, it may simply be a sacrificial layer. Where frost damage is a key threat to ruined walls, placing an extra layer of mortar and stone on the wall top will protect underlying stone from extremes of temperature, but the cap itself will be vulnerable. In many cases, hard caps will naturally develop their own soft capping on top as mosses grow and the whole process of succession takes effect.

1.3 Project design and overview

1.3.1 Pilot Testing

The aim of the small-scale laboratory tests was to answer three simple questions. Can soft capping:

- insulate the top of the wall and prevent freezing?
- hold rainwater to minimise ingress and runoff?
- absorb rainwater, then dry, and continue to hold and release moisture?

The tests were designed jointly by English Heritage and researchers at the School of Geography and the Environment, University of Oxford. They were carried out between March and May 2000 and described fully in Viles et al. 2002. The tests simulated measured conditions from Hailes Abbey, near Cheltenham, Gloucestershire. The 'thermal blanketing' experiments compared soft caps of different depths and soil types with hard caps and bare stone. Temperatures were measured on the stone surface (below the soft and hard caps and on the bare stone) in an environmental cabinet. This cabinet produced controlled cycling of temperature and humidity repeatedly going from conditions found on a cold January night to those on a hot July day. Samples of soft capping, hard capping and bare stone were each set up in perspex boxes (Figures 1.13a-b).

Soft caps were trialled with soil depths of 50 mm, 100 mm and 200 mm. Results showed that surface temperatures on bare stone and under hard caps regularly fell below freezing. In the case of soft capping, this only occurred once, under 50 mm of soil. Unsurprisingly, the caps with the greatest soil depths were the best at buffering external temperatures and humidities.

The water penetration tests used perspex boxes and a rainfall simulator to find whether rain penetrated through soft caps to the underlying stone. The water flow through the soils was observed by eye, but sampling and chemical analysis were also carried out. It was discovered that 100 mm of soil was usually sufficient to prevent rain penetration, even following heavy rainfall.

The water holding experiments compared the rate of drying of a bare stone block with ones covered with 100-mm and 200-mm thick soil and grass. Wire baskets were insulated with perforated polystyrene so that drying could occur. After water was sprayed on (equivalent to a 20-mm storm over a 15 minute period), the boxes were left on the laboratory roof in a semi-sheltered position to dry naturally. The 100-mm sample began to dry out after 15 days. However, the samples were re-wetted by heavy rain, and the 200-mm sample never dried during the 35-day test. The bare stone showed repeated cycles of wetting and drying.

The success of these pilot tests meant that a larger-scale testing programme could be devised. This included more extensive, comprehensive laboratory testing, site trials, monitoring and recording, and observations of both natural and man-made soft cappings.

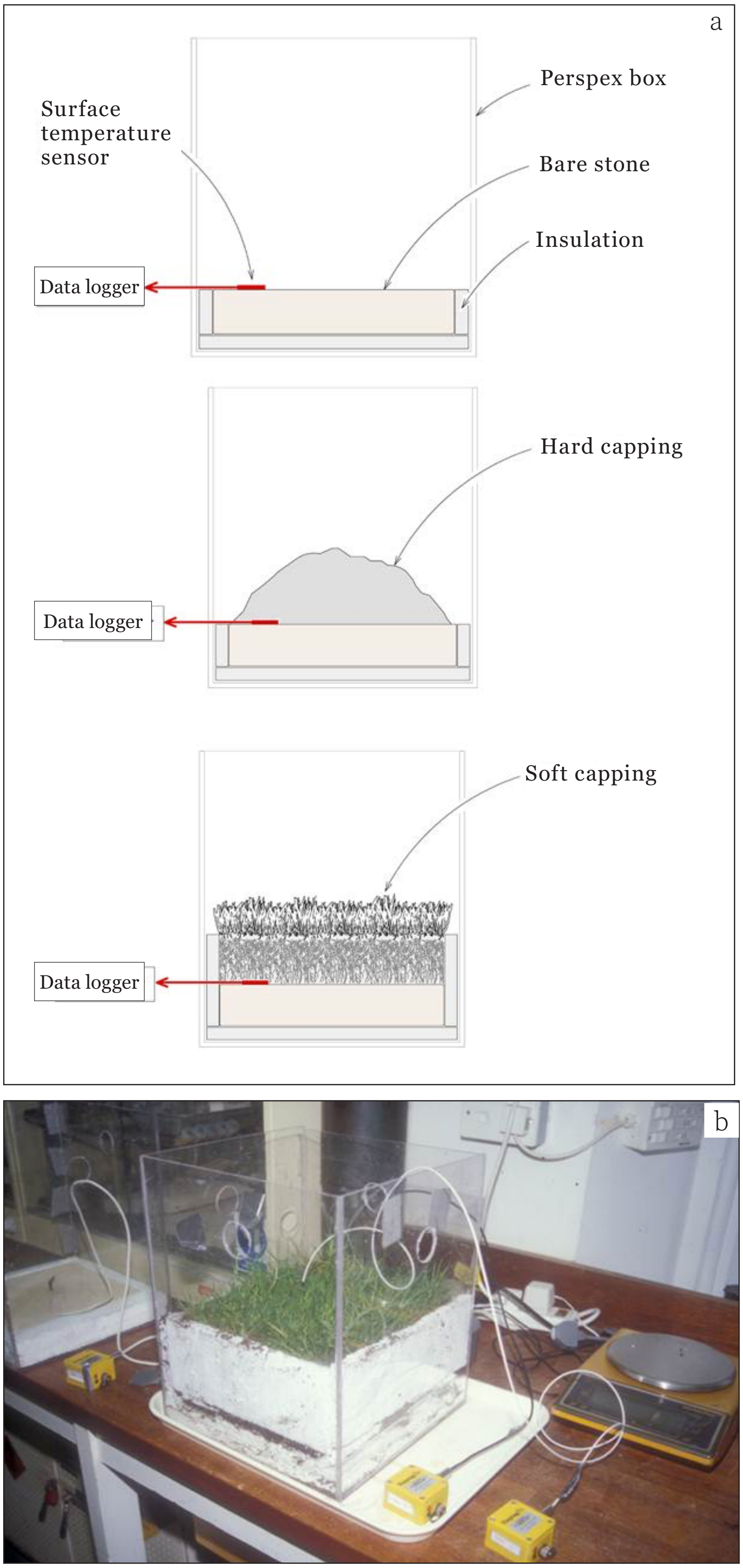

Figure 1.13a, b Experimental set-up with stone and soft capping in Perspex boxes.
(a Iain McCaig © Historic England, b Chris Wood ©Historic England)

Box 1.4 The history of conservation of ruined sites in England

The selection of sites for trials was determined primarily by their potential to provide opportunities for specific testing and where the need was most apparent, as well as the enthusiasm of individuals within English Heritage's regional teams to engage in the work.

The main sites selected were medieval stone-built former monasteries which offered a range of building types, materials, and conditions. They had all been dissolved in the middle of the 16th century and most had then reverted to agricultural uses and been used as sources of building materials for local people up until the time the state took them into guardianship in the early years of the 20th century.

Although the ruins had been neglected for centuries, the quality of materials and workmanship meant that significant standing remains survived (see Figure 1.14).

Observation and petrographical analysis of the ruins at Byland Abbey showed there to be four types of stone used, all coming from the same quarry (Jefferson, 2006). The very best stone was used in the first phase of building in the 12th century for the main church with later material being less dense and containing more clay-like material. Careful archaeological recovery by the Ministry of Works also meant that much precious fabric was salvaged for re-use. They applied strict criteria for conserving the monuments in their care and these standards had developed over preceding decades when the protection of ancient buildings had become a national issue.

For much of the last century, it was stated by the Ministry of Works (and set out in the Venice Charter of 1966 (ICOMOS Paris)) that monuments should be 'conserved as found', with 'no conjectural restorations', and 'minimum intervention'. The purpose of repair was not to restore sites to their original condition, but rather to stop deterioration. Whenever possible, repairs were supposed to be carried out with authentic materials and be reversible. Conserved monuments were to receive regular maintenance. It was hoped that such maintenance would alleviate the need for more expensive and extreme interventions, so that resources could be concentrated on the next guardianship site.

Figure 1.14 Byland in the early 20th century. *Source: Historic England Archive (AL0581_009_01)*

However, a look at the photographic and documentary record of some monuments suggests that a liberal interpretation was taken of the mantras of minimum intervention and conserve as found. Clearly, at both Rievaulx Abbey and Kirkham Priory the walls had once been topped with a layer of grass (see Figure 1.15a), which seemed to have help preserve the walls below. But contemporary correspondence reveals that conservators strove to present these sites as more 'authentic' ruins: in other words, robbed of facework and exhibiting the core. The tops of the walls were stripped of their grass layers, no doubt a necessary precursor to consolidating the wall heads, but the works seemed to embrace far more than a conservative repair. At Kirkham the very obvious coursing of the ashlared face stones on the Reredorter (Figure 1.15b) was removed to expose the rough corework behind. The facework and heraldic shield within the spandrel of the vaulted laver were completely removed. Repairs and maintenance sought to present the appearance of ageing, with mortar joints eroded back and the tails of face stones left in the exposed core.

Figure 1.15 (a) Natural capping at Rievaulx, (b) Natural capping at Kirkham reredorter.

But it proved difficult to maintain the conserved monuments. Most work – repointing, rendering, grouting and rough racking – was carried out with cementitious mixes, since it had not yet been fully appreciated that these hard mixes eventually hasten deterioration and decay. The repairs of the wall tops were designed to shed water as quickly as possible. However, the result, as shown at Kirkham Priory (Figure 1.16), was to create distinct pathways which became rapidly colonized by Tintenstriche algae (Luttge, 1997), giving the walls a stained appearance even when dry.

This level of intervention attracts criticism today. Yet it must be remembered that presenting 'dramatic' ruins with vestiges of precariously balanced masonry requires both skill and ingenuity. These features were in fact well secured with pinnings, supports and fixings hidden from view. The quality of workmanship was high, and repairs performed with the best intentions. Unfortunately, not only did the hard cement mixes eventually prove to be unsuitable materials for repair; the principle of reversibility had not always been followed. This means that when subsequent repair is needed, it can be extremely difficult, if not impossible, to unpick this work.

Figure 1.16 (a-b) Streaky walls at Kirkham Priory. *Chris Wood©Historic England*

1.4 Approach to the research

The aim of research carried out by the Building Conservation and Research Team is to provide information and practical solutions that can be directly applied by conservation practitioners.

Simplicity was key when performing fieldwork and site testing of soft capping. Many of the monuments had wall tops that had been rebuilt in concrete so all the experimental soft caps and soil were applied straight on top, with no rebuilding or reconfiguration taking place beforehand. The surface was merely brushed to remove any detritus. The soil used was a standard medium loam (in accordance with BS3882: 1994), and all turfs were cut mechanically from the site or adjoining fields. Membranes were not used so turf roots could establish a close relationship with the stone surface. Membranes were thoroughly assessed during the research. Hard capping was constructed by experienced masons using today's best practice and materials. In that way, the different approaches could be compared.

One of the principal methods of assessing the performance of soft capping against hard capping is to measure the moisture at wall-head level and within the wall. However, one of the most common difficulties in building conservation research is to accurately measure the presence or movement of water and vapour within a traditionally built solid wall. The soft capping research programme provided the opportunity to assess and compare some of the most promising methods of monitoring.

The research did not dwell on the visual consequences of soft capping. The presentation of monuments is very important, but if soft capping offered no extra protection its use would not be pursued. Inevitably comment was passed on the appearance of many of the sites which had been capped, but no scientific methodology was applied to this. Towards the very end of the work, one complex monument (Hailes Abbey, Gloucestershire) was soft capped, primarily to see whether it could reduce the damage being caused by severe frosts and this has provided an opportunity for others to pass judgement on its appearance (see Chapter 8).

1.5 Selection of test sites

English Heritage is responsible for over 400 sites and monuments. Only some of these were appropriate sites for research testing on soft capping. The following factors influenced the choice of sites:

- researchers would be able to leave the trials in place for a minimum of ten years so that long term performance could be assessed

- the sites could provide a range of different conditions, including stone types, wall heights, aspect and climate

- support given by the relevant Inspector of Ancient Monuments for the proposed trials

- support given by the regional team at English Heritage responsible for the care and management of the site

Particular attention was given to ensuring that a range of different wall heights was tested. Although relatively easy to access, low walls can suffer from challenging conditions, particularly if a site is prone to flooding or has a high water table. Visitors walking, climbing or playing on them can also exacerbate damage and decay. Animals such as rabbits and foxes can also cause damage.

Most of the sites chosen for testing were the ruins of medieval stone-built monasteries that had been dissolved in the middle of the 16th century, and used by local people for agricultural purposes or as sources of building materials. These practices lasted until the state took them into guardianship in the early years of the 20th century. However, although the ruins had been long neglected, the quality of materials and workmanship meant that significant standing remains survived (see Figure 1.14).

Byland Abbey, Yorkshire was the main centre for testing. The extensive calcareous sandstone ruins offered a range of different wall heights, aspect and at least one long wall where six different soft capping test profiles and a hard cap could be installed alongside each other. The site also allowed a number of individual experiments designed to answer specific questions to be carried out. The low cloister walls had been soft-capped a few years earlier, so it was possible to assess their performance in comparison to the test profiles.

Kirkham Priory, Yorkshire provided a good contrast to Byland. Located along the River Derwent, its walls were constructed in Hildenby limestone with a dramatic contrast in wall heights. Successful soft capping had been carried out a decade earlier by the local works team in order to reduce water penetration over a vault and along a high wall top. A number of low walls had also previously been soft capped. The archival photographic record showed natural soft capping with no streaking down the walls before the site was conserved, but since then, Tintenstriche algae highlight its dramatic occurrence.

Kirkham was also used to test hard capping alongside soft capping on one of the high walls. The work was programmed to take 3 days but took 7 because of the difficulty of removing the concrete within the wall head. Indeed, kango hammers proved inadequate. The old quarrying technique of using plugs and feathers had to be employed. What this piece of work revealed was that a high proportion of the stone in the wall head had cracked because normal movement had been constrained by the greater inflexible strength of the concrete. This discovery prompted a new question: Could the addition of soil and turf reduce the temperature range at the wall-head, in turn reducing the amount of movement attributable to temperature fluctuations?

Thornton Abbey, Lincolnshire, near the North Lincolnshire coastline, had suffered from significant decay owing to cold, frosty conditions and exposure to easterly winds from the North Sea. These conditions were exacerbated by pollution coming from nearby chemical plants. Vandalism was also a problem. The photographic record shows that the low walls in particular had suffered from the weather, with corework and mortar detached and fragmented (see Figure 1.15). The Abbey ruins display a variety of materials, including Magnesian limestone, Lincolnshire limestone and 16th century brickwork.

Whitby Abbey, Yorkshire was used to demonstrate that soft capping with soil and turf is quite sturdy, and will not be lifted off walls by extreme winds, as some people feared. A section of wall on the eastern elevation directly overlooking the North Sea, and occasionally subject to hurricane force winds, was soft capped and regularly monitored.

Rievaulx Abbey, Yorkshire provided an opportunity to see if soft capping could control the runoff down the inner face of the church at triforium level where there was a significant build-up of moss and algae. One bay was cleaned off and the horizontal surface above soft capped to try and reduce moisture and prevent the moss recolonising.

Hailes Abbey, Gloucestershire suffers from regular flooding and severe winter frosts. Mainly built in local Cotswold limestone, it was beginning to suffer severe damage, with face stones shattering and regular losses on both high and low walls. Most of the low walls at Hailes were buried and only excavated in late 20th century. Maintaining effective hard caps has proved difficult. Some early attempts at soft capping the lower walls took place in the 1980s, though no monitoring or analysis of their performance was undertaken.

The ruins at Hailes provided a timely opportunity for comparative research. One long section of cloister wall had been scaffolded and protected from the weather for 18 months by sheeting so was relatively dry. It was then possible to compare this wall with the fully exposed wet wall alongside. This continued after both had been soft-capped.

In 2013 stonework was repaired as a final trial. This repair included pinning back fractured or loose masonry. The whole monument was then soft-capped. The primary intention was to try and slow the significant cracking, detachment and loss of fabric that were occurring at wall-head height (see Chapter 8 for a full account). Laboratory research as part of this project showed that freezing conditions seldom occurred under soft capping, and that it also reduced damaging fluctuations in temperature. The secondary benefit arising from this work was that an assessment could be made of the visual appearance of a fully soft-capped monument that included walls of different heights.

Other test sites included the following:

Howbury, Slade Green, Bexley is a late medieval moated manor built in brick. The owner was happy for experimental soft capping to be placed on the wall tops adjoining the moat. This provided a good contrast to other sites, as the walls are comparatively narrow. The site is also in a much drier part of England than the other sites in the North and West. Trials included an attempt to establish soft caps grown from seeds.

Castle Acre Priory, Norfolk is another site with a relatively dry climate. The flint walls were suffering from a significant amount of detachment and mortar failure so different soft capping options were trialled, including the use of sedums. Tests were also carried out to see if water percolating through a soft cap produced an acidic residue. The previous year a vault in the ruined church was capped with sedum mats because they tolerate limited rainfall. Visual assessments have been made over the last 3-4 years.

Godstow Nunnery or Abbey, Oxford is a medieval ruin owned by the University of Oxford. Various permutations of soft capping were tried on these relatively high walls, including locally cut turf, commercial turf, seeded mat, and sedum mats, along with the addition of a water retaining gel.

Test walls at the University of Oxford's Field Centre at Wytham Woods were constructed in local Cotswold stone. All four were virtually identical and built with broken wall ends to mimic ancient ruined masonry. Two were soft capped, and the other two given mortared hard caps, one using a cement binder, the other lime. Moisture penetration into the wall was then measured with a range of different methods. The results were interpreted alongside data from a weather station positioned nearby.

Box 1.5 Common concerns and issues affecting soft capping as a conservation strategy for ruins

1. How well does soft capping protect underlying stonework in comparison to hard capping?
2. What sort of soft capping design is most effective? Factors worthy of consideration include: soil thickness, soil type, use of stone fragments within the soil, use of different vegetation types, use of ready-grown turf (both natural and commercial) as compared to individually seeded caps, and the use of geotextiles.
3. How can the benefits of soft capping be maximised and any damaging effects minimised? For example, how can the water shedding role (away from wall face) be maximised and water ingress into the underlying stonework, with its potential chemical effects, be minimised? This may involve consolidating wall heads before capping.
4. What are the soft capping requirements for different wall material types? Such as limestone, sandstone and brick.
5. Is the height and structure of the walls important to the success and design of soft capping? Considering factors such as elevation (low and high walls), overall composition of wall (rubble core and solid walls), wall geometry (flat and sloping walls), wall width (thin and thick walls).
6. Does soft capping need to be varied for different climates?
7. Does the performance of soft capping change over time? How does soft wall capping evolve in reaction to changes to vegetation communities, soil and turf loss, waterlogging, drying out?
8. What is the best maintenance and monitoring strategy for evaluating soft capping?
9. How will future climate change affect soft capping?
10. Does soft capping keep the core of ruined walls dry?
11. Does soft capping damage the wall-head?
12. Does soft capping require a membrane to separate the cap from the stone below?
13. Are naturally occurring soft caps beneficial?
14. Will grass roots damage the wall?
15. How does a soft cap become successfully established?
16. Will soft capping stay in place in high winds?
17. Will a soft cap help conserve wall flora?
18. Will a soft cap reduce fabric loss from the wall below?

There were three main project objectives, with most of the scientific research reported in this volume directed at objective (A) below:

A) To investigate the effectiveness of soft capping as a way of protecting ruined walls from further deterioration under a range of different conditions.

B) To compare the costs, maintenance requirements and effectiveness of soft capping with hard capping.

C) To determine best practice for the installation and management of soft and hard capping.

In order to address the first objective, the project focused on three main research questions, i.e.

RQ1: Does soft capping provide an effective thermal blanket for ruined walls in comparison with hard capping?

RQ2: Does soft capping provide an effective moisture barrier for ruined walls in comparison with hard capping?

RQ3: How does the performance of soft capping evolve over time in comparison with hard capping?

Figure 1.17 summarises how the main research tasks fit within the structure of the three research questions. These research tasks and the sites used are explained more fully in Chapters 2 and 3. In total, nine ruined monuments were used for field trials, with visits made to observe soft capping at a number of other sites. A dedicated test wall site was also set up at Wytham Woods, near Oxford, and laboratory experiments carried out in the Oxford Rock Breakdown Laboratory in the University of Oxford.

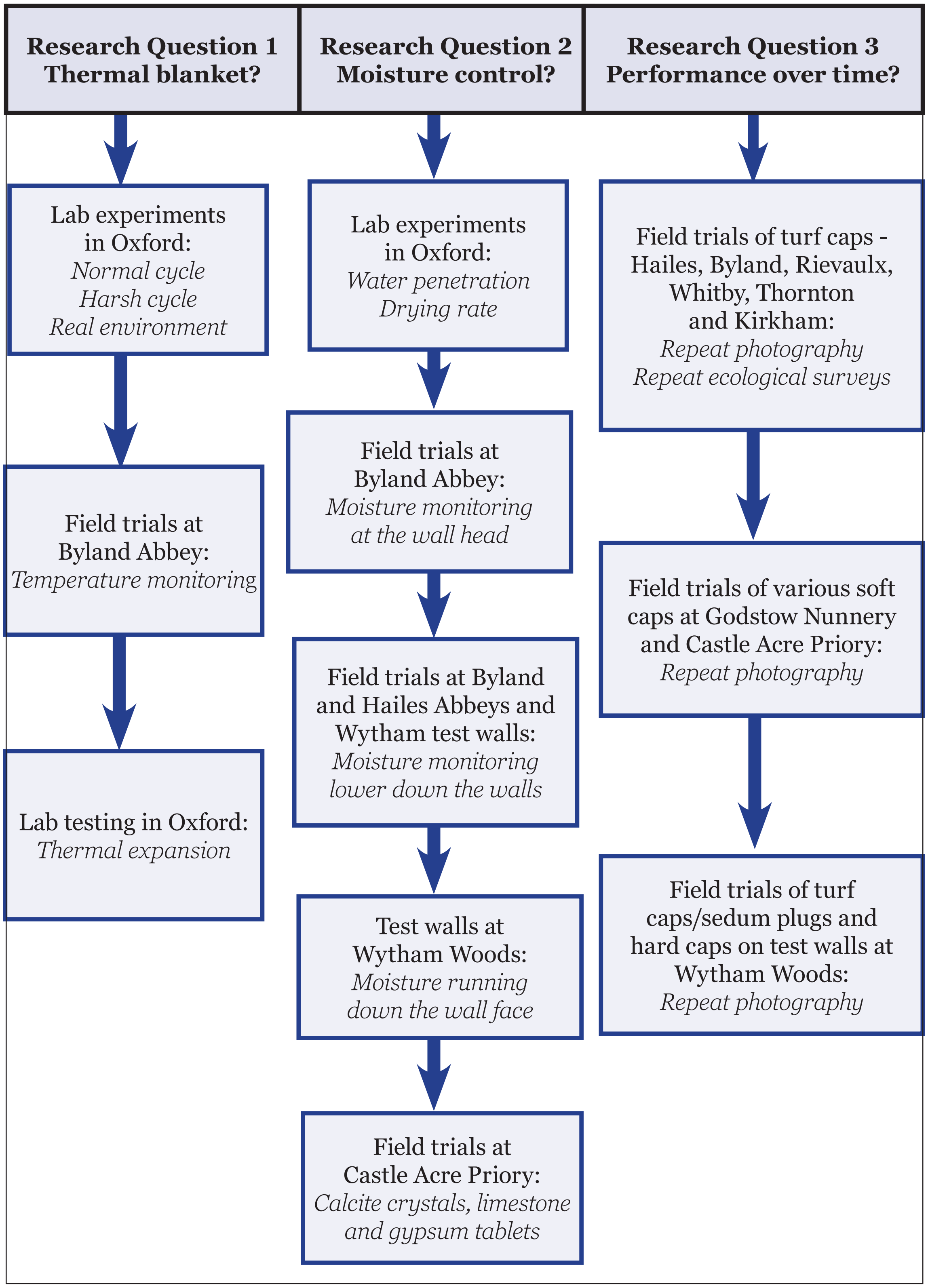

Figure 1.17 Soft capping research project tasks organised by research question.

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2 RESEARCH SITES

2.1 Introduction

The ruined monuments used in the research project provided a diverse range of environments and microclimates for testing soft cappings (Figure 2.1 shows their locations). In addition, test walls were built at Wytham Woods, outside Oxford, to monitor the effects of soft capping on replicate walls of known construction.

Long term climate data (1981–2010) from the Met Office was used to characterise the climate at each of the sites (see Table 2.1). Not all sites had meteorological stations in close proximity. In these instances, climate conditions were estimated. For example, records from two contrasting met stations were chosen to illustrate upland and lowland conditions near Byland and Rievaulx. In addition, the influence on climate conditions of local factors such as elevation, proximity to the coastline, and screening by trees were also taken into account.

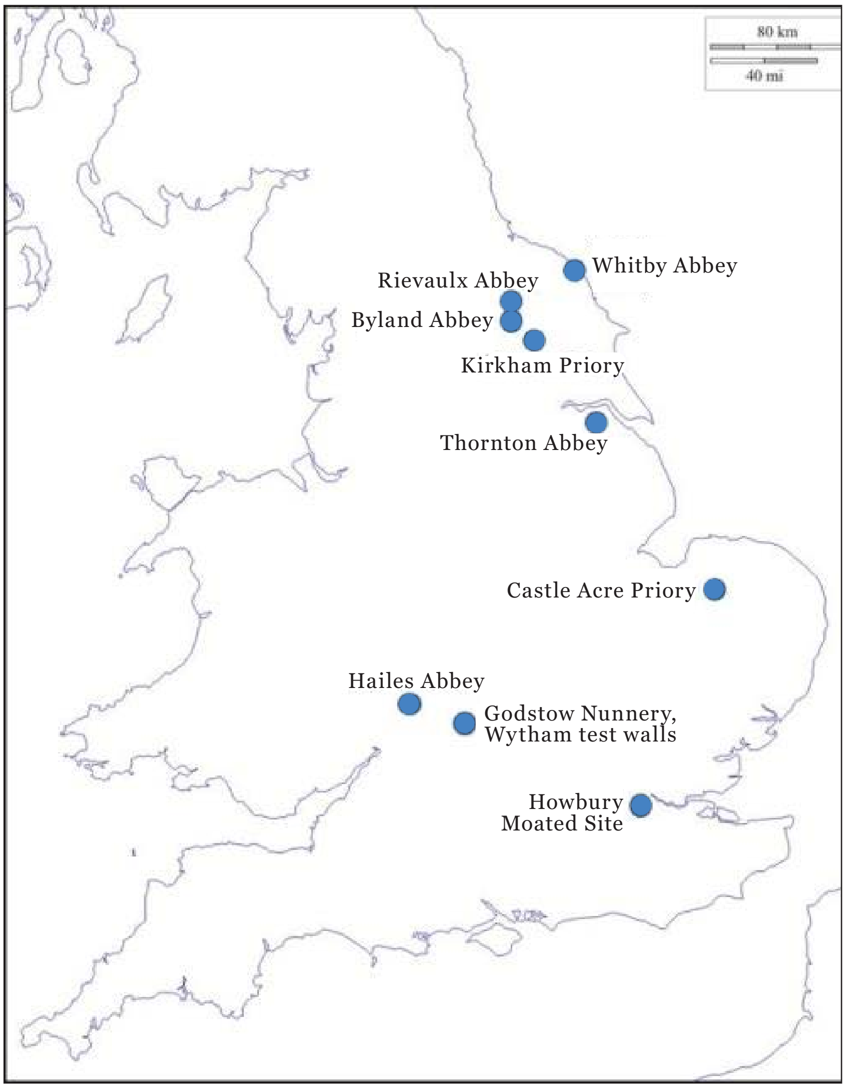


Figure 2.1 Location of soft capping research project field sites.

Met station	Grid Ref	Metres above sea level	Mean annual rainfall (mm)	Mean annual days with > 1 mm rainfall	Max annual temp (°C)	Min annual temp (°C)	Mean annual air frost days	Mean annual hours of sun	Soft Capping Research Project sites nearby
Cheltenham	51.897-2.074	58	843.4	145.6	14.7	6.8	42.2	1503.5	Hailes Abbey
Oxford	51.7513-1.2538	61	659.7	115.5	14.6	6.9	37.1	1577.9	Godstow Abbey, Wytham Woods
Marham	52.651 0.569	21	652.5	119.2	14.1	6	53.1	1560.1	Castle Acre Priory
Stanford le Hope	51.51370.4302	13	571.3	108.6	14.6	6.7	37.2	1601	Howbury Moated Site
Loftus	54.5529-0.8883	69	628.8	124.2	11.9	5.8	34	nd	Whitby Abbey
Cleethorpes	53.5571-0.0278	9	587.9	113.3	13.6	6.6	30.6	1539.8	Thornton Abbey
Topcliffe, Thirsk	54.204-1.390	25	644	117.9	13.3	4.9	58.8	nd	Rievaulx and Byland Abbeys
Fylingdales	54.362-0.673	262	978.9	149.4	11	4.7	64.8	nd	Rievaulx and Byland Abbeys
Linton on Ouse	54.045-1.250	14	626	117.2	13.6	5.7	54.1	nd	Kirkham Priory

Table 2.1 Met Office long-term average data (1981-2010) from stations close to sites used in the Soft Wall Capping Research Project. (Source: http://www.metoffice.gov.uk/climate accessed 8th August 2016).

The long-term climate data illustrate some clear temperature differences between northern and southern sites. Byland, Rievaulx, Whitby and Thornton in the north tend to be cooler than Hailes, Godstow, Wytham Woods, Howbury and Castle Acre in the south. But the distinctions in annual precipitation and number of air frost days are not so clear. Howbury stands out as the driest site, while Hailes, Byland and Rievaulx are the wettest. Castle Acre, Rievaulx, Byland and Kirkham have over 50 air frost days per year, but the other sites have less than 45.

What follows is a brief description of each site and the works undertaken during the Soft Capping Research Project. Detailed methodological information can be found in Chapter 3, and Chapter 6 explains the procedure for constructing soft and hard caps in more detail.

2.2 Byland Abbey

Location

Ryedale district of North Yorkshire, near the village of Wass. Grid Ref: SE 54951 78959. Altitude: 88 m. Address: Byland, Coxwold, North Yorkshire, YO61 4BD.

Brief description

Abbey church and monastic buildings. Late 12th century, early 13th century and 15th century.

Figure 2.2a Aerial view of Byland Abbey. © *Skyscan Balloon Photography. Source: Historic England Photo Library.*

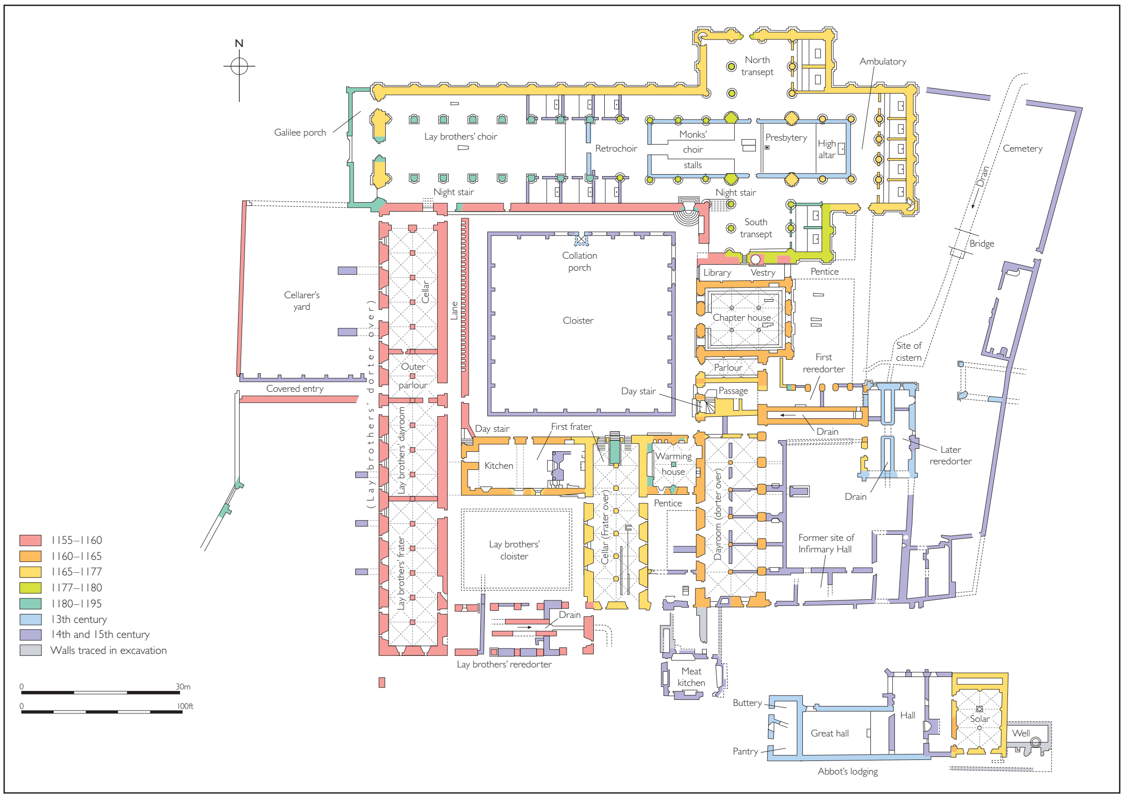


Figure 2.2b Site plan of Byland Abbey. ©*Historic England Archive*

Original building materials

Local limestone (including Hambleton Oolite) and calcareous sandstone (Lower and Birdsall Calcareous Grits) ashlar and rubble (English Heritage 2012).

Description of standing remains

The church forms the north range of the cloister and is of late Cistercian type, with square east end and ambulatory. It was built in early Gothic style, with round-arched windows but pointed vaults. The church is late 12th century, except for parts of the nave, which include the west front and the remains of its early 13th-century wheel window.

In the east range are the sacristy, chapter house and parlour, along with the abbot's lodging, monks' dorter (dormitory) and reredorter. In addition, a 12th century arch over the Byland-Oldstead road from the abbey gatehouse is still standing. The south range of the cloister also dates from the late 12th century, and contains the kitchens, warming-house and frater (or refectory). A meat kitchen was added in the 15th century. The lay brothers' quarters form the west range of the cloister. These date to the foundation of the abbey in 1177, and include a reredorter (latrine), the ruins of a vaulted undercroft, and the 'lane' providing access to the abbey church.

The standing remains and inner precinct have been in State care since 1921 and are also a Grade I Listed Building. The Abbey gatehouse is also scheduled.

Conservation history and current condition

The Office of Works cleared and excavated much of the site in the 1920s, as the collapse of walls had obscured many of the remaining architectural elements. Since then, the site has been subject to consolidation, including cement-based hard capping. Some of the lower walls around the cloister had soft capping installed in the 1980s. There is some evidence of vertical cracking resulting from cement grout and pointing (Fig 2.2c). The walls suffer from substantial deterioration, with as much as half a tonne of masonry falling from the ruins during a three-month period one winter (Figure 2.2d).

Figure 2.2 Deterioration at Byland Abbey
(c) vertical cracking along joints
(d) debris produced over a 3-month period during the soft capping trials in 2003.
(both Chris Wood ©Historic England)

Capping installed during this research project

The remains of Byland Abbey consist of many ruined walls of varying heights and aspects (Figure 2.3). Four test locations on the outer parlour and lane walls were studied during the Soft Capping Research Project. These included soft caps installed in February 2004 and a hard-capped section completed in July/August 2004. Test location 1 on the west side of the cloisters, also called 'the lane', was used to test soft capping of different thicknesses and compositions in comparison with hard capping. Soft cappings of 5, 10 and 15 cm thickness were installed in strips of 1.5 m long. For each thickness, two strips were installed: one with slate fragments (regolith) added to the soil, and one without. Slate fragments were added to establish whether they improved water retention. The hard capping was constructed using the best practice methods outlined in Chapter 5.

After carefully removing the upper 20 to 30 cm of stonework, which had previously been hard-capped with cement mortar, a moisture probe was inserted (see Chapter 3, section 3.3.1.1). A new hard capping was created with lime mortar (1 part St Astier NHL2: 2½ part graded aggregates [1½ parts Moreleys sharp sand: 1 part Sherburn soft sand]) and cleaned, re-used stones. Figure 2.3 illustrates the experimental design at site 1. Test location 2, was a 2-m long by 20-cm wide high ledge, where a hand-cut turf cap without additional soil was installed. Test location 3 was a 4-m high wall, where a 10-cm thick soft cap (with soil and slate fragments) was installed over an area 3-m long by 50-cm wide. In addition, turf (without additional soil) was installed on various small east-facing ledges at test location 3.

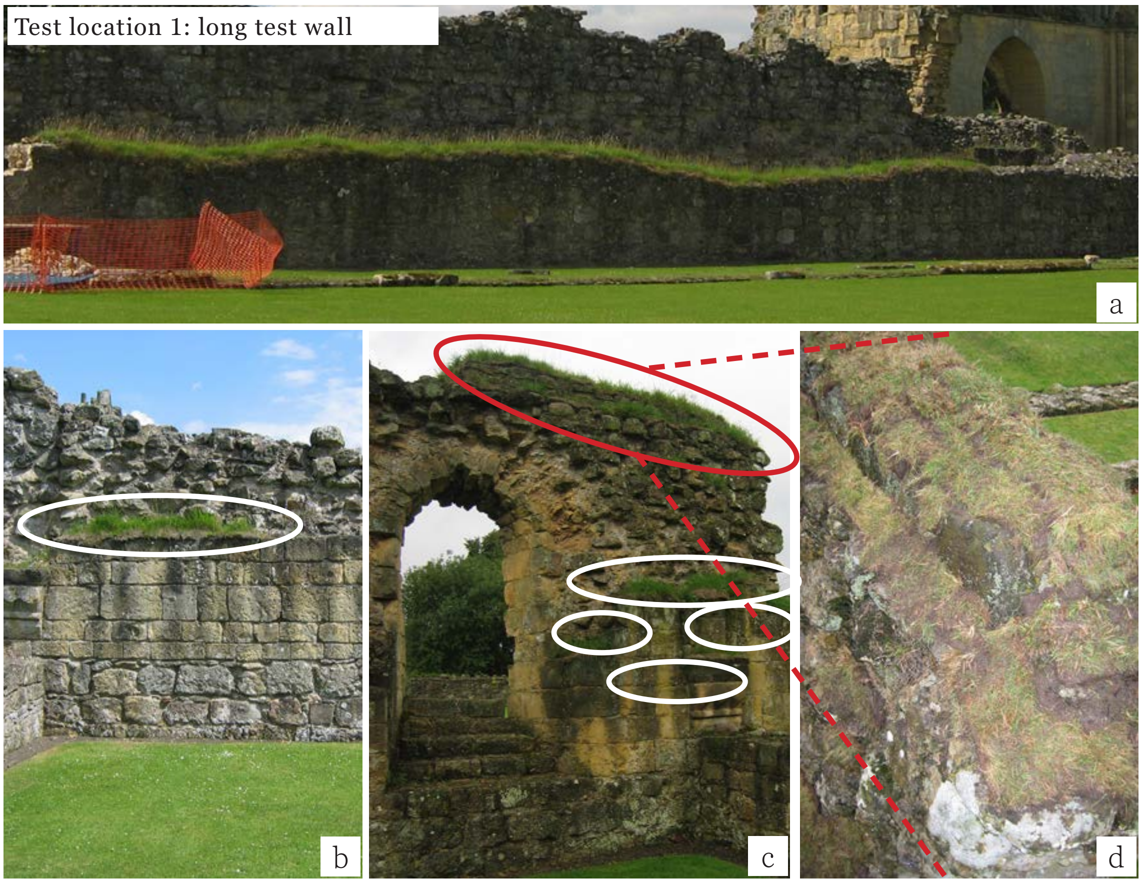


Figure 2.3 (a-d) Location of newly installed soft capping at the three sites at Byland Abbey.
(a) Test location 1 is the long test wall, with hard capping on LH side and a long section of soft capping of different thicknesses and composition.
(b) At test location 2, the circled region is the 2m long (20 cm wide) section of hand-cut local turf without soil installed onto the ledge, adjacent to an uncapped section of wall.
(c) Location of soft caps at test location 3. The uppermost red-circled region is the 3 m long (50 cm wide) soft cap of 10-cm thickness (containing regolith in the soil), with smaller turf sections on the underlying ledges. The four smaller white-circled regions are the ledges where hand-cut turf without soil was installed.
(d) is the view from above the strip circled in red on (c) just after installation.
(all Chris Wood ©Historic England)

2.3 Kirkham Priory

Location

Derwent valley near the Yorkshire Wolds between York and Malton. Grid Ref: SE 73486 65816, SE 73591 65782. Altitude: 20 m. Address: Whitwell on the Hill, Malton, North Yorkshire, YO60 7JS.

Brief description

Augustinian priory. Mid-12th century to 15th century.

Original building materials

Sandstone and Hildenby limestone ashlar and rubble.

Figure 2.4a Aerial view of Kirkham Priory. © *Skyscan Balloon Photography. Source: Historic England Photo Library.*

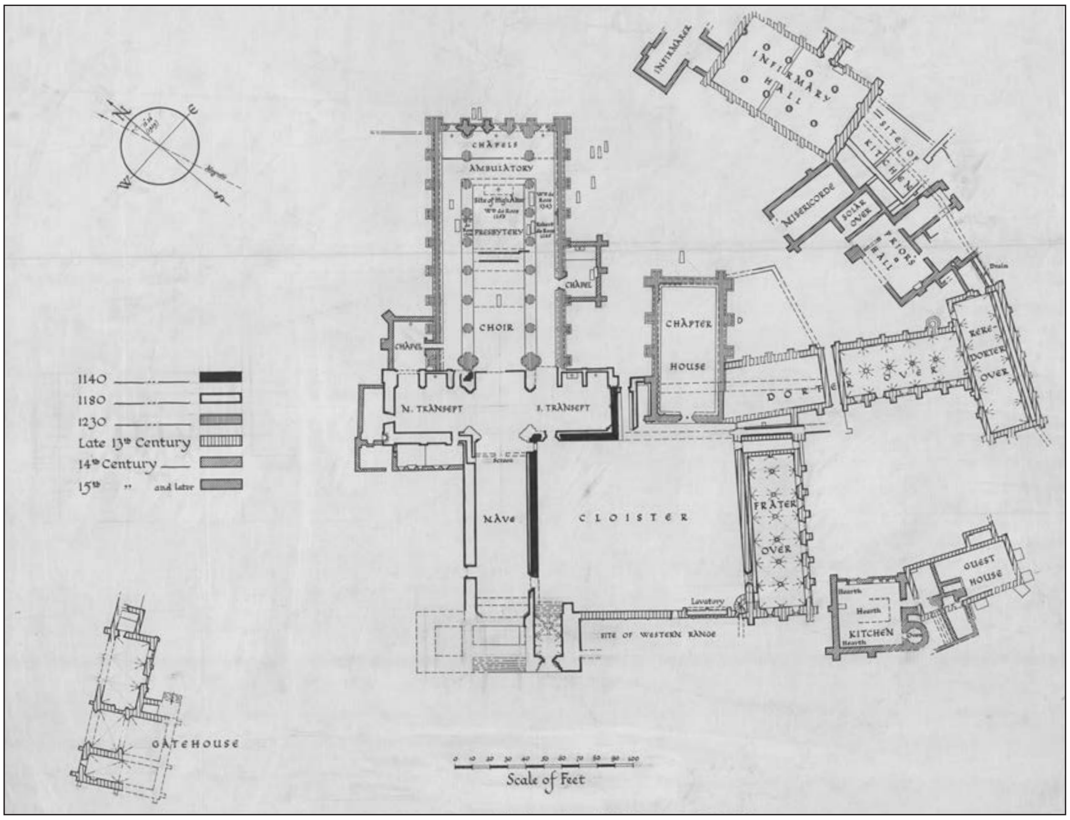


Figure 2.4b Site plan of Kirkham Priory. ©*Historic England Archive*

Description of the standing remains

Most of the standing remains at Kirkham Priory date from the 12th to 14th centuries. These include the ruins of the 12th- and 13th-century priory church, whose east front stands in part nearly to full height. The nave of the church forms the north range of the cloister. The late 13th-century chapter house and dorter (sleeping quarters) form the east range. To the south of the east range sits a complex of late 13th- and 14th-century buildings, comprising the kitchen, Prior's lodging, infirmary and reredorter (latrine). The frater (refectory) is located to the south. Additional domestic buildings make up the west side of the cloister, with a separate guest house and kitchen to the south.

A separate and nearly complete 2-storey gatehouse dating from the late 13th century lies to the northwest, and the stump of a square-section 14th-century cross stands outside.

Kirkham Priory is scheduled.

Conservation history and current condition

There is evidence of previous soft capping, probably installed in the 1980s or early 1990s, on the vaulted chamber, over the laver and on several sections of low walls in the choir. Previous cement-based consolidation of an unknown date is also widespread, and appears to have contributed to the cracking of approximately 20% of the face stones in some areas, possibly due to thermal contraction/expansion stresses.

Capping installed during this research project

New soft caps were installed in February 2004 at two test locations (see Figures 2.4c-d and 2.5). The first test location was above the laver alcove, alongside a patch of existing soft capping from the 1980s/1990s (approx. 4 m high), and on a small ledge between the arches at a lower elevation over an area approximately 30 cm long and 15 cm wide (Figure 2.5a). The new soft caps were 10 cm thick, formed from turf cut from the site and slate fragments were added to the soil. The second test location was along a portion of the north-west frater wall with pronounced runoff streaking, where a small section of hard capping had been installed in July/August 2004. As work began, it became clear that the existing hard cap was a cement-based thick layer of about 1 m in depth. Hammer and chisels proved inadequate to remove this, as did Kango road hammers. In the end, quarrying techniques using plugs and feathers were needed to remove the capping. The cap was reconstructed with lime mortar (1 part St Astier NHL3.5: 2½ part graded aggregates (1½ parts Moreleys sharp sand: 1 part Sherburn soft sand)). Reused stone was used where possible, along with other stone obtained from the on-site store.

c

d

Figure 2.4 c, d Installation of soft capping on top of the laver alcove on the southwest side of the cloister (test location 1) and on the top of the northeast cloister wall (test location 2) at Kirkham Priory in February 2004. *(both ©Heather Viles, University of Oxford)*

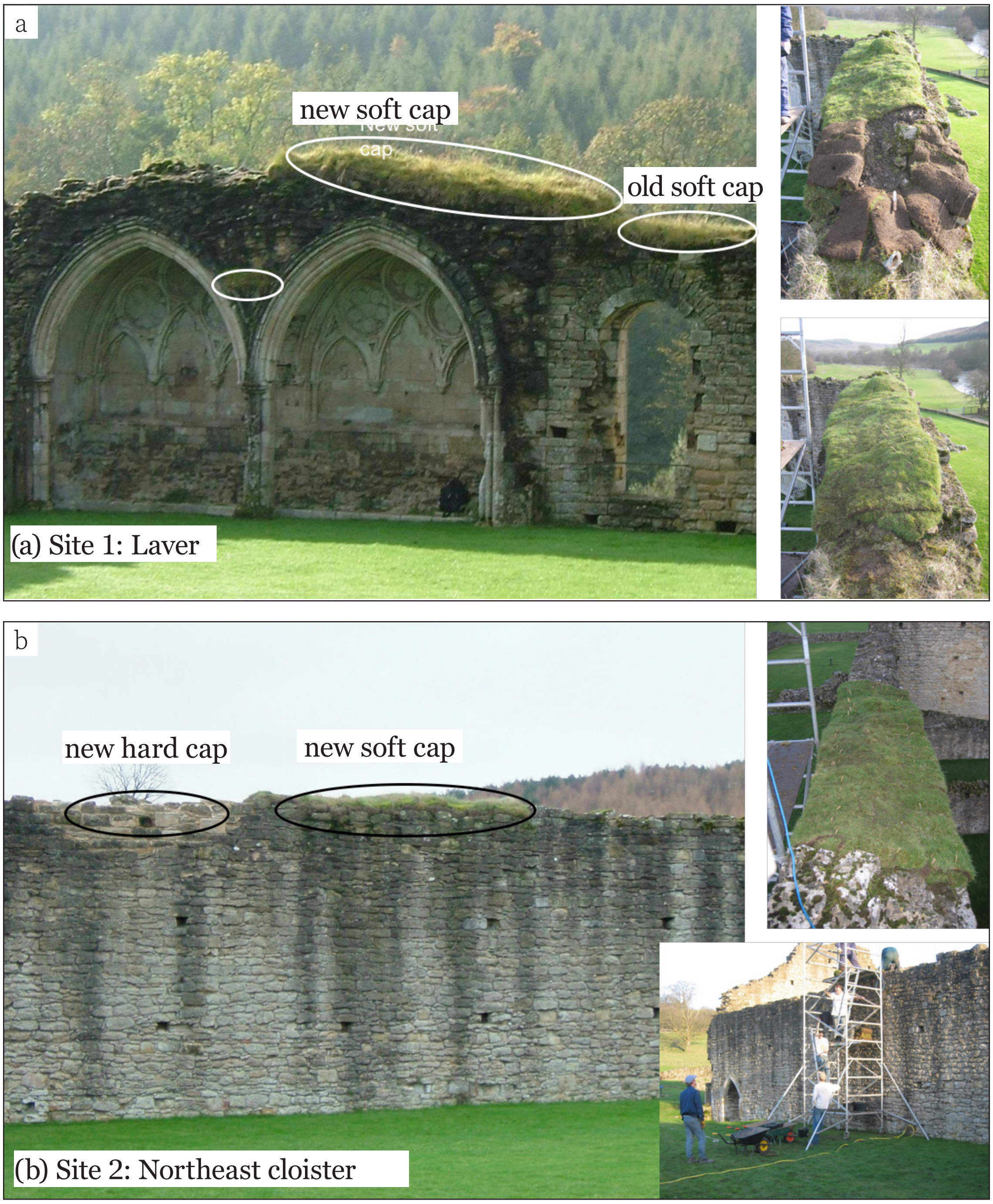


Figure 2.5 Location of newly installed soft capping at Kirkham Priory.
(a) Site 1, the laver alcove, where a 5 m long (1.3 m wide) section of 10 cm thick soft capping (using local turf and soil containing regolith) was installed on the top of the wall (see insets of installation). A 30-cm (15-cm wide) section was also installed, at the top of the column between the arches (lower white circle).
(b) Soft capping (3.9 m long, 50 cm wide 10 cm thick soft capping using local turf and soil with regolith) and hard capping (3.9 m, 50 cm wide using lime mortar and stone) on the north east cloister wall, at site 2.
(all ©Heather Viles, University of Oxford)

2.4 Thornton Abbey

Location

North Lincolnshire, 2 miles from Thornton Curtis, and about 5 miles from Immingham. Grid Ref: TA 11784 19009. Altitude: 7 m. Address: Thornton Curtis, Ulceby, North Lincolnshire, DN39 6TU.

Brief description

Augustinian monastery used post-Dissolution as a secular college. Primarily dating to late 12th–late 14th centuries, with minor late 15th–early 16th-century additions. 1382 gatehouse and wing walls, with later 14th–15th-century extensions and a 15th–16th-century barbican.

Original building materials

Gatehouse of brick with limestone ashlar dressings and decorative details. Precinct walls are of squared chalk and chalk rubble with outer brick facing. Barbican of brick with chalk and limestone ashlar dressings. Remains of the Abbey Church and monastic ranges are chalk, limestone and ironstone rubble with limestone ashlar facing and dressings. There are sections of later brickwork in the south and east monastic ranges.

Figure 2.6a Aerial view of Thornton Abbey. ©*Crown Copyright. Historic England Archive.*

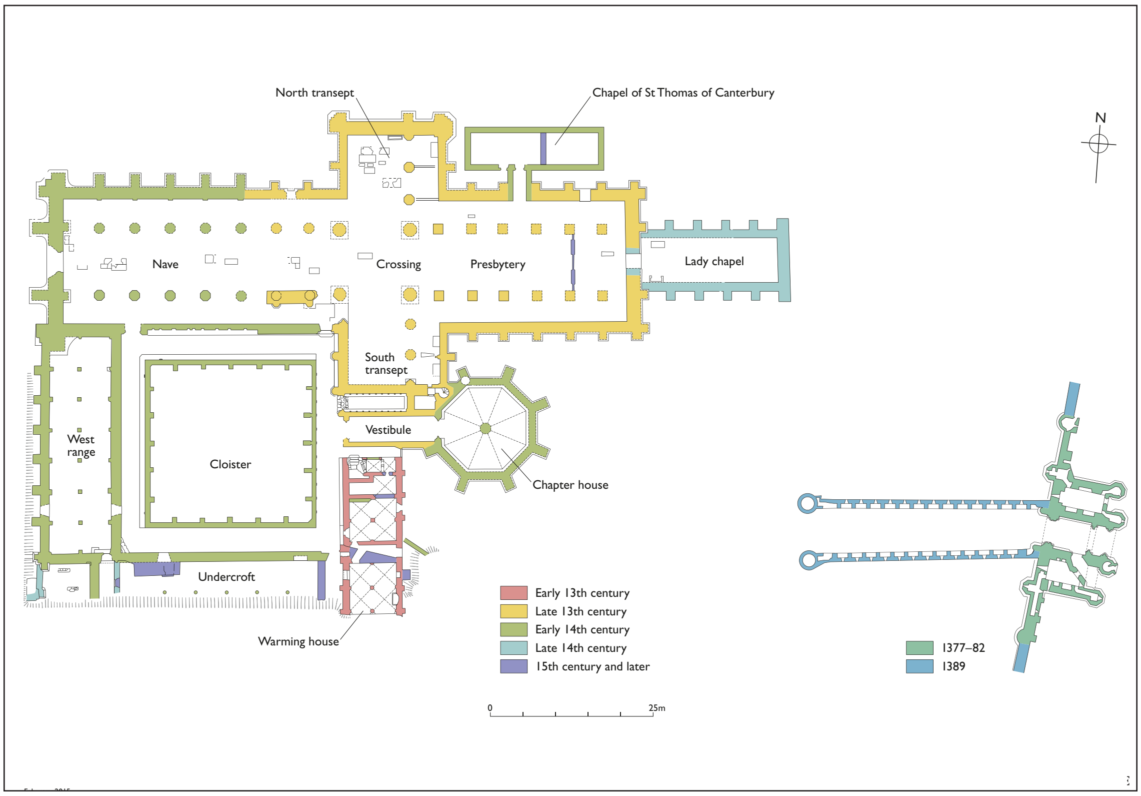


Figure 2.6b Site plan of Thornton Abbey. ©*Historic England Archive*

Description of the standing remains

The late 14th-century gatehouse and barbican, which survive almost intact, are the best preserved of any monastery in the country. Little remains standing of the cloister buildings, although their foundations are still in place. Excavations in the 19th century revealed much of the ground plan. The earliest visible remains are of the early 13th-century vaulted undercroft of the east cloister range. North of the undercroft are the late 13th-century remains of the vestibule and a narrow room. The vestibule leads into the chapter house which was built in 1282-1308. There are some surviving walls of the chapter house, as well as the stone seating that lined the walls on either side of the entrance into the vestibule. The north range of the cloister comprised the abbey church. The surviving foundations indicate a late 13th-century building with alterations made to the nave in the early 14th century when the southern aisle was added. Several other additions were built on the site at this time.

The gatehouse and cloister buildings have been in State care since 1938. The barbican, precinct walls, the remains of the church and abbot's lodge are Grade I listed. The coach house, the ruins of the south precinct gateway, the garden and orchard walls, and the bridge are listed Grade II.

Thornton is scheduled.

Conservation history and current condition

The bricked gatehouse has been the focus of repair work which is now completed. There is evidence of considerable frost-related damage at the site (Figure 2.6c,d). Many walls, both high and low, have been consolidated and hard-capped. There is also evidence of old soft caps (probably installed in the 1980s or early 1990s) on low walls and a few sections of high walls.

c

d

Figure 2.6 c,d Frost damage at Thornton Abbey on (a) brick and (b) stone. Image (a) shows a pile of frost-shattered brick debris swept carefully from the surrounding brick surface.
(both ©Heather Viles, University of Oxford)

Capping installed during this research project

Soft caps were installed on low walls at three test locations in February 2004 (Figure 2.7). The soft caps were 10 cm thick, made of soil containing regolith and turf cut from the site. The first test location was a sloping fan-shaped brick section on the north wall of the undercroft. The section alongside and immediately to the south was left uncapped for comparison (Figure 2.7b). The second test location was a 60-cm high brick wall with a flat top (Figure 2.7c), while the third test location was a cambered, rough-racked limestone wall (Figure 2.7d, e). A section of limestone wall south west of the Chapter House was hard-capped in July/August 2004 (as shown in Figure 2.7f). Here, the old render that had extended to the top of the wall was lost in the process of removing the existing cement cap (some 20 cm thick). Lime mortar (1part NHL 3.5:3 parts graded aggregate) was used to repair a fracture and complete the hard-capping. Finally, the wall face was re-rendered.

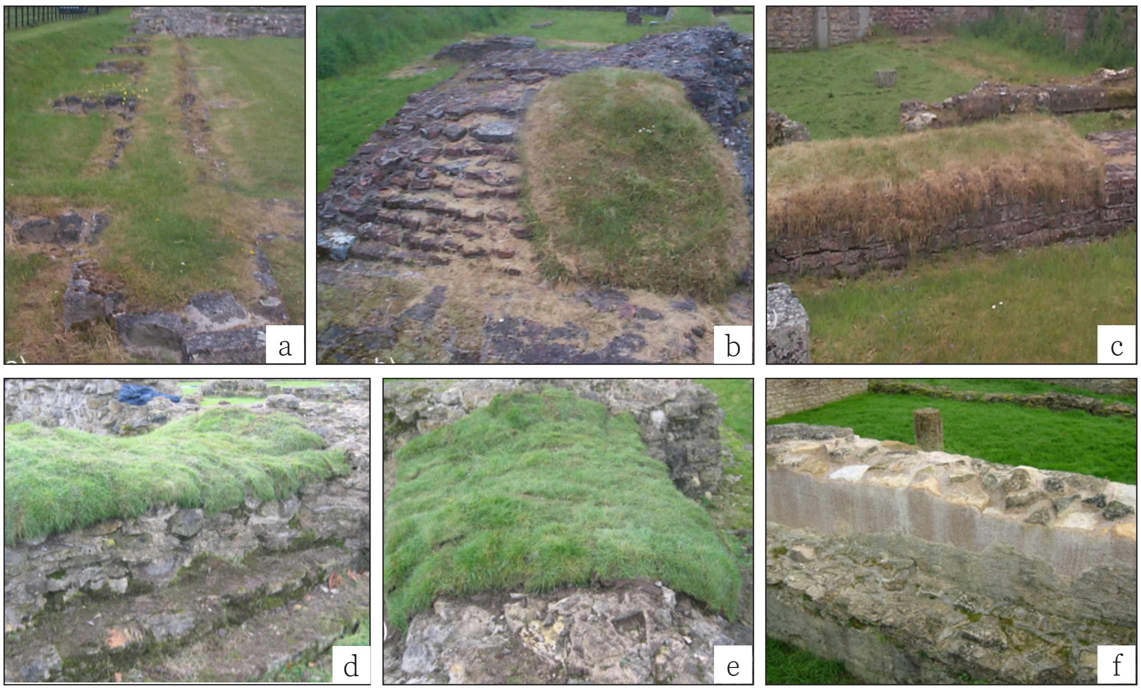


Figure 2.7 The test locations monitored at Thornton Abbey.
(a) An old soft-capped wall, installed in the 1980s.
(b) New soft capping (2.5 m long, 1.5 m wide 10 cm thick soft cap with soil and regolith, using turf from the site) on a sloping brick wall where a brushed section to the left was left for comparison.
(c) New soft capping (2.6 m long, 1.2 m wide 10 cm thick soft cap with soil and regolith, using turf from the site) installed on a 60 cm high brick wall.
(d, e) New soft capping (2.6 m long, 1.9 m wide, 5-10 cm thick soft cap with soil and regolith, using turf from the site) on a low Lincolnshire limestone composition, cambered wall with rough top.
(f) Hard capped Limestone wall, 3.75 m long, 50 cm wide, using lime mortar and stone.
(all ©Heather Viles, University of Oxford)

2.5 Rievaulx Abbey

Location

Rievaulx, near Helmsley, Ryedale District of North Yorkshire. Grid Ref: SE 57632 84971. Altitude: 90 m. Address: Rievaulx, Nr Helmsley, N Yorks, YO62 5LB.

Brief description

Abbey Church and monastic buildings. 12th–15th centuries.

Original building materials

Sandstones (including middle Jurassic and Saltwick formation) and limestones (including Hambleton Oolite) (English Heritage, 2012).

Figure 2.8a Aerial view of Rievaulx Abbey. *Historic England Photo Library*

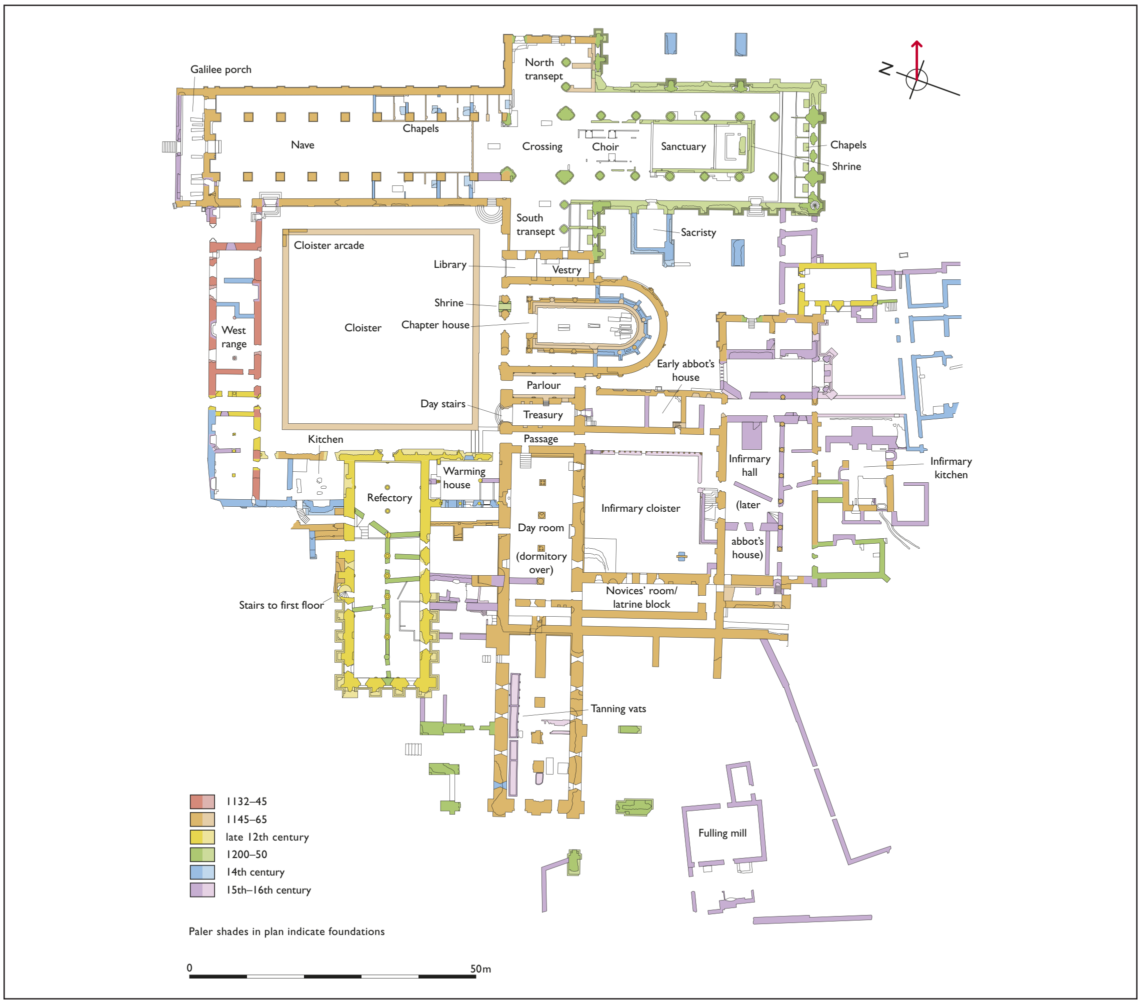


Figure 2.8b Site plan of Rievaulx Abbey. ©*Historic England Archive*

Description of the standing remains

The earliest remains at Rievaulx are those of the nave and transepts of the church, built between 1140 and 1150 soon after the founding of the abbey. The east end of the church and the quire were rebuilt and extended in the 13th century. In the 14th century, flying buttresses were added to support the vault above the quire. The east cloister range includes the remains of the library, vestry and chapterhouse. East of the chapterhouse is the infirmary, built in the late 12th century and partly remodelled circa 1500. Along with a 13th century chapel, 14th century infirmary buildings and the 15th century abbot's kitchen, this encloses a small court and forms the east range of the infirmary cloister. The remains of other late 12th century buildings enclose the infirmary cloister, including the Long House, and the reredorter or latrine. A passage joins the infirmary cloister to the main cloister. The west range of the main cloister comprises the late 12th century lay-brothers' quarters and an outer parlour remodelled in the 14th century. A complex of domestic buildings made up the south range.

The abbey ruins were taken into state guardianship in 1917, and is scheduled.

Conservation history and current condition

Unusually, the ruins were not excavated in the 19th century. Minor repairs were carried out in 1907, but much more work was needed to prevent collapse. In 1918 Sir Frank Baines, Principal Architect, Office of Works, developed engineering techniques such as inserting concealed reinforced concrete beams into the upper walls to stabilise the buildings. The site suffers from significant deterioration. Some soft caps of unknown date exist.

Capping added during this research project

Two bays at triforium level in the eastern nave of the main abbey church were soft capped in February 2005 (see Figure 2.8c,d). The aim of the trial in this location was to test the ability of soft capping to withstand the conditions at high level on an exposed site sheltered from direct rainfall. Deterioration in the form of pronounced streaking discoloration caused by mosses and lichens had been noted under the ledges. We wanted to test whether soft capping would prevent this occurring.

Cleaning work

Immediately below the trial area of soft capping, the spandrels and label moulds above the nave arcade were colonised by substantial growths of moss and lichen (Figure 2.9). To see what effects soft cappings might have on the future growth of organic material, the moss and lichen were removed in one bay with soft hand brushes. In the adjacent bay, the existing growth was photographed but left untouched.

Figure 2.8 c, d The soft capping installed high at triforium level in the wall of the main abbey church nave at Rievaulx. *(both ©Heather Viles, University of Oxford)*

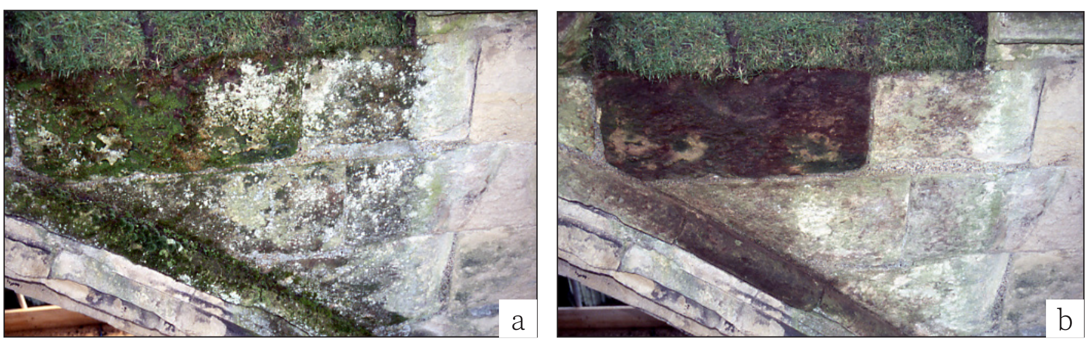


Figure 2.9 a,b Cleaning of stonework below the newly installed soft capping. *(both ©Heather Viles, University of Oxford)*

2.6 Whitby Abbey

Location

On East Cliff overlooking the North Sea, above the fishing port of Whitby, Scarborough District of North Yorkshire. Grid Ref: NZ 90303 11217. Altitude: 50 m. Address: Abbey Lane, Whitby, North Yorkshire, YO22 4JT.

Brief description

Saxon monastery from the 7th–9th centuries, and church from the early 12th–14th centuries.

Original building materials

Sandstone.

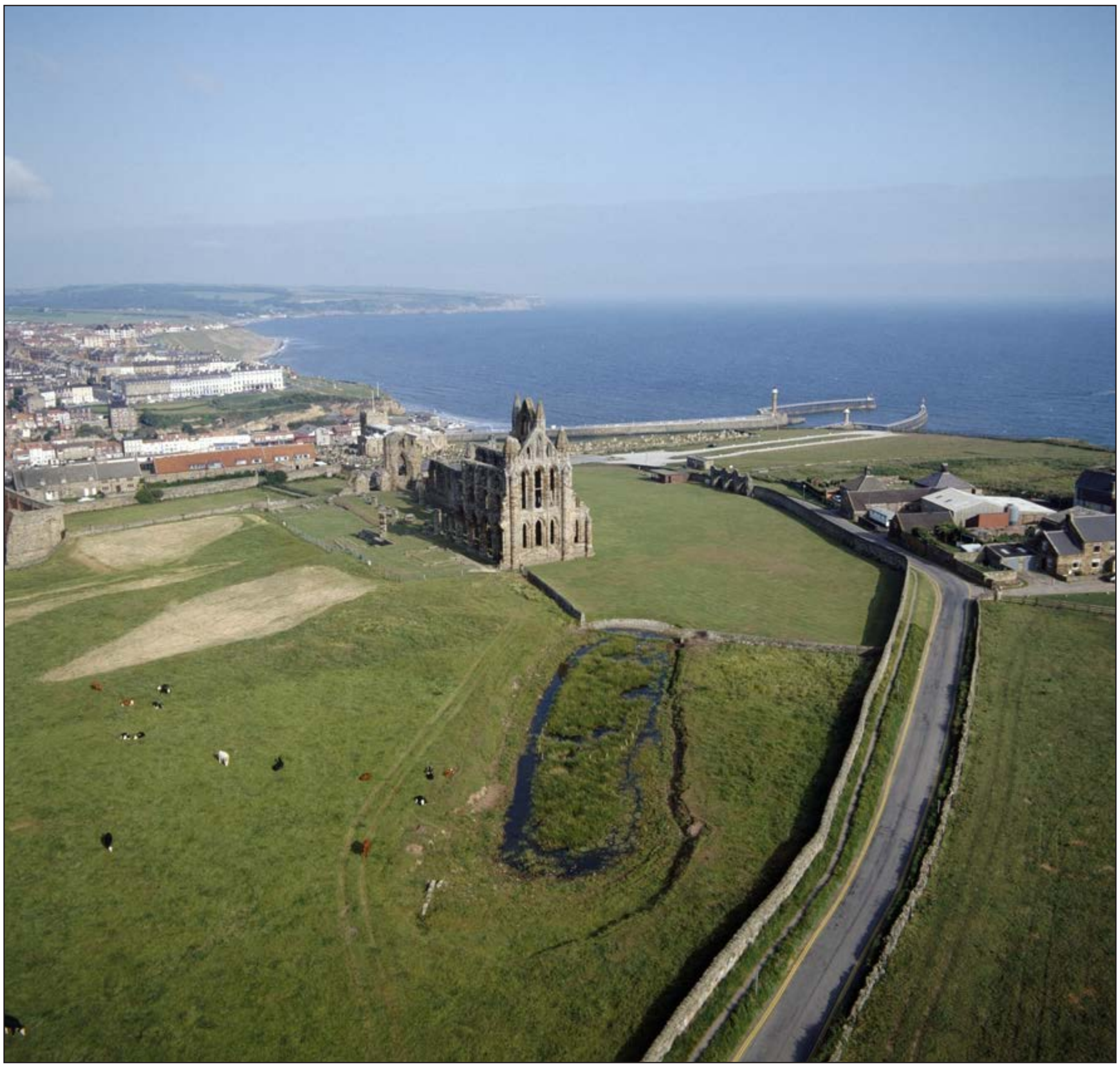


Figure 2.10a Aerial view of Whitby Abbey. © *Skyscan Balloon Photography Source: Historic England Photo Library*

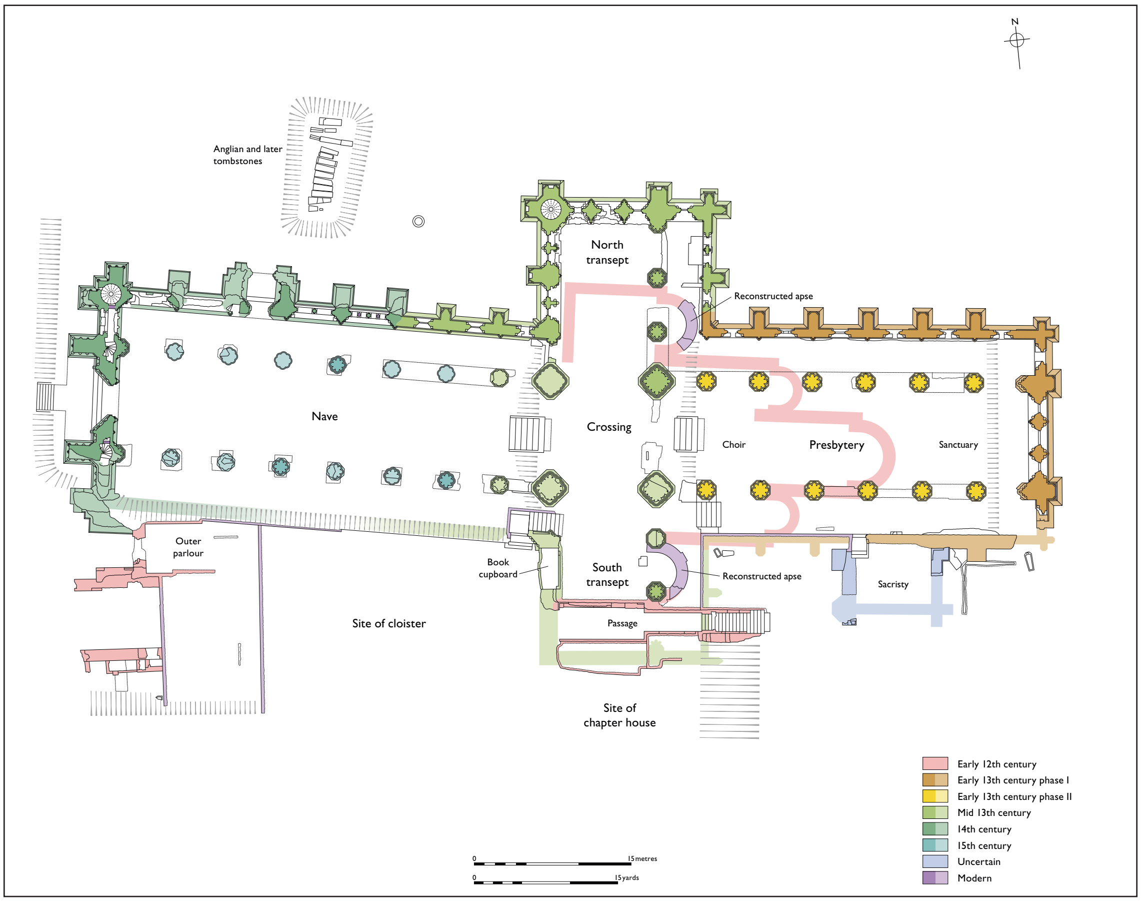


Figure 2.10b Site plan of Whitby Abbey. ©*Historic England Archive*

Description of the standing remains

Although there have been church buildings on this site since the 7th century, the only standing remains date from the 11th to the 15th. These include the foundations of the 11th century Benedictine monastery, and the eastern arm (or presbytery) and the north transept of the 13th century abbey, which stand almost to their original height.

The site was damaged by direct hits from cruisers of the Imperial Germany Navy in 1914. The abbey has been in State care since 1920, and the Banqueting House since 1935. Both are scheduled.

Conservation history and current condition

The exposed location of this site on Whitby Head has resulted in accelerated decay and weathering from salt blown off the North Sea and cold winter temperatures.

Capping installed during this research project

A high-elevation section of the West Front, which is exposed to wet and windy conditions, over an archway rebuilt following damage in WWI was soft capped in February 2005 (Figure 2.10c,d,e). The aim was to test whether soft capping could survive and protect under windy, coastal conditions (Figure 2.11).

Figure 2.10 c,d,e (left) The soft capping installed at high elevation on the west Front wall at Whitby Abbey. *(all ©Heather Viles, University of Oxford)*
Figure 2.11 (right) Windy conditions on the soft capping at Whitby Abbey, January 2015. *©Alan Cathersides*

2.7 Hailes Abbey

Location

Near Cheltenham, Tewkesbury District, Gloucestershire. Grid Ref: SP 05044 29999. Alt: 105 m. Address: Hailes, Nr Winchcombe, Cheltenham, Glos, GL54 5PB.

Brief description

Cistercian Abbey. Mid-13th, 15th and 16th centuries.

Original building materials

Rubble and Cotswold limestone ashlar stone.

Figure 2.12a Aerial view of Hailes Abbey. © *Skyscan Balloon Photography Source: Historic England Photo Library*

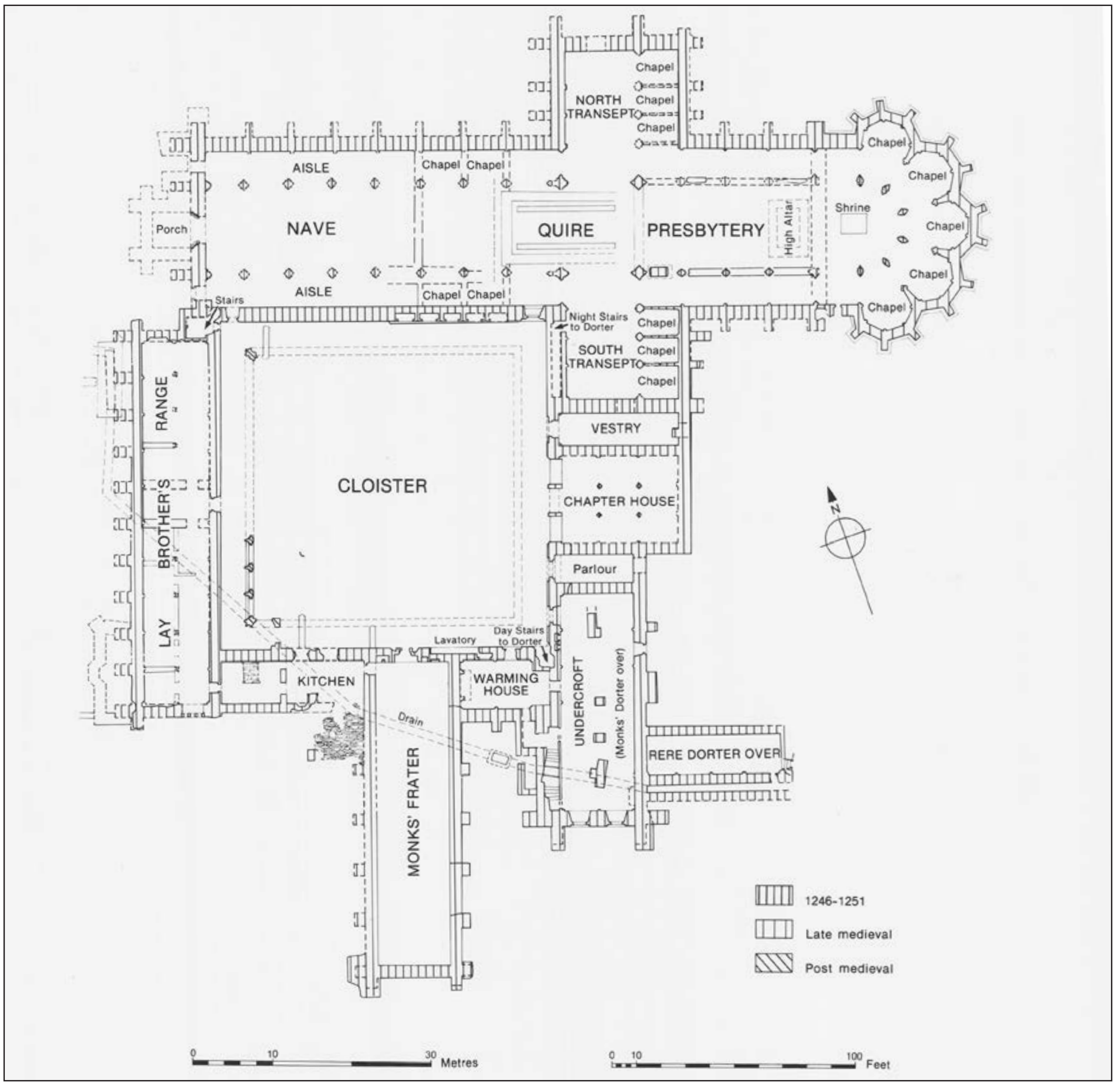


Figure 2.12b Site plan of Hailes Abbey. *Source: Historic England Archive*

Description of the standing remains

The ruins of the 13th abbey church were excavated in the early 20th century. Only the foundations – including the base of a shrine at the east end built for a phial of 'holy blood' – survive. The foundations of the cloister also survive, along with three bays at the south end, which survive to full height.

The monument was donated to the National Trust, and is now in the care of the Secretary of State and looked after by English Heritage.

Conservation history and current condition

The site is prone to flooding and damage from freeze-thaw activity due to its location in a frost hollow. Many of the low walls at the site are heavily deteriorated and have been hard-capped repeatedly. Some small sections of low wall were soft-capped in the 1990s. Little information is available about the techniques used during this early soft capping, although investigation at the site revealed a permeable membrane beneath a thin layer of soil and turf.

Capping installed during this research project

Part of the longest section of cloister arches on the west wall of the parlour and chapter house had been covered by scaffolding in the 18 months prior to the start of the Soft Capping Research Project, and considerable deterioration had occurred. It was scaffolded in autumn, 2002 and covered while plans were drawn up for any necessary conservation work. This section was chosen to be the test site, as it provided a good opportunity to study the affect of soft capping on a well-dried out wall. Soft capping using approximately 10 cm thick turf cut onsite (Figure 2.12c) was installed in autumn 2004. Half of the test area had previously been consolidated and lime mortared, and the other half was simply cut back and then soft-capped.

c

Figure 2.12c Soft capping was installed over the wall head in the east cloister at Hailes Abbey, where previous consolidation and lime mortar repairs had been carried out.
©*Heather Viles, University of Oxford*

2.8 Howbury Moated Site

Location

Kent, East London, near Slade Green. Grid Ref: TQ 52788 76672. Altitude: 4 m.

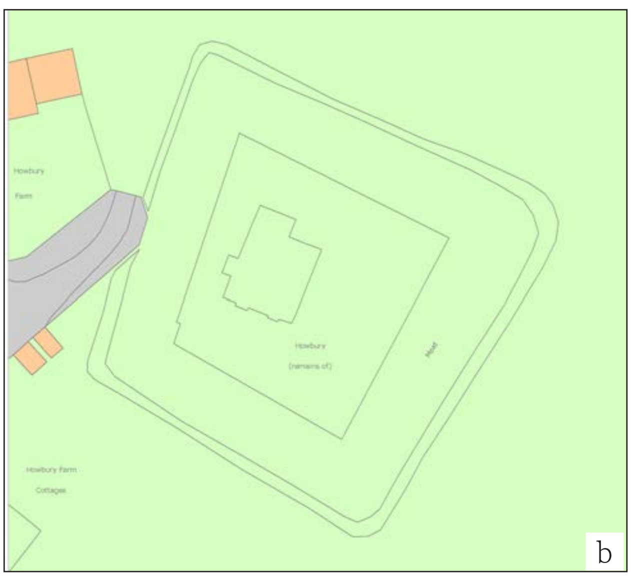
Brief description

Original building materials: brick and stone.

Description of the standing remains

The moat is subrectangular, and about 7m wide. At the centre is an island once accessed by a drawbridge (whose timber remains could still be seen in the late 19th century). An ashlar and brick wall encloses a ruined house known as 'Howbury', dating from the 16th or 17th century and built of red brick in English bond. The house was used as a farm building until 1935, when it suffered blast damage, and eventually collapsed. It is now a privately owned, scheduled monument.


a



b

Figure 2.13
(a) Howbury moated site
©*Alan Cathersides*
(b) Site plan of Howbury moated site
(© Crown Copyright and database right 2016. All rights reserved).

Conservation history and current condition

In 2001, consolidation work was carried out. The moated walls were pointed underwater, corners were stitched with stainless steel bars grouted into the substrate, and masonry was repaired with ragstone salvaged from another site and non-hydraulic lime mortar.

Capping installed during this research project

Two areas of narrow wall were soft capped during this project. The first test location was on top of a 3.45-m long by 30-cm thick section, with a consolidated stone wall-top that was considerably eroded and frost damaged and contained loose stonework. A 7.5-cm thick soft cap was installed. The second test location was a 3.9-m long by 37–40 cm wide section composed of brick that had been hard-capped during works in 2001, and had cracked in places. Here a 10-cm thick soft cap was installed. At both test locations two small sections of soil with seed were also emplaced (Figure 2.13c,d).

Figure 2.13 Soft capping work at Howbury Moated Site, (c) Site 1 and (d) site 2.
(both ©Heather Viles, University of Oxford)

2.9 Godstow Abbey (also known as Godstow Nunnery)

Location

North Oxford, Oxfordshire. Grid Ref: SP 48745 09482. Altitude: 60 m.

Brief description

Benedictine abbey and nunnery, 12th–16th centuries.

Original building materials

Oolitic limestone.

Description of the standing remains

The claustral buildings are represented only by walls standing on the north, south and east sides, and in part on the west side. There is also a small private chapel standing to roof height in the south-east corner. The claustral enclosure measures about 70m north-south and 56m east-west. At their highest, the walls stand between 3m and 4m. The small two storey building in the south east corner of the claustral enclosure, possibly the abbess' chapel, is the only building remaining from the nunnery's domestic ranges. A courtyard known as Sanctuary Field lies to the west of the cloisters. A wall of rough uncut limestone that is supported on the inside by two modern concrete buttresses, forms the north boundary of the courtyard.

First scheduled in 1949, the remains are Listed Grade II.

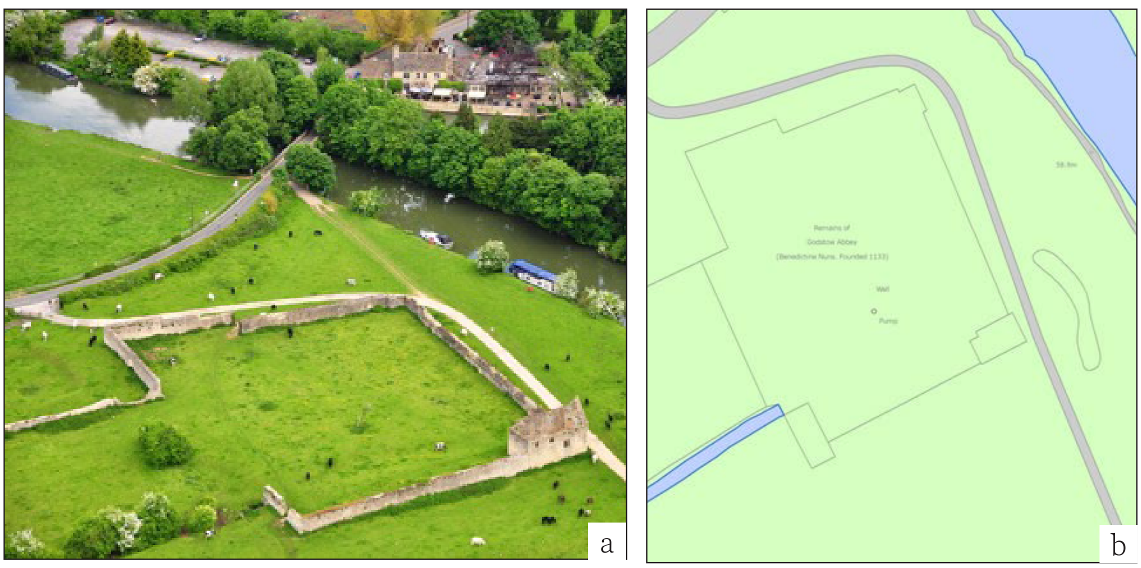

a
b

Figure 2.14a-b
(a) Aerial view of Godstow Abbey. *(Dave Price http://www.geograph.org.uk/photo/3491591)*
(b) Site plan of Godstow Abbey *(© Crown Copyright and database right 2016. All rights reserved).*

Conservation history and current condition

The history of conservation is largely unknown. There are many signs of frost damage, especially towards the top of high- level walls.

Capping installed during this research project

In February 2009, eight sections of 2m-long soft capping were installed on top of part of a wall running roughly from north to south (Figure 2.14c). The soft caps varied in composition and design so that the performance of different types of turf, seeded mat and sedum soft capping could be compared, and the usefulness of water-retaining gels evaluated. The natural soft caps were local turf, commercial turf, seeded matting and sedum matting, and the commercial turf was Rolawn Minster Pro turf. The seeded mat (Covamat) consisted of a layer of seed retaining paper, a natural fibre matrix of straw and polypropylene mesh, and the sedum mat was an Enviromat sedum carpet. Sedum plugs were added to the edges of the two turf capping strips in November 2010.

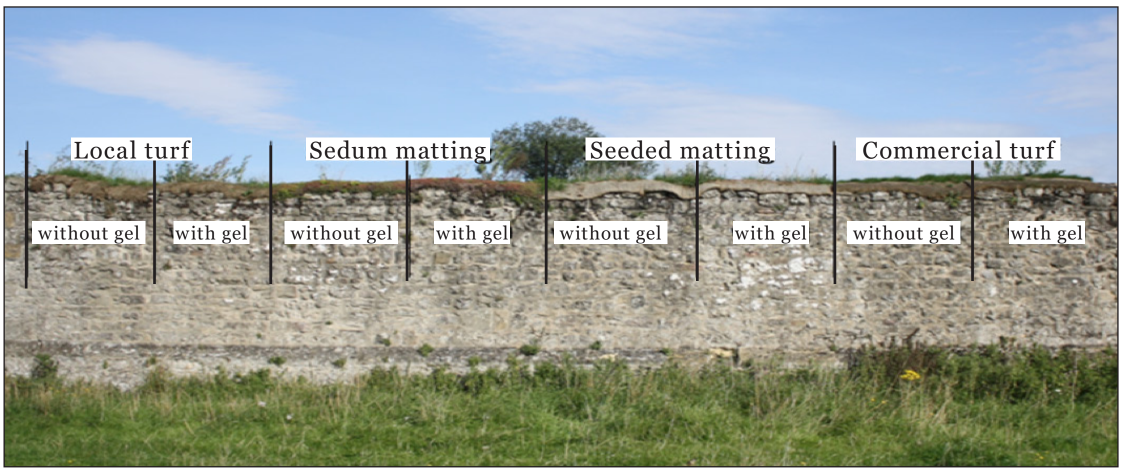


Figure 2.14c Soft capping installed at Godstow Nunnery, 2009. ©*Heather Viles, University of Oxford*

2.10 Castle Acre Priory

Location

Castle Acre, Norfolk. Grid ref: TF 81426 14757 52°42′1.9″N 0°41′0.8″E Altitude: 25 m. Address: Castle Acre, King's Lynn, Norfolk, PE32 2XD.

Brief description

Cluniac Priory, 12th to 16th century.

Original building materials

Flint, stone.

Description of the standing remains

Stone-faced, early 12th-century flint-built church and flint monastery with chapter house, dormitory with undercroft, reredorter, and 14th- to 15th-century gatehouse. There are several earthworks and a ruined boundary wall.

The monastery was surrendered to the crown in 1537. The site was scheduled in 1937.

Figure 2.15a Aerial view of Castle Acre Priory. © *Historic England Photo Library*

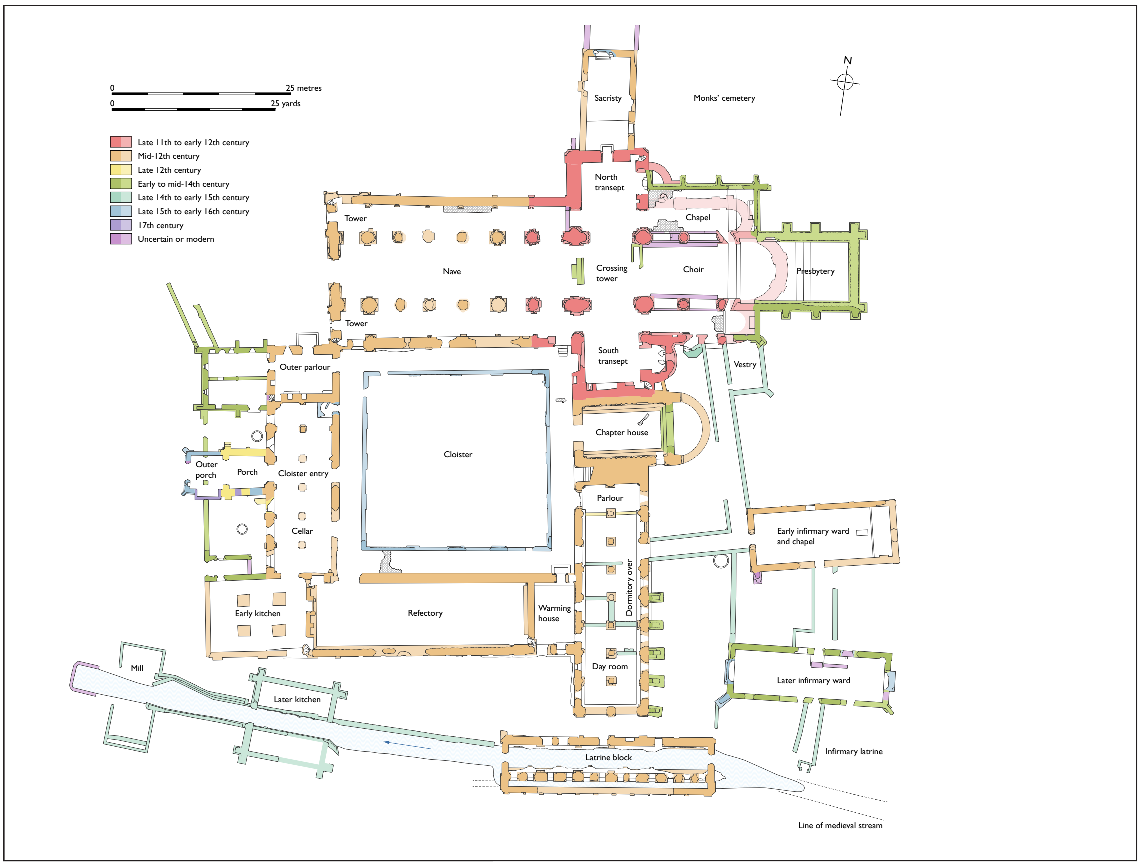


Figure 2.15b Site plan of Castle Acre Priory. ©*Historic England Archive*

Conservation history and current condition

There is evidence of recent lime mortar repointing and hard capping, as well as signs that the hard cap is detaching from the underlying stonework (Figure 2.15c). Soft capping has also recently been installed over the vault.

Capping installed during this research project

The vaulted ceiling of the ground storey in the partially walled and roofless SW church tower had been damaged by water and frost penetration through the concrete floor/covering in the storey above. It was decided to soft-cap the concrete floor.

Even though the tower was roofless, it was felt that the walls were so tall they would prevent enough rain from falling for grass to thrive. A sedum mat was used instead, although there were concerns that the site would be too shady for sedum.

The work was carried out in 2011, and appears to be working effectively (Figure 2.16). By 2013, the sedums appeared to be surviving only towards the edges of the area. By 2015, virtually the whole capping consisted of Pellitory-of-the-Wall (*Parietaria judaica*). This displays the dynamics of soft capping flora, as species suited to the particular conditions dominate. It will be interesting to see if this develops further over time.

Figure 2.15c Detachment of hard capping from underlying low walls, at Castle Acre Priory in 2012. *©Heather Viles, University of Oxford*

Figure 2.16 (a-d) Sedum-based soft capping installed in the SW Church tower. *(a, c, d ©Alan Cathersides, b ©Heather Viles, University of Oxford)*

Three *c*.1-m long strips of soft capping were emplaced on a low (*c*.1 m high) wall constructed of mixed flint, brick, chalk and other stones (Figure 2.17). Strips 1 and 2 were made of 10-cm thick soil and a cover of turf cut from an adjacent field. Strip 1 also had sedum plugs added to the edges at *c*.5 cm spacing. Strip 1 had 10-cm thick soil overlain by a sedum mat, with a range of sedums growing in it (identical to the mats used at Godstow Nunnery). The work was carried out in February 2012. Its aim was to test the comparative performance of turf and sedum capping and evaluate the effect of sedum plugs at the edges of turf capping within a dry environment in eastern England. Small tablets of limestone and gypsum, as well as calcite crystals, were also emplaced under the capping, to test whether the soil enhanced chemical weathering.

Figure 2.17 Soft wall caps installed at Castle Acre Priory, February 2012. ©*Heather Viles, University of Oxford*

2.11 Wytham Woods test walls

Location

In the bow of the Isis River to the northwest of Oxford, between Eynsham, Wytham and Botley in Oxfordshire. Grid Ref: SP462083. Altitude: 70 m.

Brief description

Four test walls built in a research enclosure in a pasture to the East of the Great Wood and North of Marley Wood.

Original building materials

Limestone (Cotswold stone – Grange Hill cream and Oxleas white), cement and hydraulic lime mortar.

Description

In 2008, four stone walls, roughly 1.5-m long by 1-m wide and 2-m high, were built specifically for this project (as seen in Figure 2.18a). The walls were built on a gently sloping open hillside in a fenced-off compound. The walls were constructed with a central rubble core and finished with either a hydraulic lime or cement cap. Lead flashing and guttering were built into the walls on both sides under the second course from the top, to allow runoff to be collected and funnelled off into downpipes and then into measured containers.

Figure 2.18a Wytham Woods test walls. ©*Heather Viles, University of Oxford*

Conservation history and current condition

N/A

Capping installed during this research project

In order to compare the performance of soft vs. hard capping, four walls were constructed in July and August 2008. In November 2008, hard caps were installed on two of the walls, and soft caps on the other two (see Figure 2.18b). Locally sourced turf cut from a nearby field, screened loam soil, and slate chippings were used for the soft capping. Sedum plugs were added to the edges of the turf capping in November 2010.

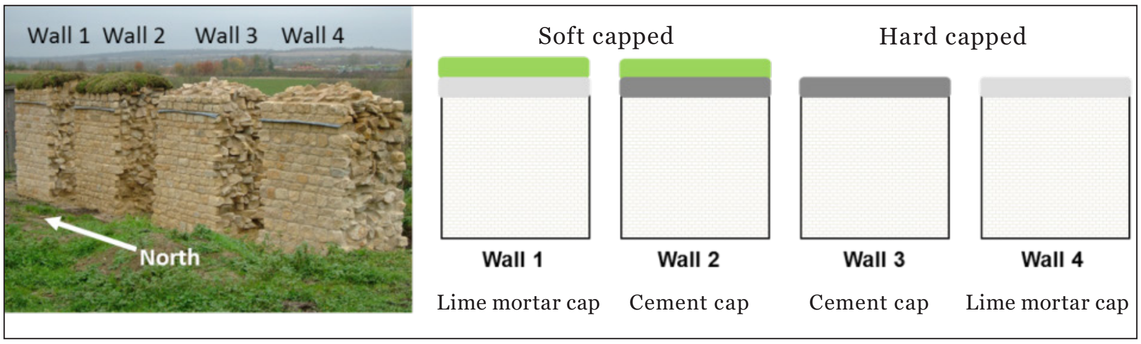


Figure 2.18b Layout and materials used for the test walls at Wytham Woods, near Oxford.

2.12 Other sites

A number of other sites were visited as part of the Soft Capping Research Project as shown in Table 2.2. Some sites had natural soft capping, and others had soft capping that had been installed, as well as other interventions.

Table 2.2

Monument	County	Nature of capping
Jervaulx Abbey	Yorkshire	Natural soft capping and vegetative growth in profusion
Wigmore Castle	Hereford and Worcester	Natural soft capping removed, stored and then replaced on walls by English Heritage between 1997 and 1999
Fountains Abbey	Yorkshire	Rory Ogilvy commissioned soft capping here in late 1980, after previous hard capping had caused loss of historic decorative facework
Corfe Castle	Dorset	The National Trust carefully removed natural soft capping and replaced it in mid 2000s (with earlier turf capping?)
Barton Court, Abingdon	Oxfordshire	Soft capped using commercial turf in 2002
Hemyock Castle	Devon	Soft capped with commercial turf in 2005
Garrison Walls, St Mary's	Scilly Isles	Soft capped in 1992
Southwell Bishops Palace	Notts	Soft capped in 2013
Sherborne Old Castle	Dorset	Steps soft capped with membrane
North Leigh Roman villa	Oxfordshire	Part of site soft capped in 2009
Sandsfoot Castle, Weymouth	Dorset	Soft capped around 2010
Craswall Priory	Herefordshire	Soft capped with membrane
Thirlwall Castle	Northumberland	Soft capped in 2000 and 2001
Myross	Co Cork, Ireland	Natural soft capping
Smailholm Tower	Kelso, Scotland	Barrel roof soft-capped by Historic Scotland (now Historic Environment Scotland) in 2011-12

References

Historic England 2012 *Strategic Stone Study: A building stone atlas of North Yorkshire East and York,* available on https://www.bgs.ac.uk/mineralsuk/buildingStones/StrategicStoneStudy/EH_atlases.html

Jefferson, D 2006 'Byland Abbey, North Riding of Yorkshire. An overview of the stone use in the construction of the abbey and the implications for 'soft capping''. *English Heritage Research Report C/300192/A/001*

3 MATERIALS AND METHODS

3.1 Introduction

This chapter details the materials and methodologies employed during laboratory experiments and field tests. Methods for constructing soft and hard caps are reviewed in Chapter 6. The thermal blanket (research question 1) and moisture control effects of soft capping (research question 2) were examined both in the laboratory and onsite. Additionally, the performance of soft capping over time (research question 3) was monitored in the field (see Figure 1.17 for summary of the different experiments, field tests and field monitoring).

3.2 Laboratory testing

3.2.1 Thermal blanket effect of soft capping

Materials and methods

Laboratory experiments to evaluate the thermal blanketing roles of hard and soft capping followed the methodology developed in the pilot study (Viles et al., 2002). Stone slabs (*c*.240 x 240 x 30 mm) with insulated sides and bottoms were placed in boxes (perspex or wire) and covered with soft (usually 5 or 10 cm thick, some 15 or 20 cm thick) or hard caps (*c*.10 cm thick). Most of the experiments were carried out using weathered stone from the store at Kirkham Priory, although some experiments used freshly cut samples of local stone used for recent repairs at Hailes Abbey (obtained from the quarry). The experiments also employed turf cut onsite at Kirkham Priory and the same types of soil and slate fragments used for the field trials. The hard cap was built using lime mortar and small blocks of stone from the store at Kirkham Priory by Colin Burns, using NHL 3.5 mortar from St Astier (1:1 ratio).

In the pilot study, Perspex boxes of around 30 x 30 x 30cm in volume (with open tops and holes cut in the sides to allow ventilation) were used to house the experimental blocks and cappings. Wire boxes, (which prevent ponding of water and allow better airflow around the turf) were also used. Preliminary results showed no significant difference between comparable soft or hard caps in Perspex and wire boxes.

In order to monitor the impact of the capping on thermal regimes, a flexible temperature probe connected to a data logger was placed on each stone block. Temperatures were recorded at regular intervals (in this case every 15 minutes) by Tinytag surface thermistor probes connected to Tinytag data loggers (all equipment supplied by Gemini Data Loggers). The data was then stored for later analysis. Figure 3.1 shows the experimental set up for soft, hard and uncapped stones.

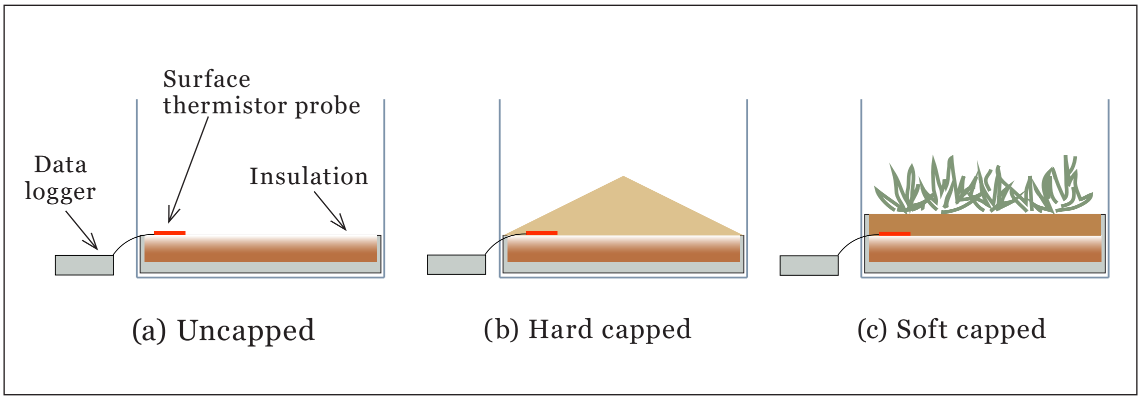


Figure 3.1 Experimental set-ups used in the thermal blanketing experiments.

A number of experimental runs were carried out in a Sanyo-FE 300H/MP/R20 environmental cabinet that can be programmed to cycle through a wide range of temperatures and relative humidities to simulate external conditions. Two cycles were devised. The first, known as the 'Standard cycle' (as used in the pilot study), was based on 1999 data from the Oxford Radcliffe Meteorological Station to simulate the full range of conditions experienced by wall tops from a cold January night to a hot July day. During this cycle, temperatures went from -1.5°C to 30°C over a 24-hour period, with concomitant changes in relative humidity. The second cycle, known as the 'Intense cycle,' was designed to simulate conditions during winter cold spells, with temperatures cycling from 5°C to -5°C over a 24-hour period. In both cases, temperatures ramped up and down at realistic rates. While the cycles were also designed to replicate realistic relative humidity trends over 24 hours, this (RH) proved much harder to control, as the large amounts of turf and soil placed in the cabinet meant that the RH rose beyond programmed levels.

A further experiment was also carried out. This was known as the 'Long term field experiment'. Three of the boxes were placed on the roof of the School of Geography and the Environment for 1 year (5-cm and 10-cm thick soft caps and 5-cm hard cap) the soft-capped boxes were tested in the environmental cabinet before and after the year-long exposure period to see if there was any change in performance as the cap matured (Figure 3.2).

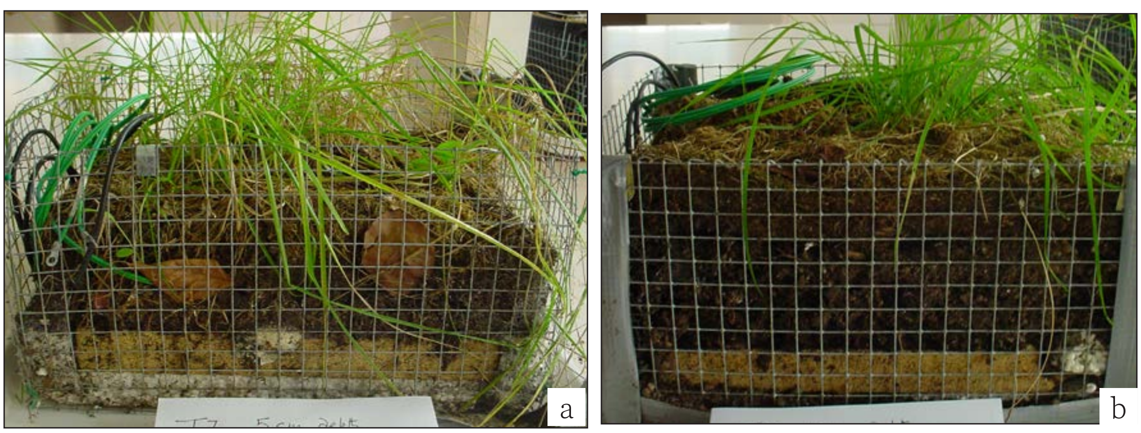


Figure 3.2 (a) 5-cm and (b) 10-cm thick soft caps after the 'Long term field experiment'. ©*Heather Viles, University of Oxford*

It was only possible to use a maximum of 4 boxes within the environmental cabinet in each experimental run because of their relatively large size. Experiments were run for a minimum of 3 cycles and a maximum of 5, with the first 6–7 hours used for equilibration. Figure 3.3 presents a schematic view of the experiments and the set-up of stone, capping and box used in each one. Initial testing showed there was a good comparability in performance of the boxes between experiments so that meaningful conclusions could be drawn.

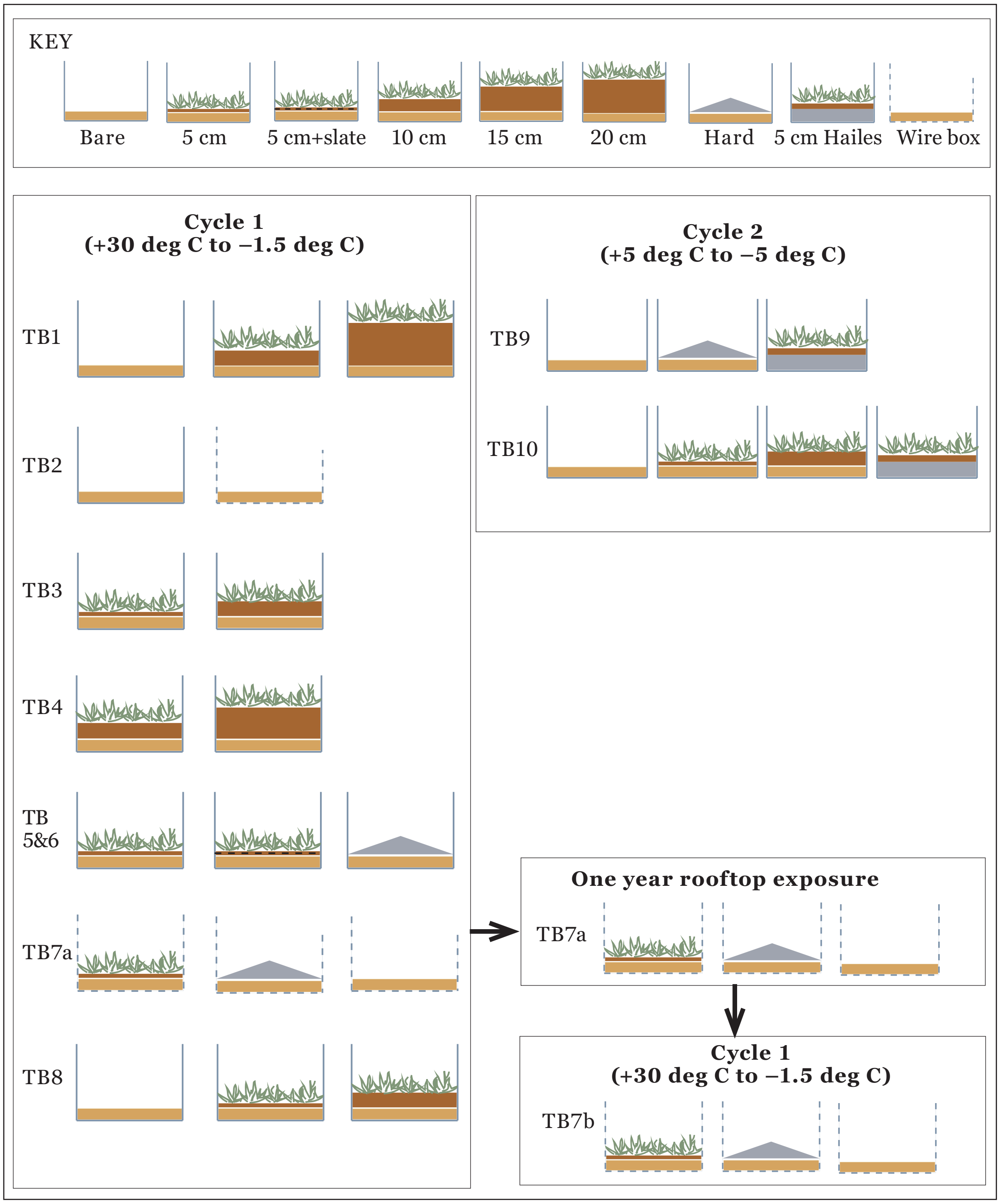


Figure 3.3 Thermal blanket experimental runs.

Cement mortars have low coefficients of thermal expansion in comparison with many stones and lime mortars. Thus cement-capped walls will expand and contract differentially, leading to cracking. We hypothesised that in walls that contained stones with high thermal expansion coefficients, soft capping could reduce damage by moderating temperature extremes at the wall-head.

There were clear signs of cracking at several sites. They appear to have resulted from uneven thermal expansion and contraction of stonework that had been consolidated and hard-capped. In order to determine whether soft capping could stabilise environmental conditions at the wall-head, the thermal expansion characteristics of major stone types found at Hailes Abbey, Kirham Priory and Byland Abbery were studied.

To assess the thermal expansion characteristics, a modified version of the standard Nordtest methodology was applied to test specimens of stone of known dimensions (15 x 3 x 2.5 cm), from Kirkham, Byland and Hailes (Figure 3.4). The aim was to measure how much a block expands when its temperature is raised by 1 degree C.

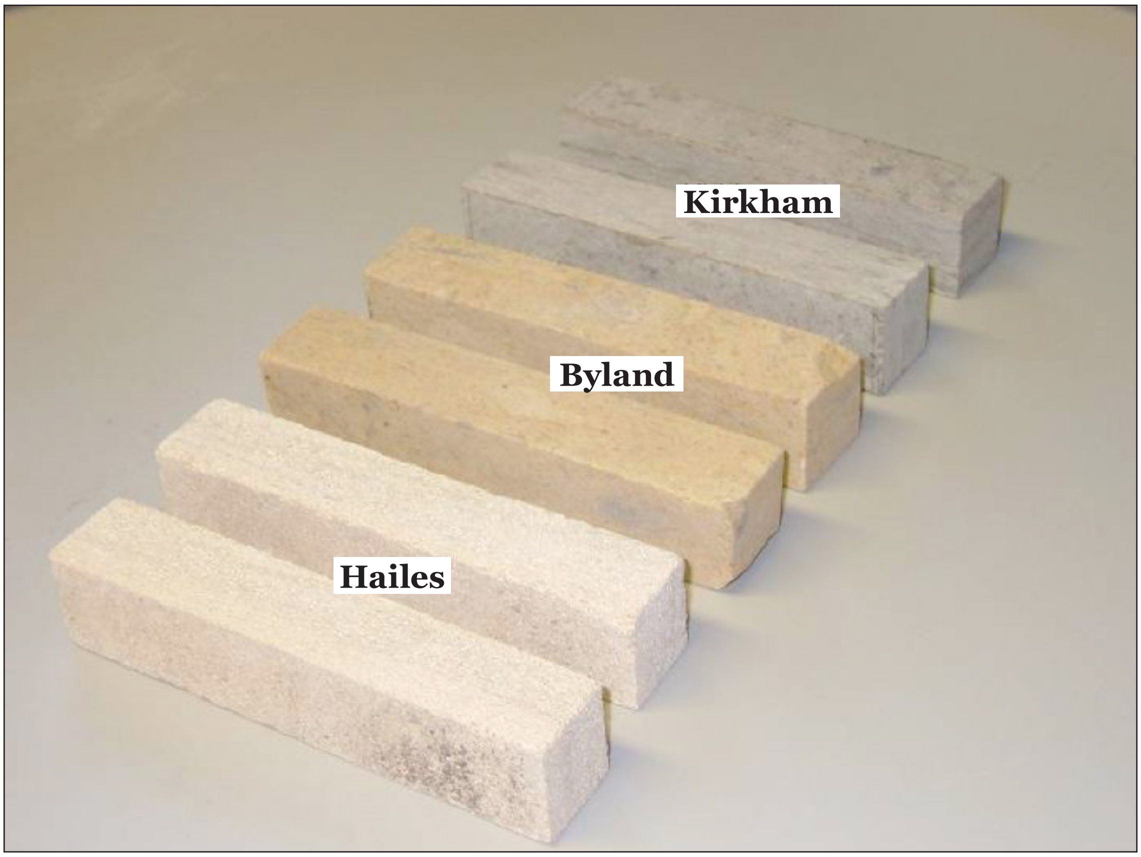


Figure 3.4 Test blocks used in the thermal expansion experiment.
©Heather Viles, University of Oxford

3.2.2 Moisture barrier effect of soft capping

Two sets of simple laboratory experiments were carried out to evaluate the success of soft capping in providing a moisture barrier. These experiments proved to be challenging to run, and produced frustratingly little useful data. The first experiment investigated how soft capping might prevent water escaping from the underlying wall through reducing drying rates. The second focused on the effectiveness of soft capping in reducing water penetration into the underlying wall.

(a) Soft capping and drying rates

Materials and methods

This experiment used stone obtained from Byland Abbey, Hailes Abbey and Kirkham Priory, cut to approximate dimensions 240 x 240 x 30 mm. Each stone slab was placed in a wire box (as described in section 3.2.1. above) and either left uncovered or covered with soft capping. The soft caps were made with the same type of soil used in the field trials and turf cut at Kirkham Priory. The boxes were placed on a high capacity (up to 600 kg), high accuracy (to 10 g) balance (Sartorius, isi20) so that drying rates could be monitored (using weight change as a measure of moisture loss). A fan was used to enhance drying from the bare stone/ grass surface. Each run lasted at least four days, or until the drying rate had levelled off (a week in the case of the soft-capped stones). In addition, wetness at the stone surface was measured with leaf wetness sensors (impedance grid sensors, supplied by Gemini Data Loggers). The following sequence of experiments was run (totalling 26 runs):

- Blocks of Byland, Kirkham and Hailes stone without capping (bare stone) that had been soaked (without insulation around the sides and base).
- Blocks of Byland, Kirkham and Hailes stone without capping (bare stone) that had been soaked (with insulation around the sides and base).
- Blocks of Byland, Kirkham and Hailes stone that had been soaked and then covered with a 5-cm thick soft cap (soil and turf).
- Blocks of Byland, Kirkham and Hailes stone that had been soaked and then covered with a 10-cm thick soft cap (soil and turf).
- Blocks of Hailes stone that had been soaked with 5-cm and 10-cm soft cap (newly made) and 5-cm and 10-cm thick old soft caps (that had been used in the year-long roof top thermal blanketing experiment).

(b) Soft capping and water penetration

This experiment was designed to test the effectiveness of soft caps of varying thicknesses (5 and 10 cm) and age (fresh and those after one year of growth on the roof) in preventing rainwater penetration to underlying stone. In Chapter 1, it was suggested that soil and vegetation act as a sponge by soaking up rainfall for plant growth. The thicker and more established caps that have a good root network should be better at retaining moisture and stopping it from penetrating into underlying stone.

Materials and methods

Soft caps were constructed in wire test boxes of approximately 300 x 300 x 150 mm dimensions (as used in thermal blanketing and drying rate experiments). Damp soil was used. Two sets of experiments were run. One used 5- and 10-cm thick soft capping, with grass newly cut from Kirkham Priory and the standard soil type used in the field trials. The second used 5- and 10-cm soft capping that had previously been exposed for 1 year as part of the rooftop experiment. The soils were placed in the boxes without any underlying stone or insulation. A geotextile was placed under and around the sides of the soil to prevent it from falling out of the wire box.

When cobalt chloride comes in contact with water, it turns from blue to purple or red. In order to monitor water penetration through the soft caps, cobalt chloride paper was placed in a tray under the wire-box containing the soft cap. A drip-type rainfall simulator (constructed in SOGE laboratories with 0.7 mm inner dimension Tygon tubing and 0.55 mm thick fishing wire [Bowyer-Bower and Burt, 1989]) was used to sprinkle drops on the boxes. Photographs of the cobalt chloride paper were taken at 5 second intervals to record the timing and spatial patterning of water penetration (Figure 3.5). In total, 15 experimental runs were carried out.

Results

There were several problems encountered during these experiments. In particular, water leakage down the sides of the wire box was often a serious problem, and the rainfall simulator produced rain of much higher intensity than is usually found in the UK. Due to these flaws, and the complex data that was collected (each run displaying very different behaviour, even when using the same thicknesses of soft capping), the results are not presented in detail in this report.

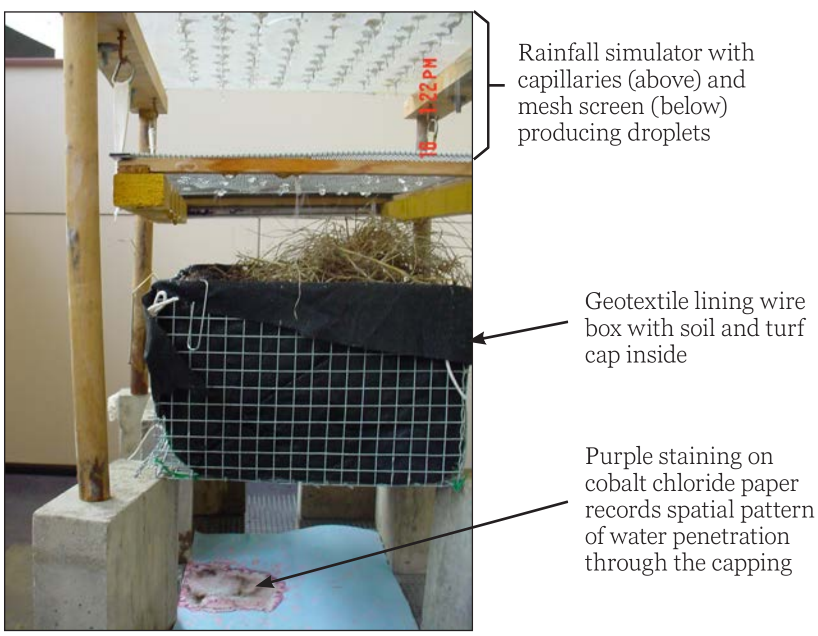


Figure 3.5 Water penetration experiment in action with 10-cm thick new soft capping. ©*Heather Viles, University of Oxford*

3.3 Field instrumentation

Four sites were chosen for detailed field-testing of the thermal blanketing and moisture barrier properties of soft and hard capping.

At Byland Abbey, three methods of monitoring were employed. Part of the wall bordering the west side of the cloisters (called 'the lane') was monitored using a telemetric data logging system to investigate temperature and moisture conditions at the base of soft and hard capping; wooden dowels and 2D resistivity surveys were used to monitor moisture levels in the lower areas of the walls.

At Hailes Abbey, dowels and 2D resistivity surveys were used to monitor moisture conditions in a wall that had been scaffolded and covered (and thus dried) for two years before the installation of soft capping.

At the test site at Wytham Woods near Oxford, four test walls were built specifically for this project, and their moisture contents monitored using 2D resistivity surveys and wooden dowels. Monthly Protimeter surveys recorded the surface moisture conditions of the walls, and guttering was used to collect runoff from the face in a series of field experiments. In order to provide preliminary data on the comparative chemical impacts of soil water and rainwater on underlying stone, field experiments were carried out, using blocks of Cotswold limestone (Oxleas White) and calcite crystals.

Finally, field experiments were carried out at Castle Acre Priory using calcite crystals and small tablets of limestone and gypsum to determine if soft capping causes or increases chemical weathering.

3.3.1 Byland Abbey

As described in Chapter 2, soft capping trials were installed on the lane wall at Byland Abbey. The trials included 6 sections of different soft capping treatments, as well as one hard-capped section and one area left without any capping. Figures 3.6 and 3.7 illustrate the location of the telemetric data loggers and probes, the wooden dowels and the 2D resistivity surveys.

(a) Temperature and moisture data collection – telemetric data logging system

A telemetric data logging system was installed (see Box 3.1) to collect and store data on the temperature and moisture conditions at the base of the soft capping and within the hard capping. The system used pairs of small temperature and soil moisture probes connected by wire to data loggers set to record at 30-minute intervals. The data loggers transmitted wirelessly to a base unit. Pairs of probes were placed at the base of the soft capping. The soil moisture probe built into the mortar of the hard cap (some 15 cm below the surface), and the temperature probe was located under one of the smaller stones within the upper part of the cap (some 5cm below the top of the capping). Figure 3.6 shows the location of the probes.

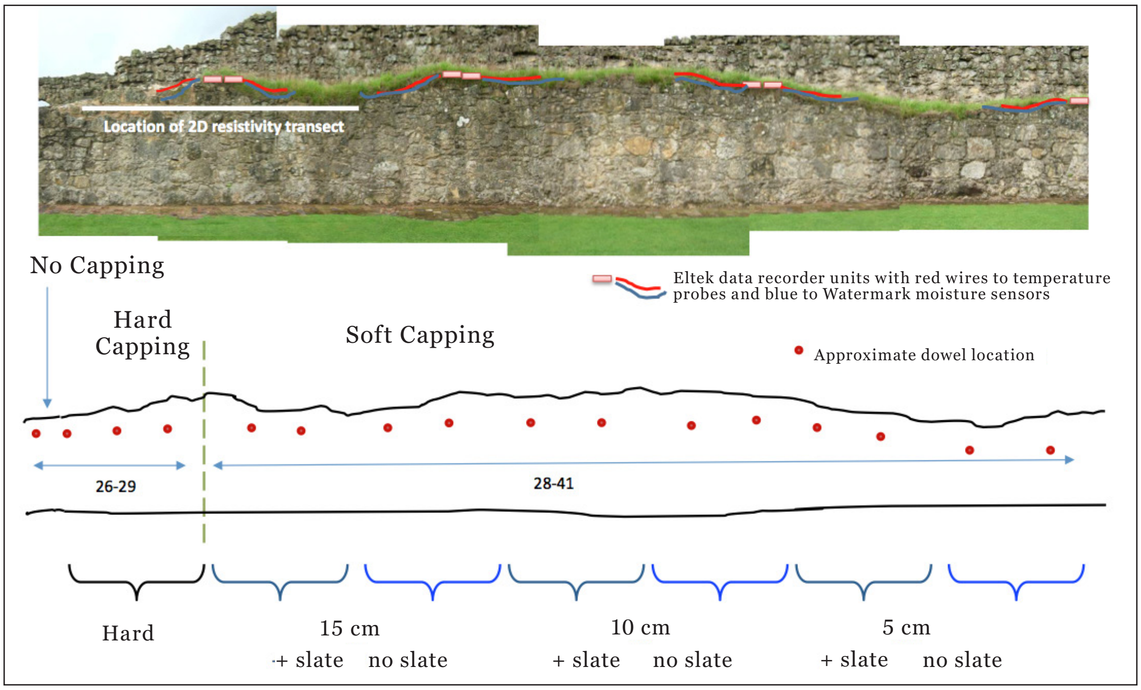


Figure 3.6 Location of the telemetric logging system, 2D resistivity surveys and wooden dowels, east facing side of the lane wall, Byland Abbey. ©*Heather Viles, University of Oxford*

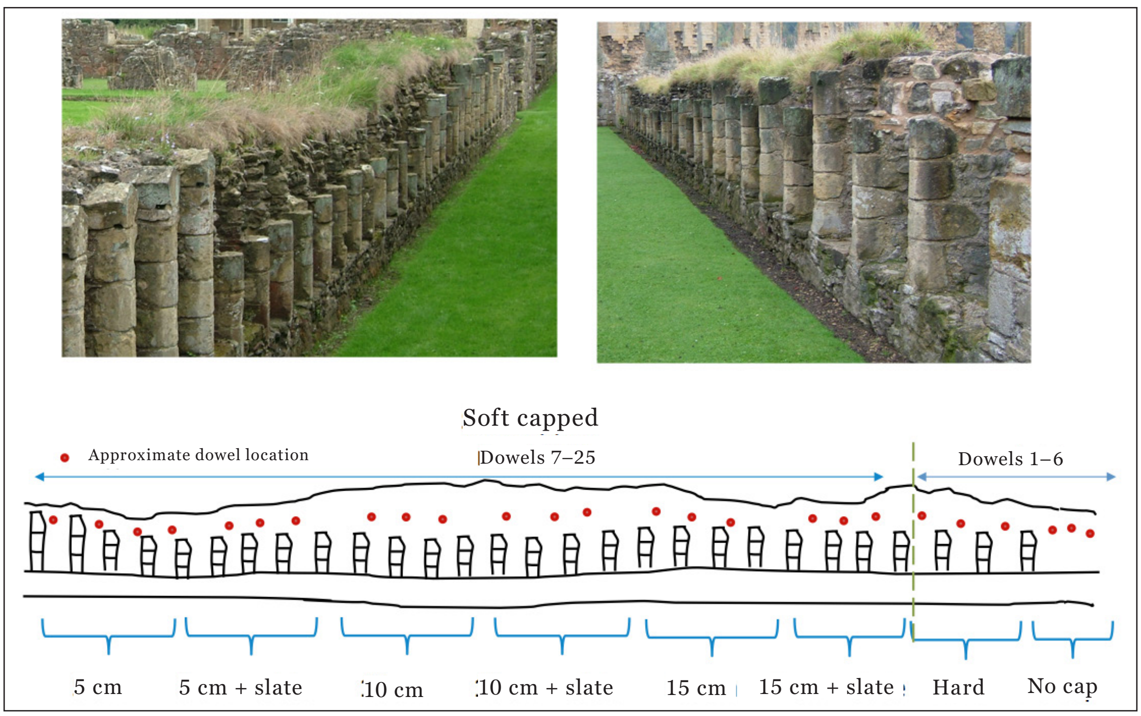


Figure 3.7 Location of wooden dowels, westfacing side of Lane wall, Byland Abbey. ©*Heather Viles, University of Oxford*

Data was collected over a one-year period from all soft and hard capped sections (from Feb 2005 to Jan 2006). Additional data was collected from the hard capped section, and the 5, 10 and 15 cm thick soft capping sections containing slate fragments for a further six month period, from Feb 2006 to July 2006, giving 18 months data in all. Some data gaps occurred as a result of equipment failure.

(b) Wooden dowels

Forty-one wooden dowels, each 40 cm in length, were installed in the wall at Byland Abbey between 15 and 40 cm below the wall-head, with 25 dowels on the west facing side and 16 on the east facing side(as laid out in Figures 3.6 and 3.7.) The protocol described in box 3.2 was used to install and monitor the dowels. Dowels were installed in autumn 2004, and data collected at roughly monthly intervals until January 2006.

Box 3.1 Monitoring temperature and moisture in soft and hard capping

Monitoring temperature and moisture conditions in different types of capping is important for comparing their effectiveness. However, it is not always practical to remain on site to collect information. This is especially true when the remoteness of the site makes constant monitoring difficult. A telemetric data logging system is a good solution to this problem. It collects data regularly and sends it wirelessly to a base unit, which in turn sends it via a phone line to the researcher.

At the Byland site a bespoke telemetric data logging system (Eltek) was connected to small thermistor temperature probes (Campbell) and Watermark soil moisture probes (Irrometer) set to record at 30-minute intervals. Watermark sensors are composed of two concentric electrodes buried in a reference matrix material and surrounded by a synthetic membrane (to protect against deterioration). An internal gypsum tablet provides a buffer against salinity. The Watermark probes are temperature-sensitive, and need a simple temperature correction to be applied. Output in microsiemens can be converted to soil water potential in KPa. The base unit was a 1000 series Squirrel data logger.

Figure 3.8 Emplacement of the Watermark sensor in the hard capping at Byland Abbey. © *Chris Wood, Historic England*

Box 3.2 The Oven Balance (Wooden dowels) methodology (BRE Digest 245)

This is a commonly used technique to monitor moisture levels in walls. This research employed 40 cm long dowels of 6 mm diameter, fitted with wire at one end for ease of removal from the wall. Dowels were inserted into *c*.9 mm diameter holes, drilled into mortar joints, in order to allow space for swelling of the dowels as they become wet in contact with the damp stonework. The dowels were left in place to absorb water over time (usually 4–6 weeks), before they are removed and replaced by fresh, dry dowels. Once removed the dowels were tightly wrapped in cling film to retain moisture and transported to the laboratory, where moisture contents were calculated on the basis of moisture mass gain in the dowels (compared to their dry weight). In order to obtain information on moisture contents at different distances inside the wall each dowel was divided into four 10-cm sections (Figure 3.9). These values were then aggregated in order to produce summary measurements of moisture gain values for the entire dowel.

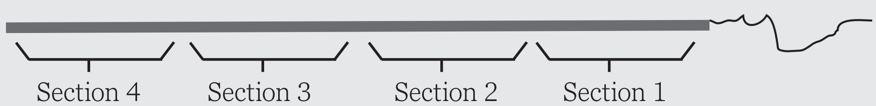


Figure 3.9 A wooden dowel showing the locations of the four sections.

(c) Probing moisture in walls: 2D resistivity surveys

Resistivity provides a proxy measure of moisture contents, as moisture levels largely control the electrical resistance of a porous material. Salinity, temperature and porosity also influence the resistivity values obtained. 2D resistivity surveys using GeoTom equipment from Geolog2000 were carried out in April 2005 and September 2006 to assess moisture levels within stonework under hard and soft capping (Figure 3.10) An array of 100 electrocardiogram (ECG) electrodes was stuck temporarily to the stonework across a 6 m profile on the east-facing side of the Lane wall (see Figure 3.6) at 6 cm intervals along a transect at the same height as the dowels under both hard-capped and 15 cm soft capped sections. This array allowed an assessment of the moisture conditions up to 40 cm inside the stonework. This technique has been used in other studies of historic walls (Sass and Viles 2010a and 2010b), and details of methodology and preliminary results from Byland Abbey published in Sass and Viles (2006).

Figure 3.10 2D resistivity survey on the east face of the long test wall at Byland Abbey. The blue dots are adhesive ECG electrodes. The left-hand side is the hard-capped section. © *Chris Wood, Historic England*

3.3.2 Hailes Abbey

A long stretch of the cloister arches at Hailes Abbey was used for experimental soft capping, as explained in Chapter 2. Dowel monitoring started here in April 2004 and finished in September 2006. The northern section had been scaffolded and covered for 18 months previously as part of ongoing conservation work, and had probably dried to equilibrium. It thus offered an excellent opportunity for monitoring moisture contents in both dried and normal conditions before the soft capping trials started. A total of 56 dowels were emplaced at around 10 to 40 cm below the wall-head (14 each on the scaffolded west facing and east facing sides, and 14 each on the unscaffolded west and east facing sides). Soft capping was installed on the previously scaffolded section in January 2005. A suite of 28 additional dowels (14 on east facing and 14 on west-facing sides) was emplaced in January 2005 at the northerly end of the soft-capped section. Figures 3.11 and 3.12 depict the layout of the dowels. As at Byland, dowels were removed and new ones replaced approximately every month. Moisture contents were measured gravimetrically for every 10-cm section of each dowel.

2D resistivity surveys using the Geotom equipment were also carried out between March and May 2005 on the west and east-facing sides of the wall, just as was done at Byland Abbey. Two horizontal profiles were measured at about 20–25cm below the wall head, covering sections of both soft-capped and uncapped wall. One vertical profile was also measured on the east-facing side under the soft capping. Each profile consisted of 50 electrodes, and measured almost 3 m in length (6-cm electrode spacing). The location of the 2D resistivity surveys is shown in Figures 3.11 and 3.12.

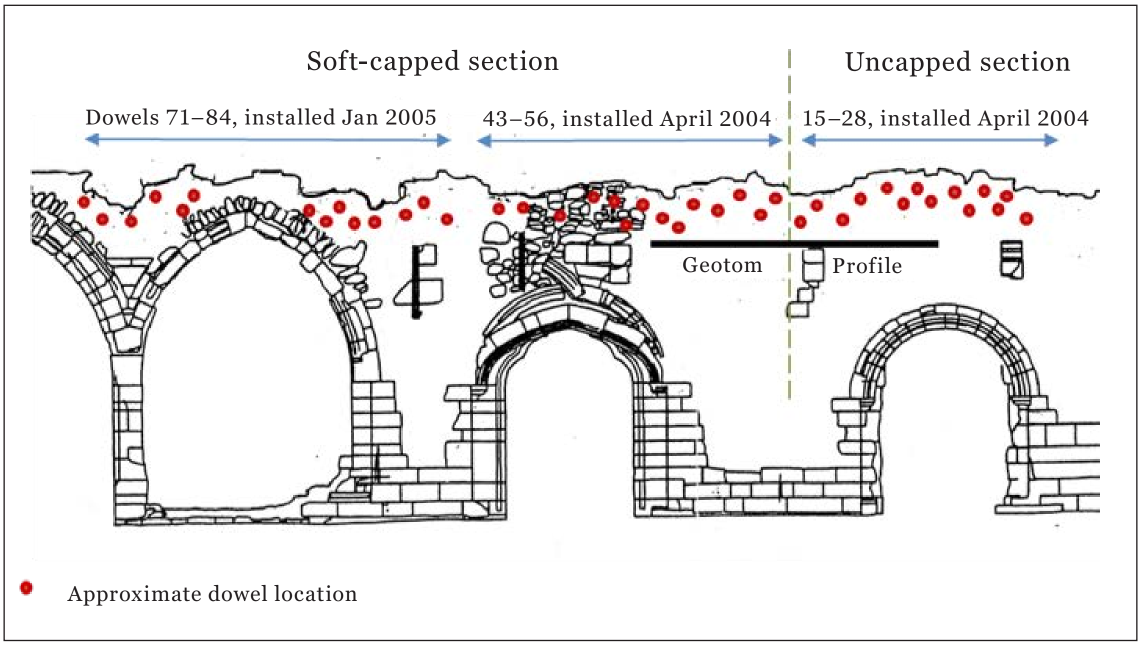


Figure 3.11 Location of wooden dowels and 2D resistivity profile, west-facing side, cloister arches, Hailes Abbey.

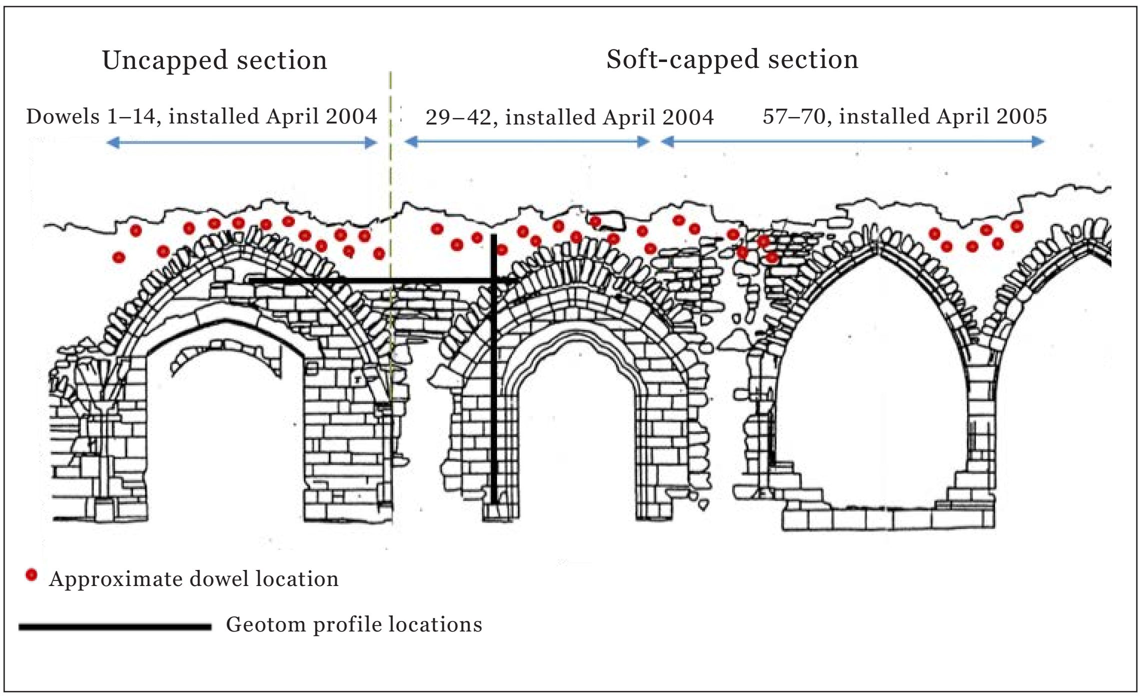


Figure 3.12 Location of wooden dowels and 2D resistivity profiles, east-facing side, cloister arches, Hailes Abbey.

3.3.3 Wytham Woods test walls

Four test walls were built at Wytham Woods specifically to compare soft and hard capping, as documented in Chapter 2. A range of field monitoring methods was deployed on the test walls. First, there were moisture measurements with wooden dowels, 2D resistivity surveys, Watermark probes, and surface moisture surveys using the Protimeter to evaluate the impacts of hard and soft capping within the walls. Then, there were test substrates (calcite crystals and limestone blocks) to evaluate the impact of soft capping on soil acidity and weathering of wall heads. And finally, there were runoff collection after storms and experimental rainfall application to test how well both soft and hard caps reduce runoff down the wall face.

(a) Dowels and 2D resistivity measurements

Wooden dowels were emplaced in each of the four walls to provide monthly measurements of the moisture contents. As at Byland and Hailes Abbeys, 9-mm diameter holes were drilled to depths of just over 40 cm to allow insertion of 6-mm diameter wooden dowels of 40 cm length. Four pairs of dowels were inserted in each wall at different heights above the ground on both east- and west-facing sides (see Figure 3.13). Dowels were collected at approximately monthly intervals, cut into 10-cm sections and moisture contents derived gravimetrically. A new set of dowel holes was installed in April 2013 to provide more detailed information on moisture conditions within the upper parts of the walls. Dowel surveys began in April 2009 and continued until April 2014.

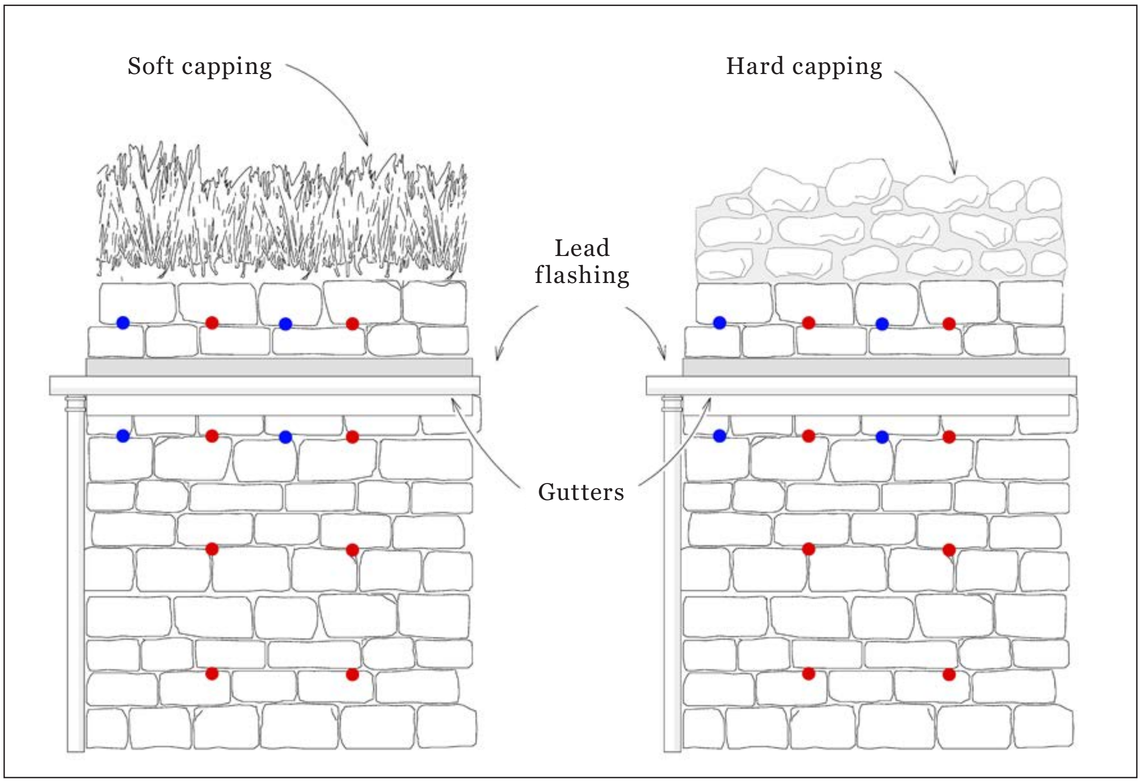


Figure 3.13 Diagrams of the test walls, showing the position of initial dowel arrays (red circles) and later additions (blue circles), and the presence of lead flashing. *Iain McCaig, ©Historic England*

To provide more detailed spot measurements of the moisture regimes inside the four walls, 2D resistivity surveys were carried out using the Geotom equipment in June 2010 and February 2012 to capture conditions in summer and winter. One vertical transect was taken down the middle of each face of each wall. Approximately 40 electrodes were used (the exact number depending on the exact height of the individual wall) at 4 cm spacing, giving a penetration into the wall of around 20–40 cm (depending on the array used). Additionally, at the time of measuring these profiles, a Protimeter reading (as described below) was taken adjacent to each medical electrode to give a summary picture of surface moisture levels along the profile.

(b) Surface moisture surveys

In order to provide data on surface moisture conditions, monthly surveys using handheld moisture meters were carried out on each wall from July 2009 to January 2012, and then from April 2013 to January 2014. The entire wall was surveyed on both sides for the first survey. For the second, only the top four rows of stone were surveyed. The equipment used was a Surveymaster Protimeter (model BLD5360) in resistance mode.

Although the Protimeter was designed to measure moisture levels in wood, research has shown it also gives reliable measurements of the surface moisture conditions of limestone (Eklund et al., 2013). As Protimeter data are recorded in units of %WME (i.e. wood moisture equivalent which can be conceptualised as the % moisture contained in a wooden block in hygric equilibrium with the stone surface), they are an indirect measure of real moisture levels. Calibration curves can be produced using gravimetric methods to calculate the absolute % moisture contents for individual limestone types corresponding to the measured %WME values.

A detailed plan showing the location of each limestone block was drawn up. This was used to enable protimeter readings to be taken at the centre point of each stone block on the survey dates (Figure 3.14). The contour plots of moisture were then recorded with SigmaPlot software.

Figure 3.14 Location of points for Protimeter surveys, July 2009 to January 2012 on wall 1 as an example of the method used on both sides of each wall. ©*Heather Viles, University of Oxford*

(c) Monitoring moisture levels in the soft capping

A network of 9 Watermark soil moisture probes (Irrometer) was deployed from April 2009 to April 2013 in the soft capping on wall 1. The Watermark probes were placed at the base of the soil (as they were at Byland Abbey) to capture conditions at the interface with the wall-head. Telemetric data logging was not available here, and so the probes were recorded manually every four weeks or so to provide spot measurements. The 9 probes were emplaced in three rows crossing the wall from west to east, towards the north, south and middle of the wall-heads.

(d) Monitoring water runoff down the face of the walls

A simple system of lead flashing, guttering and downpipes was developed on the Wytham Woods test walls to test the comparative ability of soft and hard capping to influence water flow down the face. A 2-lb lead flashing was built into the mortar joint two courses below the wall-head on the east and west faces of each wall. Immediately below this flashing, half-round guttering (8 cm wide and 3.5 cm deep) was fixed (see Figure 3.15) to wooden boards. This enabled water to run easily down the face whenever it rained and be collected in the guttering. At the left-hand end of each gutter, a downpipe was installed, which discharged into a securely fixed bottle to collect all the harvested rainwater. (Figure 3.16).

Two methods were used to evaluate the impacts of soft and hard capping on runoff. First, natural rainfall events were used to measure the response of the walls in the period between August 2010 and September 2012 The bottles were emptied every few weeks, and when possible, after every incidence of heavy rain. The volume of water collected was measured with a measuring cylinder. Sometimes the bottles had filled up before they could be collected, so this method provided a rather imperfect record of rainfall/runoff relations.

Figure 3.15 Guttering with lead flashing to collect runoff. *©Heather Viles, University of Oxford*

Figure 3.16 (a, b) The test walls with guttering installed,and the set up for collecting runoff in a container, which was then emptied and measured at regular intervals between August 2010 and September 2012. ©*Heather Viles, University of Oxford*

The second method of collecting runoff information utilised a field experimental approach described in detail in Hanssen and Viles (2014). These experiments were carried out during a dry spell in July 2013. In each experiment, 1 litre of water was sprayed with a 5 litre pressurised sprayer over the entire length of one of the wall caps (focusing on a 20-cm wide belt from the edge towards the centre). Each simulation delivered 2.2 mm of rainfall, which is equivalent to an hour of moderate rainfall in England. Five experimental runs were carried out on both sides of the two soft-capped walls, as well as on the cement-capped wall 3, giving a total of 30 experiments. A second gutter (slightly above, and 1 cm further away from the wall than the original gutter) that fed into a separate bottle (Figure 3.17) enabled researchers to monitor both runoff and water shed away from the face. Moisture measurements before and after experimental runs were made with a ThetaProbe soil moisture sensor ML2x (Delta T devices) in the soft capping, and with a CEM handheld moisture meter on the hard-cap surface and all wall faces.

Figure 3.17 (a) Layout of the two-gutter system to collect runoff and shed water separately (b) spraying in action on the cement hard cap. ©*Heather Viles, University of Oxford*

(e) Assessing the chemical weathering effects of soft capping

All four test walls were used for this experiment, which was designed to test the relative amounts of chemical weathering occurring on stone in contact with rainfall and stone beneath the soft capping. Twenty calcite crystals (calcite being the major mineral in limestone) were cleaved from large pure crystals to produce fresh-faced crystal of *c*.2 x 2 x 2 cm dimensions. The crystals were dried, air brushed to remove any surface debris, and weighed on a high accuracy balance (Sartorius, BL120S) to an accuracy of 1/10,000 of a gram. The crystals were then carefully sealed into individual bags and transported to the field site, where 5 were installed on each test wall in November 2010. The crystals were carefully placed at the bottom of the soft capping on test walls 1 and 2 by digging small pits in the soil while they were stuck onto the hard capping of test walls 3 and 4 with bathroom sealant (bathroom sealant provides a semi-permanent bond that should be removable when the experiment ends; see Figure 3.18). All crystals therefore had one face in contact with the underlying stone (or sealant), and 5 faces in contact with soil (in the case of soft caps) or air (in the case of hard caps). Crystals were collected and reweighed in May 2012 after 18 months of exposure to detect any weight loss caused by dissolution of the calcite by soil moisture (in the case of soft caps), or rainfall (in the case of hard caps).

Figure 3.18 The emplacement of calcite crystals at the base of small pits dug in the soft capping on (a) wall 1 and (b) wall 2, and stuck to the top surface of (c) wall 3 and (d) wall 4. See text for further details. ©*Heather Viles, University of Oxford*

3.3.4 Wytham Woods test blocks: Optical scanning to evaluate any chemical weathering impacts of different soft capping types

Limestone is susceptible to the chemical weathering process of dissolution, in which calcium carbonate is dissolved by water enriched with acid. Rainfall is naturally acidified by carbon dioxide, and water often becomes more acid as it reacts with higher carbon dioxide concentrations within the soil. By measuring the weight and volume loss of bare limestone blocks and blocks covered by soft capping, it was possible to monitor the different rates of chemical weathering (see Box 3.3).

For this experiment, eight test blocks of the same limestone used to construct the test walls (Cotswold limestone Oxleas white) were cut to approximate dimensions 25 x 25 x 10 cm. The surface of each block was similar in finish and roughness to the blocks used in the wall faces. At the start of the experiment, all the blocks were carefully cleaned with a stiff brush to remove any debris. A number of rustproof screws were fitted into the sides of each block to provide fixed points against which any change over time could be measured. Each block was then scanned, using high resolution optical scanning by Sam Jackson of Inition Ltd., to provide a high resolution topographic 'map' of the top surface. This produced detailed digital elevation models of the surface of the blocks (scans using between 700,000 and 2,500,000 measurement points per scan, which has a potential 0.05 mm accuracy). The screws acted as the fixedreference points from which changes to surface elevation resulting from the field exposure could be assessed.

After initial scanning, six of the blocks were covered with different soft capping types (as detailed below), while blocks 7 and 8 were kept bare (Figure 3.19). Block 8 was kept in the laboratory as a control, whilst block 7 was left out at Wytham Woods with the others, to record any chemical weathering effects of direct rainfall. Blocks were emplaced in December 2008 and removed and rescanned in January 2010.

Box 3.3 Wytham test blocks: Selection of materials and soft capping designs

Three different soft capping types were trialled, each with and without water-holding gel. Each block was firstly insulated around the sides and base with polystyrene. Following this, the commercial turf, seeded mat or sedum mats were placed upside down with a narrow strip resting on two opposite sides of the top surface of the block. A layer of screened loam soil approximately 5cm thick was then added across the whole of the top surface, anchoring the edges of the soft capping mats. Each mat was then gently bent over to cover the soil entirely, and pegged into place with small bamboo sticks. The blocks were left near the test walls on a pallet, with a tarpaulin sheet under and around them to prevent them becoming overgrown by native vegetation.

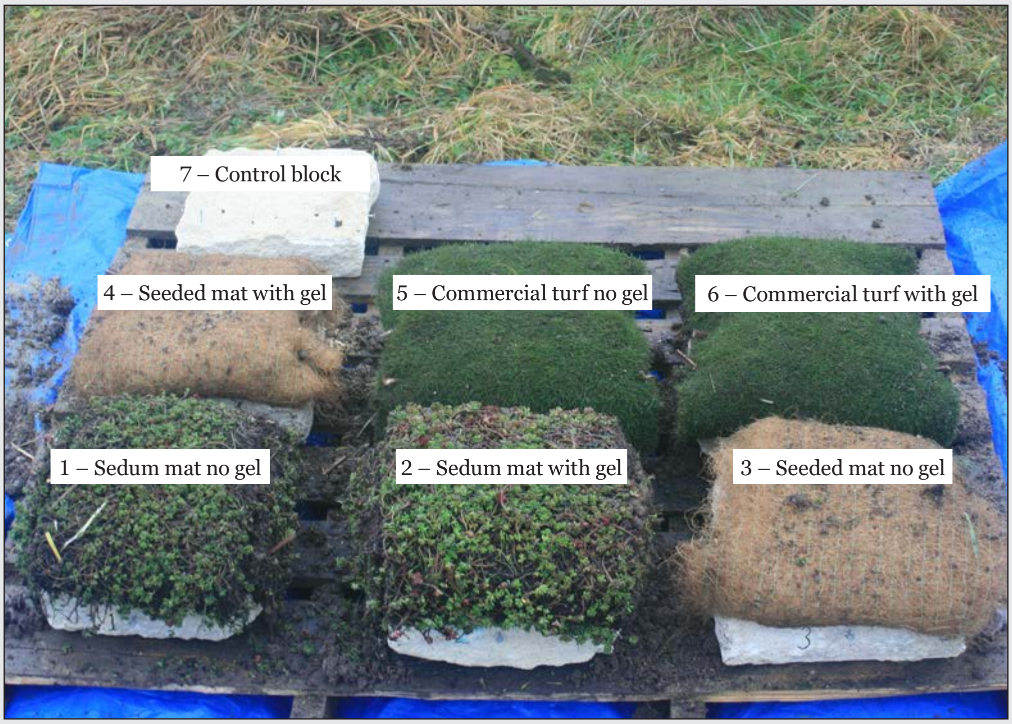


Figure 3.19 The six soft capped test blocks and one uncapped test block exposed for 1 year at Wytham Woods. ©*Heather Viles, University of Oxford*

3.3.5 Castle Acre Priory: Test blocks to evaluate chemical weathering at base of soft capping

While both the calcite crystals and limestone blocks at Wytham Woods provided some data on likely chemical weathering in soft capping and on hard capping, a fuller field experiment was carried out at Castle Acre Priory. Installation of a suite of test samples of limestone, calcite and gypsum in soft capping and hard capping was carried out on 23rd February 2012. The aim of this experiment was to build on the tentative findings of the calcite crystal experiment at Wytham Woods. As described in Chapter 2, three adjacent 1-m strips of soft capping (turf, turf with sedum plugs, and sedum mat) were installed on a low (*c*.1 m high) wall constructed of mixed flint, brick, chalk and other stones at Castle Acre Priory. Test blocks of gypsum, limestone and calcite crystals (4 of each per strip) were placed on the wall-head, then covered with soil (Figure 3.20). Four control blocks of each type were placed on higher walls out of sight. A further batch of samples was kept in the lab as controls. The samples were left *in situ* for two years. They were then examined to compare the weathering rates of limestone and calcite (the main mineral component of limestone) covered by soft capping soils to bare stone directly exposed to precipitation. Gypsum, which is known to weather rapidly in wet, acidic conditions and is often used in soil hydrology research, was also used to provide comparative data.

Figure 3.20 Gypsum and limestone blocks and calcite crystals on test strip 3, before covering with the sedum soft capping. ©*Heather Viles, University of Oxford*

Each block was weighed before and after emplacement using the high accuracy balance referred to above, then laser scanned (Konica Minolta Vi9i) and photographed. Small areas were photographed under an optical microscope (Figure 3.21). Some samples were also viewed with the scanning electron microscope (SEM).

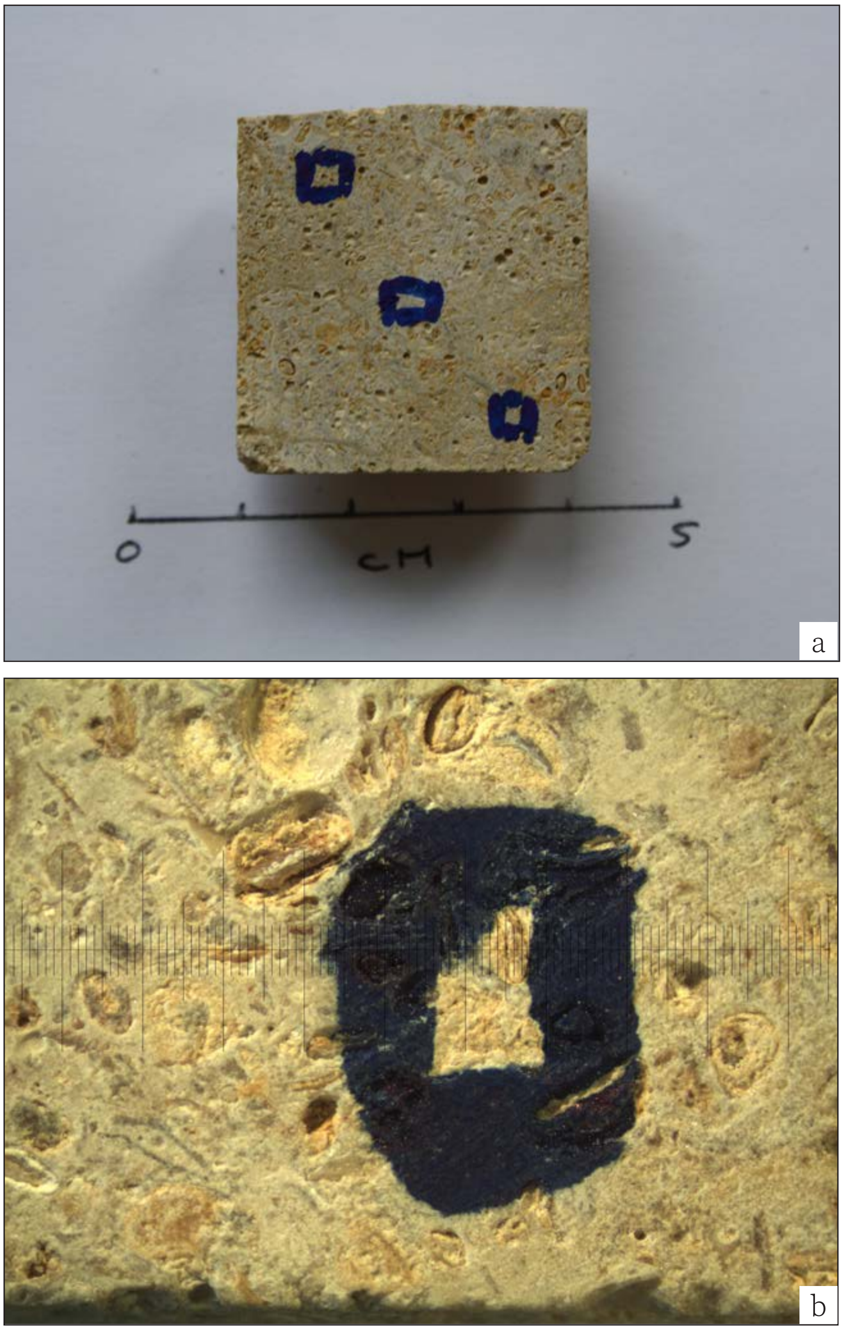


Figure 3.21 (a) Photo before emplacement of one of the limestone blocks (scale bar = 5 cm) and (b) microscope image of the area surrounding the pen mark in the lower right hand corner of the block (width of image c. 1 cm). ©*Heather Viles, University of Oxford*

3.4 Observations of performance of soft capping

3.4.1 Photographic surveys

A detailed photographic record was made at the start of the soft capping experiments at Byland, Kirkham, Thornton, Hailes, Howbury and Castle Acre. Thereafter, photographs were taken annually or at 6-monthly intervals. At Thornton and Kirkham, photos were also taken of pre-existing soft capping which had been emplaced in the 1990s. At Kirkham and Hailes, it was difficult to take effective photographs because of the height of the walls on which the capping was trialled. More intensive rephotography was carried out in spring 2010 at Byland, Kirkham, Thornton, Whitby and Rievaulx, when ladders were used to get closer access to high walls. At Godstow and the Wytham Woods, monthly photographs of the test walls were taken whenever possible, allowing a more detailed view of the changing conditions on soft capping.

3.4.2 Ecological surveys

Ecologist John Thompson undertook a vegetation survey when soft capping was installed at Byland, Kirkham and Thornton. He then took another vegetation survey in 2007, in order to assess any species changes in the turfs (Figure 3.22). There were some logistical difficulties with high elevation sites where scaffolding had been removed (and for this reason, areas immediately adjacent to the places from which the turf had been cut/sourced were also examined as part of the survey). A final detailed survey was undertaken in April 2010, with the intention of assessing how the soft capping had performed over 5–6 years. In addition, some observations were made at Whitby.

Figure 3.22 Ecological surveys being carried out at Thornton Abbey.
© Chris Wood, Historic England

The vegetation survey used the DAFOR scale (D=Dominant, A=Abundant, F=Frequent, O=Occasional, R=Rare) in compiling species lists and estimating the relative frequency of different plants. In conjunction, the prefix L was used to indicate that the distribution was localized rather than generalised. Nomenclature for species follows Hubbard (1984) and Stace (1991). In 2007, the percentage of remaining living cover was roughly estimated.

At Hailes Abbey, a more detailed survey of the turf in the soft capping was carried out in 2007 to compare it with the vegetation growing in the field from which the turf had been cut in 2005. The survey was repeated in 2011. In both 2007 and 2011, a modified version of the Common Standards Monitoring methodology was used. This involved sampling 20 points each on the wall head and in the field. The survey also employed 5 quadrats (25 x 25 cm) on the wall head and in the field to provide more detailed data. Within the quadrats, % cover of all vascular plants was recorded, and the results used to determine the National Vegetation Classification (NVC) type.

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4 RESULTS

4.1 Introduction

This chapter introduces the three research questions underpinning the soft capping research project and the results. It uses the framework laid out in Figure 1.17.

4.2 Research Question 1

Does soft capping provide a more effective thermal blanket for ruined walls than hard capping?

4.2.1 Laboratory testing

As explained in Chapter 3, and illustrated in Figure 3.3, three sets of laboratory experiments were carried out: a standard thermal cycling experiment, an intense thermal cycling experiment and a long term (1 year) field experiment, with standard thermal cycling experiments run before and afterwards. The results from each of these sets of experiments are reported below.

a) Standard thermal cycling experiment

The results of subjecting soft and hard-capped test blocks (of stone from the store at Kirkham Priory) to air temperature cycling from 30°C to -1.5°C in the experimental cabinet demonstrate that soft capping provides a significantly more effective thermal blanket than hard capping (Figure 4.1).

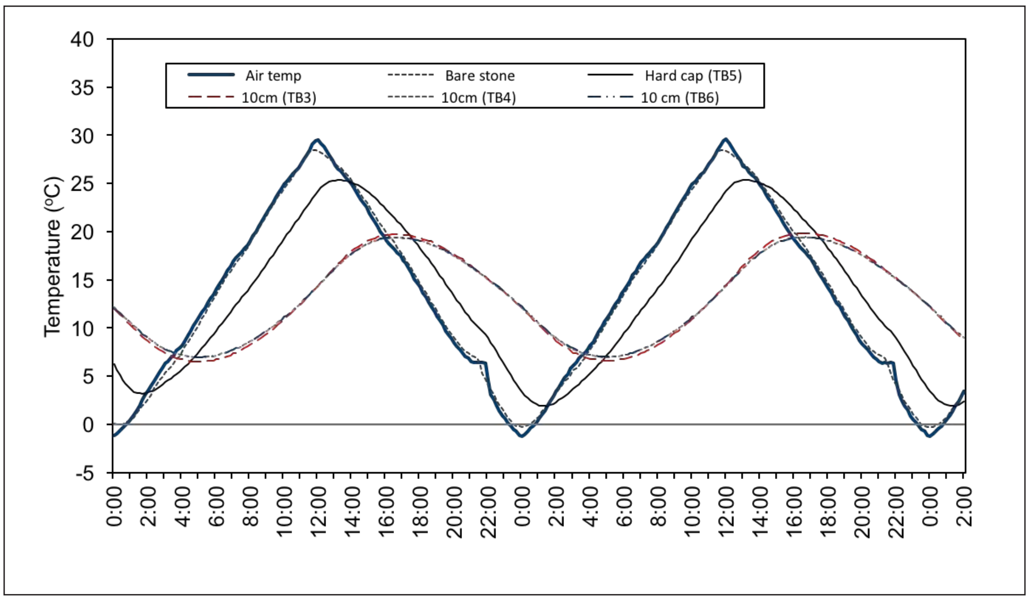

Figure 4.1 Temperatures during the standard thermal cycling experiment for air temperature and bare stone, hard-capped stone and three stones capped with 10-cm soft capping.

Figure 4.1 illustrates the temperature fluctuations of the stone surface beneath 10-cm thick soft caps (three separate repeat runs) during two complete simulated diurnal cycles. These are plotted alongside air temperature (dark blue line), the temperature on the surface of a bare, uncapped block of stone (thin, grey dotted line, which tracks the air temperature closely) and the temperature on the stone surface under a 5 cm thick hard cap (dark black line). Figure 4.1 indicates a time lag in the temperature cycling response between the bare stone and the capped samples (about 2 hours for the hard cap and about 4.5 hours for the 10-cm soft cap). This experiment showed that soft cap has a greater muting effect on temperature extremes than either hard cap or bare stone. The minimum temperatures under the soft-capped samples were approximately 6°C warmer than under hard cap, and 8–10°C warmer than bare stone; the maximum were 5°C lower than the hard cap, and 7°C lower than bare stone. Figure 4.1 also demonstrates good reproducibility between the responses of a 10-cm thick soft cap in three separate runs of the experimental cabinet.

Figure 4.2 illustrates the differences in thermal blanketing effect observed during the standard thermal cycling experiment for 5, 10 and 15 cm thicknesses of soft capping in comparison with the 5-cm thick hard cap.

Figure 4.2 shows that the 10-cm and 15-cm soft caps exhibited a slightly greater thermal blanketing effect (warmer minimum temperatures and cooler maximum temperatures) than 5-cm soft caps.

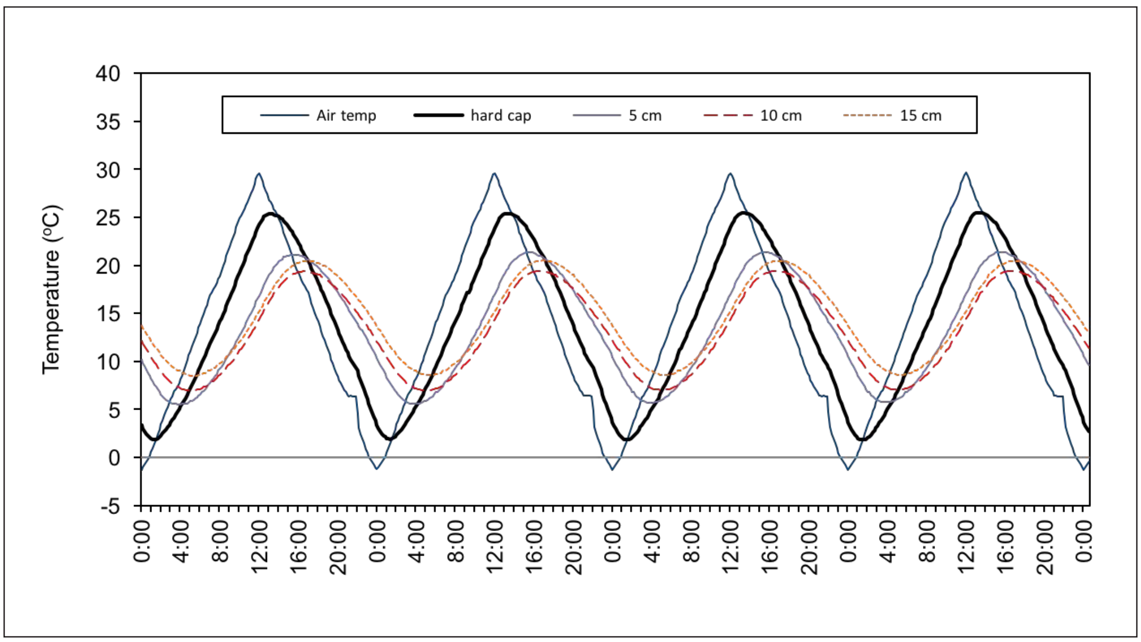

Figure 4.2 Temperatures recorded at 10-minute intervals over 4 cycles of the standard thermal cycling experiment at the base of 5 cm hard cap, and 5, 10 and 15 cm soft caps in comparison with air temperatures in the environmental cabinet.

Thicker soft caps have a greater thermal blanketing effect than thinner ones. Walls beneath 10-cm soft caps are 1°C warmer than walls beneath 5-cm thick soft caps. Walls beneath 15-cm soft caps are 2.5°C warmer than under the 5-cm thick soft cap. However, the impact of thicker soft caps is not so clear on maximum temperatures. The 10-cm thick soft cap reduces maximum temperatures by ~1 to 2°C compared to the 5-cm thick soft cap, while the 15-cm cap only reduces them by ~0.5°C. There is some evidence for a progressive time lag in the occurrence of maximum and minimum temperatures between the hard cap and the 5-cm and thicker soft caps.

The standard thermal cycling experimental data can also be used to examine whether there is any difference in thermal blanketing effect with and without the addition of regolith (slate chippings), as illustrated in Figure 4.3. There is a small amount of variation between repeat runs of the same thickness and composition, but no effect relating to soft cap composition.

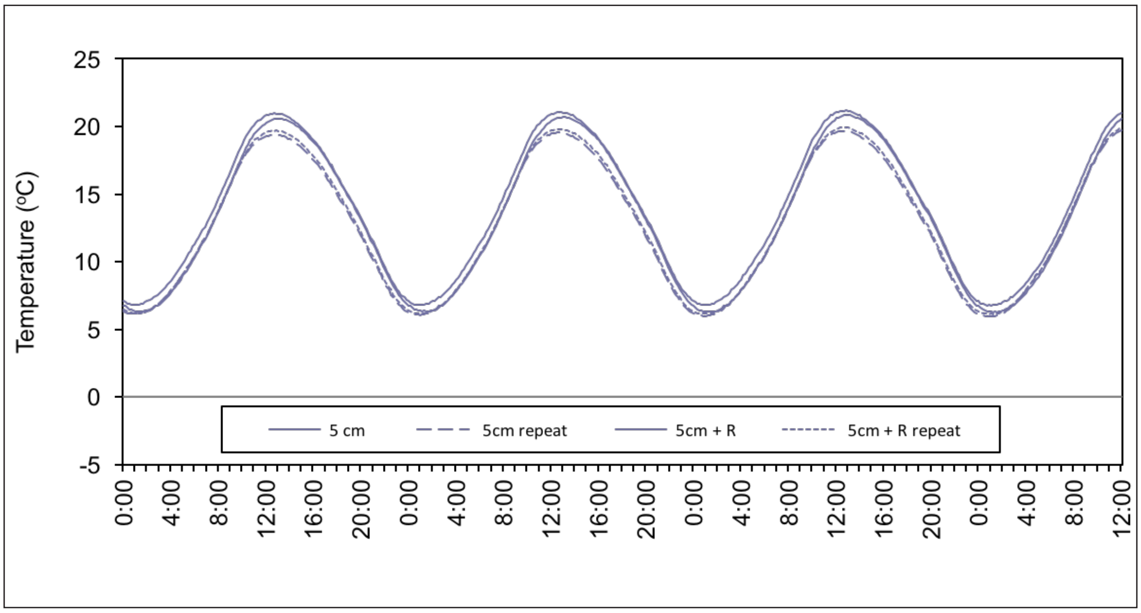

Figure 4.3 Temperature fluctuations (measured at 10 minute intervals) at the base of 5 cm thick soft caps under standard thermal cycling experimental conditions with and without regolith.

(b) Intense thermal cycling experiment

An intense thermal cycling experiment using a 24-hour cycle from 5°C to −5°C was designed to look at the performance of soft capping as a thermal blanket under extreme low temperature regimes. The results indicated that the soft caps froze and did not defrost again (Figure 4.4). While the thinnest soft cap (5 cm) showed some fluctuations in lower temperatures, the 10 and 15 cm soft caps remained just under freezing. This suggests that some thermal regulation is offered by the presence of the soft caps, but at least under experimental conditions, soft capping cannot prevent temperatures from falling slightly below freezing under a 5°C to −5°C temperature regime. Because the environmental cabinet only heats by convection and not radiation, and the experimental set-ups are small with relatively large edge effects, the cooling regime here may be unrealistically harsh.

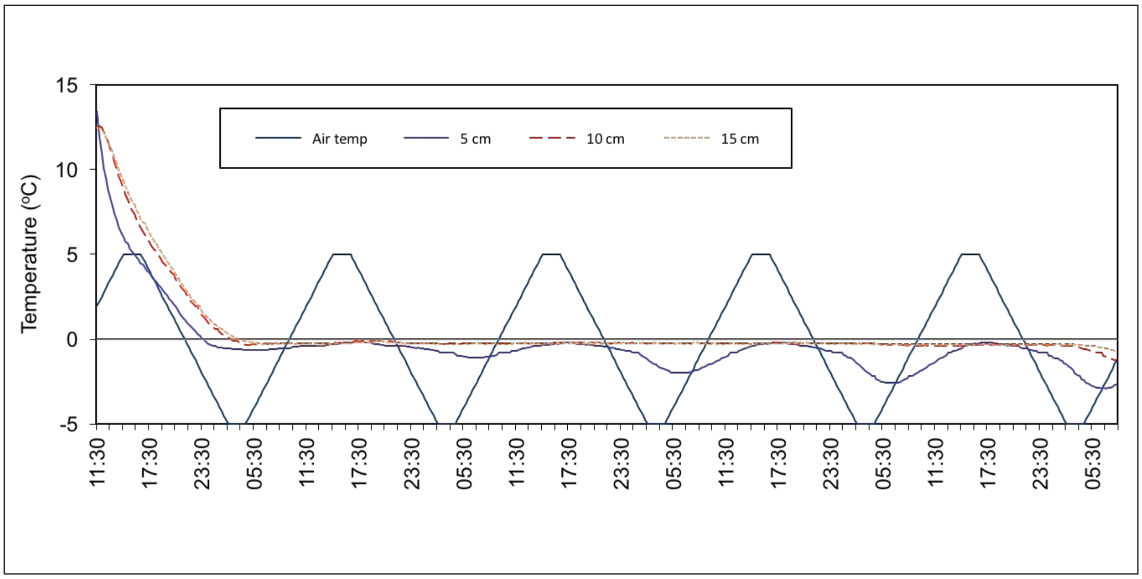

Figure 4.4 Temperatures during the intense thermal cycling experiment for air within the environmental cabinet and under soft caps of 5 cm, 10 cm and 15 cm thickness.

(c) Long-term field experiment

After an initial standard thermal cycling experiment on a hard-capped stone (capping 5-cm thick) and two soft-capped ones (5-cm and 10-cm thick capping), the three boxes were left out on the roof of the School of Geography and the Environment in central Oxford for 1 year, from December 2004 to November 2005. Data on air temperatures and temperatures at the base of each of the three caps were collected over the course of the year (with reliable data only available for March to May and July to October 2005 because of equipment malfunction). The data demonstrates that under more representative conditions than those found in an environmental cabinet, soft capping has a better thermal blanketing effect than hard capping.

Figure 4.5 illustrates monthly maximum and minimum temperatures experienced under the 5cm thick hard cap, and 5 cm and 10 cm thick soft caps for March to May and July to October 2005. The temperature fell below zero several times in March and April 2005. Soft caps were demonstrated to be effective at preventing the temperature of the stone beneath from going below freezing during the period of measurement (unlike the 5 cm hard cap). Monthly minimum temperatures underneath the soft caps were always higher than those under the hard cap (Figure 4.5a), and monthly maximum temperatures lower, apart from Oct 05, when the temperature under the 10-cm thick soft cap was marginally higher than under the hard cap (Figure 4.5b).

Unlike the standard thermal cycling experiment, the long-term roof data revealed that different thicknesses of soft cap have a negligible effect. Minimum temperatures in July 2005 underneath the 10-cm soft cap were ~1°C warmer than under the 5-cm soft cap, suggesting a slightly more effective thermal blanket at temperature minimums. However, maximum temperatures were 0.5 to 2°C warmer under the thicker soft cap (Figure 4.5b).

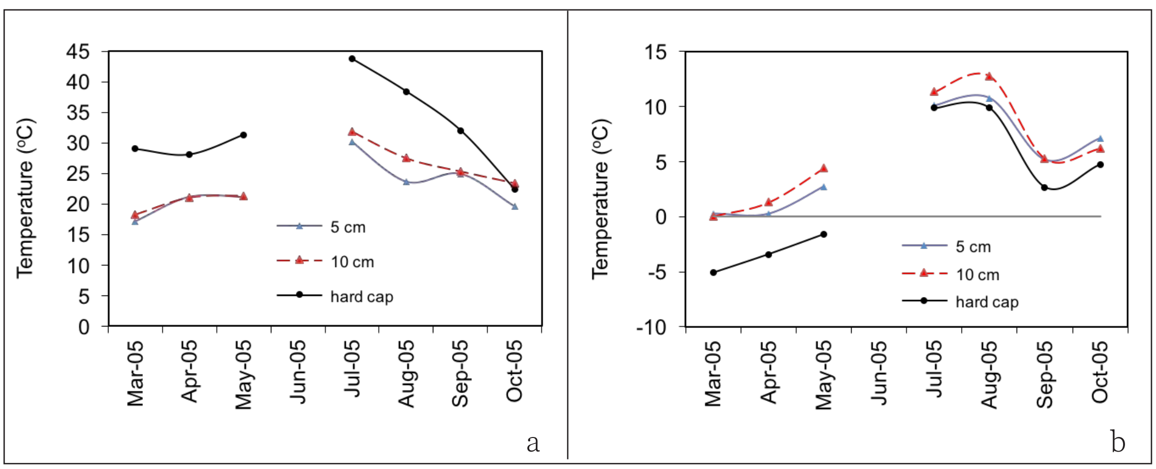

Figure 4.5 (a,b) Monthly temperature minima (a) and maxima (b) of the wall in the long term roof monitoring period.

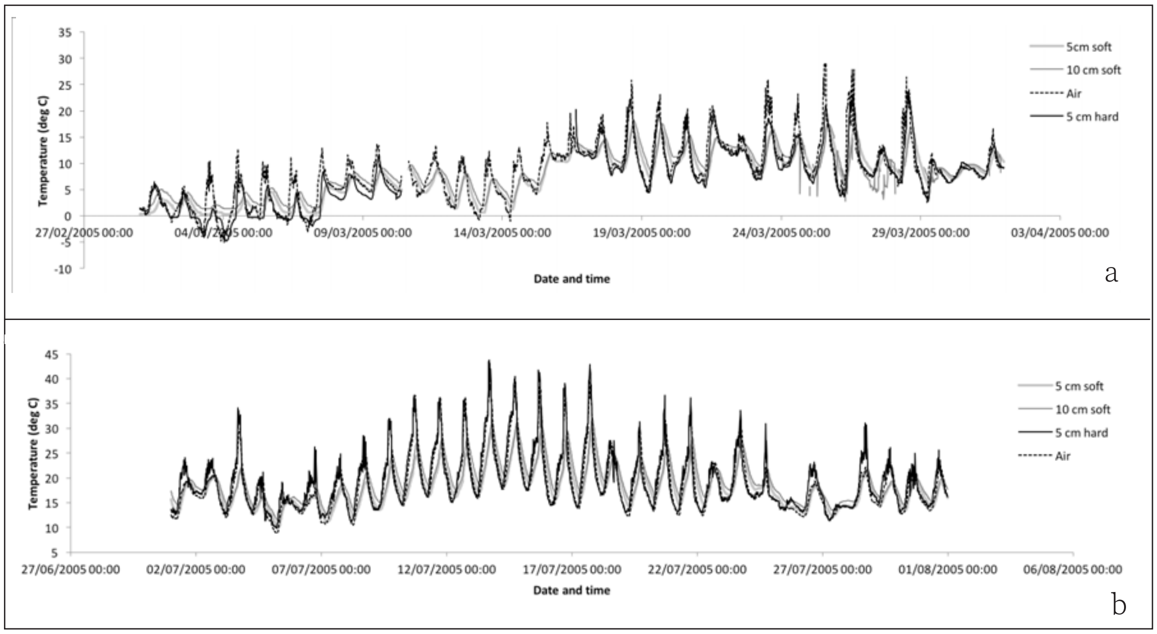

Figure 4.6 (a,b) Daily temperature fluctuations during the roof top experiment under 5cm hard cap and 5 and 10 cm soft caps (a) March 2005 and (b) July 2005.

This experiment showed that soft capping is more effective in reducing diurnal temperature fluctuations than hard capping (although this effect was less pronounced than in the field at Byland Abbey; see section 4.2.2). Figure 4.6 illustrates that in a cool spring month (March 05, Figure 4.6a) minimum temperatures did not fall below freezing under the soft caps, but fell below freezing under the hard ones. Furthermore, in a warm summer month (July 2005, Figure 4.6b) soft capping was very effective at reducing the maximum temperature reached (Figure 4.6b). The magnitude of this effect was different every day, ranging from 1 to 15°C cooler, with an average value of 9°C (higher than observed in the laboratory experiments, but comparable with the data from Byland Abbey).

(d) Thermal expansion experiment

The thermal expansion experiment tested the vulnerability of some of the monuments' stone types to damage from heating and cooling. The results are shown in Table 4.1. A coefficient of expansion (in mm/mm per degree C temperature rise) was calculated for each stone. It was found that Byland stone was particularly susceptible to expansion on heating (its coefficient of thermal expansion, as with those of many sandstones reported in the literature, was around 3 times that of the limestone from Hailes and Kirkham).

Table 4.1 Thermal expansion values 10^{-6} mm/mm per degree C) for stone from Byland, Hailes and Kirkham	
Byland	20
Hailes	7
Kirkham	6.5

The data from the Byland Abbey test site revealed that in June 2005 the daily temperature range under the soft capping was between 3 and 5°C, whereas it was from around 5 to 20°C under the hard capping. Assuming the block of stone was 1 m in length, the linear expansion of that block under these two temperature ranges can be calculated. In the case of the Byland stone, which had the highest coefficient of thermal expansion, soft capping reduced the linear expansion and contraction of the block each day from 0.1–0.4 mm to 0.06–0.1 mm. In the case of Hailes and Kirkham stones, expansion and contraction were reduced from around 0.03-0.14 mm to 0.02–0.03 mm.

This reduction in temperature ranges is beneficial to stones with high thermal expansion coefficients especially those that have been consolidated with hard mixes with low thermal expansion coefficients.

4.2.2 Field testing at Byland Abbey

The results of the experiments on the long test wall at Byland Abbey provided additional evidence of the thermal blanketing effect. Hard capping and 5-, 10- and 15-cm thick soft capping were all tested. As well, the thermal response of soft capping with regolith (slate chippings) was also assessed.

There were some technical issues with data loggers at Byland. Some months did not contain a full set of 30-minute interval observations for every day in that dataset. Table 4.2 records what data is missing from which months for reference (as a percentage of measurement points missing per month). This might be important/ significant for the monthly maxima and minima data where the quality of the dataset drops (more data is missing). The temperature probe on the hard capping recorded the temperatures under a small stone within the top layer of the capping (around 5 cm deep), but might not be truly representative of conditions within a solid, undamaged hard cap.

Figure 4.7 illustrates the monthly minimum and monthly maximum temperatures experienced underneath the six types of soft cap and the hard cap. Soft caps without regolith (Figure 4.7a and b) were monitored for 12 months, while soft caps containing regolith were monitored for 20 months, as was the hard cap (Figure 4.7c and d). In Figure 4.7, the thick black line indicates the hard cap, while the thinner and dashed lines indicate the different kinds of soft cap. The data show that all thicknesses of soft capping provide better thermal blanketing than hard capping. This can be seen in the less severe temperature minimum and maxima recorded under soft caps than under the hard caps. Temperatures under the hard caps dropped noticeably below freezing (0°C) from Nov 2005 through to Apr 2006, reaching a minimum of –3.6°C in Mar 2006. However, temperatures under the soft caps fell marginally below freezing, from between –0.1°C to –0.3°C at worst, and for shorter time periods. (note that measurements on soft caps without regolith ended in Jan 2006, while measurements on the soft caps with regolith continued until Sep 2006).

	Hard Cap	5 cm	10 cm	15 cm	5 cm + R	10 cm + R	15 cm + R
Feb-05	65	68	7	68	48	19	62
Mar-05	82	69	51	83	62	86	83
Apr-05	37	32	32	35	34	51	35
May-05		98	60	100	81	98	100
Jun-05	100	100	74	97	44	100	100
Jul-05	100	100	67	100	100	99	100
Aug-05	100	100	11	95	91	91	100
Sep-05	100	100	100	98	99	97	100
Oct-05	100	100	100	100	100	96	100
Nov-05	100	100	99	100	100	93	100
Dec-05	100	94	71	94	93	43	28
Jan-06	100	43	32	43	100	90	52
Feb-06	100				100	48	100
Mar-06	100				100		100
Apr-06	100				99	82	100
May-06	100				100	100	100
Jun-06	100				100	100	71
Jul-06	100				100	100	38
Aug-06	100				100	100	
Sep-06	100				100	100	

< 25 % data points present
< 50 % data points present
< 75 % data points present
no data points present

Table 4.2 Data quality from telemetric system (temperature and RH) at Byland Abbey.

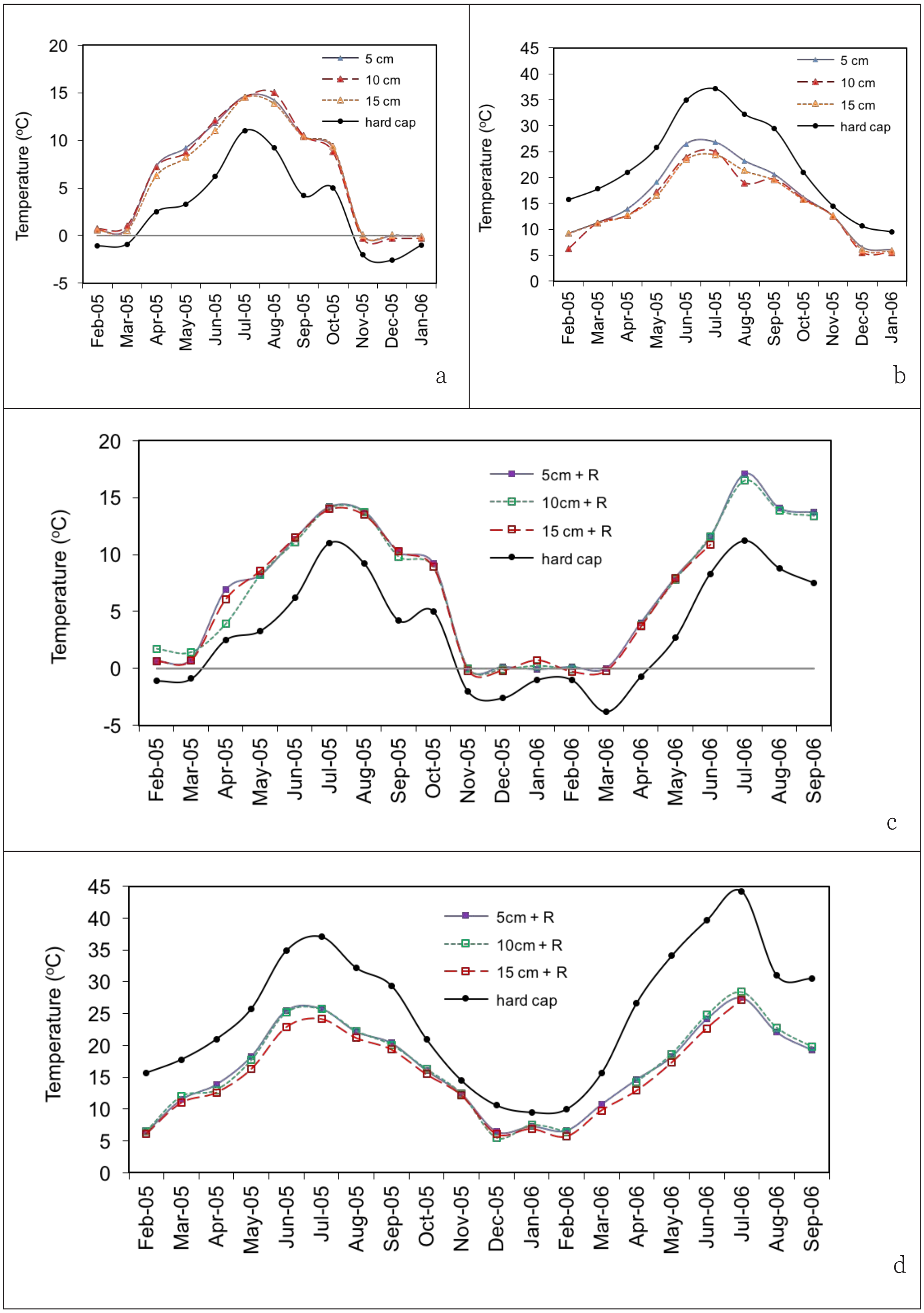

Figure 4.7 Monthly minimum temperatures (a) and (c) and monthly maximum temperatures (b) and (d) for soft capping with and without regolith in comparison with hard capping.

Month	5 cm	10 cm	15 cm	5 cm + R	10 cm + R	15 cm + R
Feb-05	1.7	1.8	1.7	1.7	2.8	1.7
Mar-05	1.6	1.9	1.4	1.7	2.3	1.6
Apr-05	4.8	4.7	3.8	4.4	1.4	3.6
May-05	5.9	5.4	4.9	4.9	4.9	5.3
Jun-05	5.6	5.9	4.8	5.2	4.9	5.3
Jul-05	3.6	3.5	3.5	3.2	3.1	3.0
Aug-05	5.0	5.8	4.7	4.6	4.5	4.3
Sep-05	6.2	6.3	6.2	6.0	5.6	6.1
Oct-05	4.2	3.8	4.4	4.2	3.9	3.9
Nov-05	2.1	1.7	2.1	2.0	2.0	1.8
Dec-05	2.6	2.3	2.7	2.7	2.5	2.4
Jan-06	1.0	0.7	0.9	0.9	1.2	1.7
Feb-06				1.1	0.9	0.7
Mar-06				3.8		3.6
Apr-06				4.7	4.5	4.4
May-06				5.3	5.1	5.2
Jun-06				3.2	3.3	2.6
Jul-06				5.9	5.3	
Aug-06				5.3	5.1	
Sep-06				6.2	5.9	

5 - 10 °C warmer
1.5 - 5 °C warmer
0.5 -1.5 °C warmer
cooler
no data

a

Month	5 cm	10 cm	15 cm	5 cm + R	10 cm + R	15 cm + R
Feb-05	6.5	9.5	6.5	9.3	9.2	9.6
Mar-05	6.5	6.6	6.6	6.3	5.8	6.8
Apr-05	7.1	8.4	8.3	7.1	8.0	8.4
May-05	6.7	8.6	9.3	7.5	8.1	9.5
Jun-05	8.4	11.0	11.4	9.4	9.7	12.0
Jul-05	10.3	12.2	12.7	11.3	11.4	12.9
Aug-05	9.0	13.3	10.9	10.0	9.9	11.0
Sep-05	8.8	9.8	9.9	9.0	9.3	10.0
Oct-05	4.8	5.2	5.3	4.9	4.7	5.5
Nov-05	2.0	2.0	1.9	2.1	2.1	2.3
Dec-05	4.1	5.1	4.5	4.1	5.1	4.5
Jan-06	3.5	4.0	3.7	2.2	2.0	2.6
Feb-06				3.3	3.6	4.3
Mar-06				4.9		5.9
Apr-06				12.0	12.4	13.8
May-06				15.8	15.4	16.8
Jun-06				15.5	14.9	17.0
Jul-06				16.7	15.8	17.0
Aug-06				8.9	8.2	
Sep-06				11.2	10.7	

15 - 20 °C cooler
10 - 15 °C cooler
5 - 10 °C cooler
warmer
no data

b

Table 4.3 Difference between hard cap and soft cap temperatures (a) degree to which monthly minimum temperatures under soft capping exceed those under hard capping and (b) degree to which monthly maximum temperatures under soft capping are lower than those under hard capping.

Table 4.3 quantifies the magnitude of the thermal blanketing effect of the soft caps. It provides a good comparison of wall-head temperatures under soft capping with near-surface wall-head temperatures under hard capping. Warmer minimum temperatures of between 0.7 and 6.3°C are found, with most months recording between 1.5 and 5°C differences. Both the laboratory thermal cycling experiment and 1-year roof experiment, in which the temperature probe was placed at the base of the hard cap, show similar trends. The presence of soft capping also results in cooler maximum temperatures relative to the hard cap, ranging from 1.9 to 17.0°C (Figure 4.7b and d, and Table 4.3b). The differences are particularly noticeable in early summer, especially in 2006. The differences between the soft and hard cap temperatures are larger and more variable than those for the minimum temperatures.

Figure 4.8 illustrates the diurnal temperature fluctuations experienced under the six types of soft cap and hard cap for a summer month (Jun 05, Figure 4.8a) and a winter month (Nov 06, Figure 4.8b). In both months, there is a striking reduction in the magnitude of the diurnal temperature cycle experienced by all soft capped sections compared to the hard capped section with the most marked differences in June.

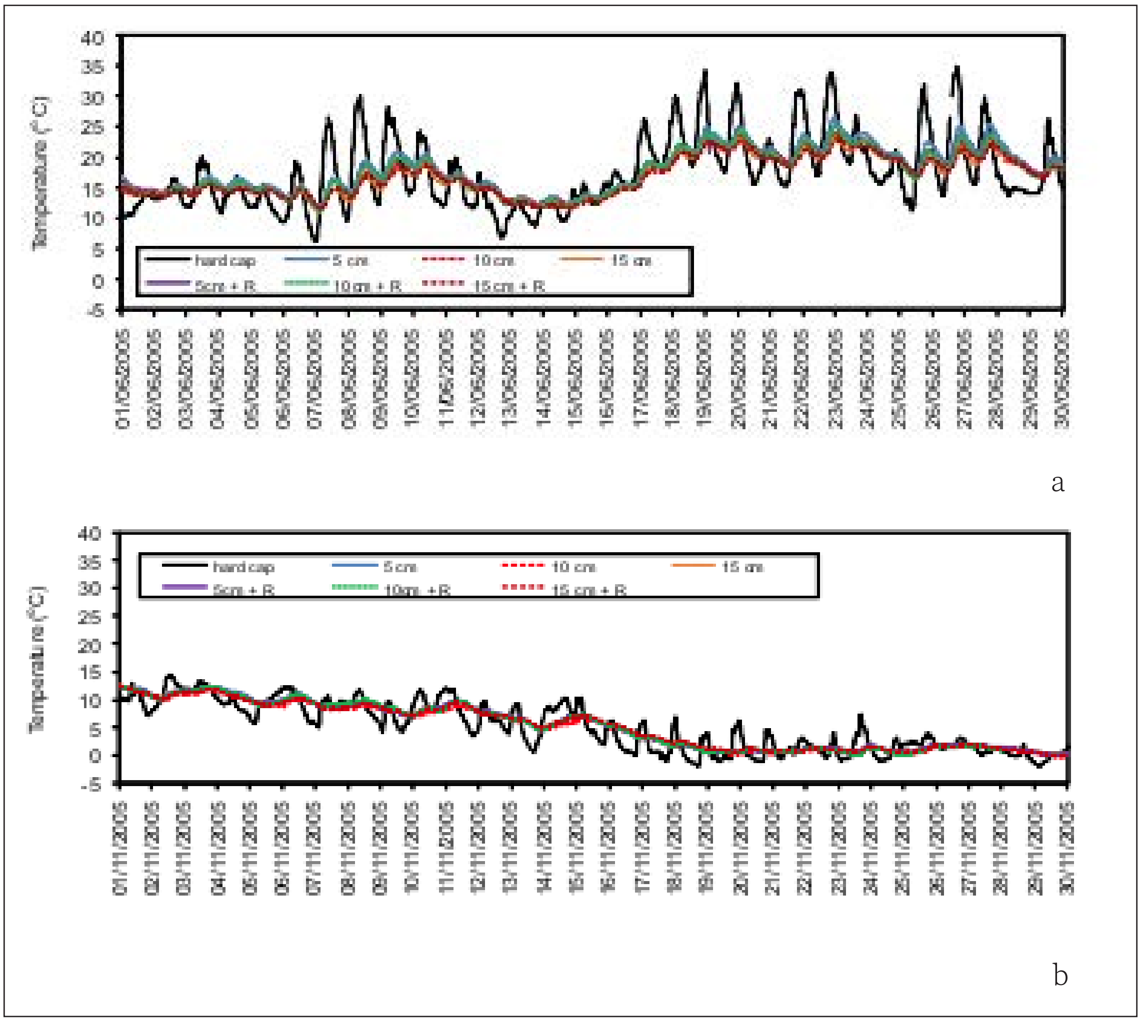

Figure 4.8 Daily temperature fluctuations (measured at 30 minute intervals) for (a) June 2005 and (b) November 2005 for the different thicknesses of soft caps with and without regolith, with hard-capping data for reference (solid black line).

In summary, the Byland Abbey field test confirms the results from the standard and intense thermal cycling experiments in the lab and the long term field experiment in Oxford: soft capping is more effective in buffering temperature fluctuations experienced at the wall head than hard capping. Soft capping reduced the magnitude of the temperature extremes for each month during the period of measurement at Byland Abbey.

The Byland Abbey data set can also be examined to provide more information about the differences in thermal blanketing performance of soil capping of different thicknesses. The differences in monthly maximum and minimum temperature at the long wall test site between the different thicknesses of soft capping (5 cm, 10 cm and 15 cm without regolith, and 5 cm, 10 cm and 15 cm with regolith) were either small or non-existent, depending on the month (Figure 4.7). The notable exception to this was the behaviour of the minimum temperatures for the 10 cm soft cap containing regolith in March 2005, which probably results from the confounding influence of large amounts of missing data from some soft cap sections. There was also some small difference observed in the soft caps with and without regolith, with greater summer cooling experienced in the 10-cm and 15-cm caps as compared to the 5-cm cap (Figure 4.7 b and d), with up to 1.5°C of extra cooling under the thicker soft capping between May–Aug 05. In summary, the Byland Abbey field monitoring confirms the laboratory findings that the effect of soft cap thickness on its thermal blanketing ability is either small or negligible. The implication is that 5-cm thick soft caps appear to be as effective as 15-cm thick soft caps.

The graphs in Figure 4.9 compare the monthly minimum and maximum temperatures at Byland Abbey for the same soft cap thickness with and without regolith in order to examine whether soft cap composition has any influence. The graphs show there is no systematic or clear difference, although for the 10-cm thick capping there is some evidence that in some months regolith was associated with reduced temperature minima and increased temperature maxima (but this is probably an artefact of missing data). Together with the laboratory experimental data, the Byland Abbey results confirm that there is no significant influence of regolith on the thermal blanketing behaviour of soft capping.

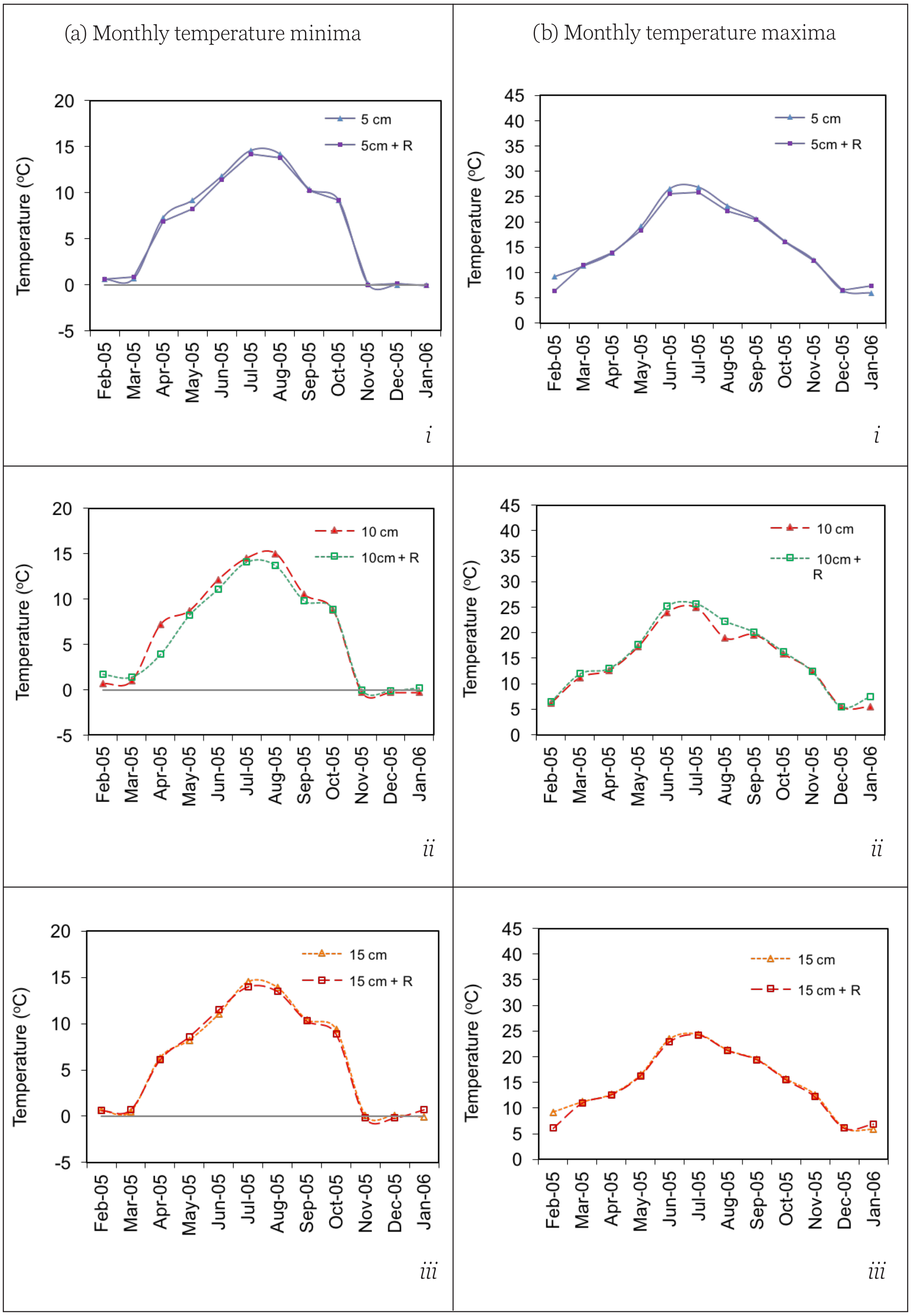

Figure 4.9 Monthly temperature minima (a) and maxima (b) of the wall head at the Byland Abbey field test site for the 12 months of data for (i) 5 cm thick soft caps with and without regolith, (ii) 10 cm thick soft caps with and without regolith and (iii) 15 cm thick soft caps with and without regolith.

4.3 Research Question 2

Does soft capping provide an effective control of moisture regimes in the walls?

In order to study the influence of moisture regimes on soft capping, it was necessary to test it through laboratory and field experiments and field monitoring, and to ask the following questions:

- How does soft capping influence moisture conditions at the wall head? How does this compare with hard capping? (see Section 4.3.1)
- How does soft capping influence moisture levels lower down in the wall (as opposed to hard capping)? (see Section 4.3.2)
- How does soft capping influence runoff down the wall face (c.f. hard capping)? (see Section 4.3.3)
- Does soft capping accelerate chemical weathering of the wall-head through acidifying water penetrating into the stone? (cf bare and hard capped?) (see Section 4.3.4)

4.3.1 How does soft capping influence moisture conditions at the wall head in comparison with hard capping?

The influence of soft capping on moisture conditions was studied by examining the volume, timing and pathways that water follows when it enters the top of the wall. These results were compared with the results of identical experiments performed on wall-heads that had hard capping. As reported below, laboratory experiments were only partially successful in answering these questions. Additional evidence was drawn from soil moisture probes deployed at the base of soft and hard capping at Byland Abbey, and in soft capping alone from the Wytham Woods test walls. The data from all of these lab and field studies are presented and discussed below.

a) Laboratory drying experiments

Laboratory drying rate experiments using bare (uncapped) stone and soft-capped stones (following the methodology described in section 3.2.2) gave preliminary indications that soft capping slows the rate of drying of the wall-head, preventing it from becoming as dry as uncapped stone. The experiments generated a large dataset, with numbers for several different thicknesses and ages of soft cap. The most useful part of the dataset, however, was the comparison between drying rates of bare stone and the drying rates of stone covered with soft capping. The results are tabulated in Table 4.4.

Table 4.4 The drying rates of three types of saturated stone under uncapped (with and without side insulation) and soft capped conditions			
Stone type	Uncapped (bare) stone	Uncapped (bare) stone + side insulation	Stone + soft cap
Byland Abbey	Lost 50% water in 14 h	In 4 days lost 93% water	In 1 week lost 13% water
Hailes Abbey	Lost 50% water in 3 h	In 4 days lost 82% water	In 1 week lost 43% water
Kirkham Priory	Lost 50% water in 34 h	In 4 days lost 89% water	In 1 week lost 45% water

The stones from Hailes, Byland and Kirkham all differ in terms of porosity, permeability, and water retention properties, and therefore absolute values cannot be compared., However, all three stone types dried faster when uncapped than they did when soft-capped. The bare stones lost 50% of their water in a matter of hours when uncapped and without insulation.

The Kirkham Priory stone took the longest time (34 hours) to dry, and Hailes Abbey stone the shortest (3 hours). But when the sides and base were insulated, the drying rates were lowered so that the stones all lost around 80-90% of their moisture over 4 days. Soft capping further slowed the rate of water loss. This result suggests that the presence of soft capping would moderate drying and wetting at the wall-head, reducing fluctuations in moisture over short time scales.

It therefore appears likely that the presence of soft capping should mediate moisture fluctuations in the stone, although the small datasets and limitations of the experimental methodology do not allow strong conclusions to be drawn. Field tests at Byland Abbey and the Wytham Woods test walls provide further and larger datasets on the influence of hard and soft capping on wetting and drying behaviour.

b) Field testing at Byland Abbey: Wetting and drying of the wall heads

Moisture level data recorded at the base of soft caps and 15 cm below the top of the hard-capped wall at Byland Abbey, using the telemetric system with Watermark sensors, can be utilised to evaluate the influence of different capping methods on wetting and drying behaviour.

Moisture data from soft caps of different thickness without regolith was collected over 12 months, whereas moisture data from the different thicknesses of soft capping with regolith and the hard cap were collected for 20 months (following the methodology outlined in section 3.3.1). This Byland dataset includes some technical issues with data loggers. Some months did not contain a full set of 30-minute interval observations for every day in that dataset (see Table 4.3). This might be important for interpreting the monthly data, particularly where data quality drops.

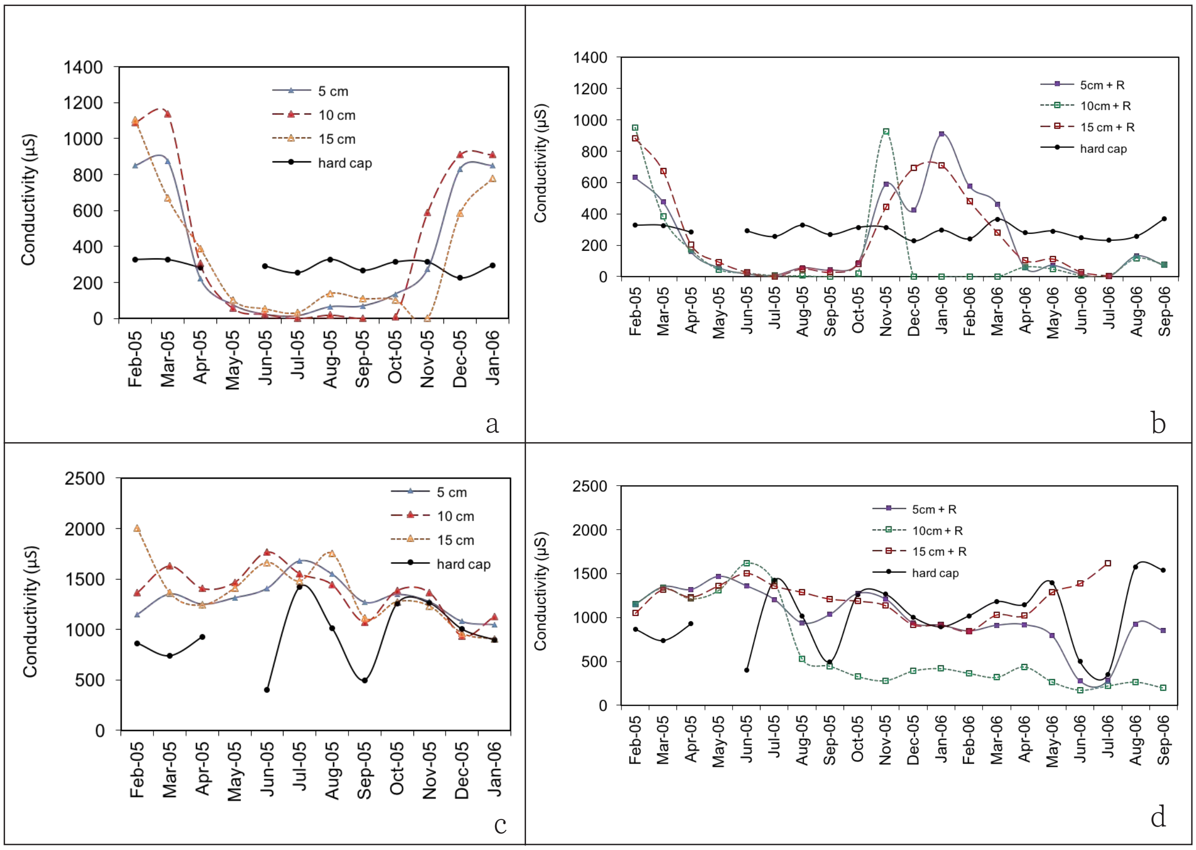

Figure 4.10 (a) Monthly moisture minima data at wall head (soft caps without regolith vs. hard cap), (b) Monthly moisture maxima at wall head (soft caps without regolith vs. hard cap), (c) Monthly moisture minima data at wall head (soft caps with regolith vs. hard cap), (d) Monthly moisture maxima at wall head (soft caps with regolith vs. hard cap).

Figure 4.10 indicates that monthly minimum moisture values are consistent across the seasons in the hard cap, while the base of the soft caps experiences variable monthly minima across the seasons (Figure 4.10 a, c). Conductivity minima are low (<150 microsiemens) under the soft caps between May and October 2005, suggesting that the wall head came close to drying out completely at some point during those months. For the soft caps with regolith, this pattern was repeated in 2006 from April to September (Figure 4.10 c).

The soft-capped wall heads also experienced higher monthly minima than the hard-capped wall (>600 microsiemens) in February and March 2005, and November 2005 to January 2006, implying wetter conditions in winter. One exception was the 10-cm soil cap with regolith, which dropped to a value of 0 in December 2005, remaining there until March 2006 (Figure 4.10 c). This most probably reflects a problem with the moisture sensor and/or data logger.

In contrast to the monthly minima data discussed above, the monthly moisture maxima exhibited variability across the seasons in both the hard cap and soft caps, as shown in Figure 4.10 b and d). In some months, the soft-capped sections had higher moisture maxima than the hard-capped section, which suggests that soft capping allows higher total moisture values at the wall head than under the hard cap. However, in other months, the reverse was true, especially under the soft cap with regolith. Variability in monthly moisture maxima was greater for the hard-capped wall. Figure 4.10 d) showed the strange behaviour of the 10-cm soft cap with regolith from August 2005 onwards, which again suggests a problem with this particular moisture sensor.

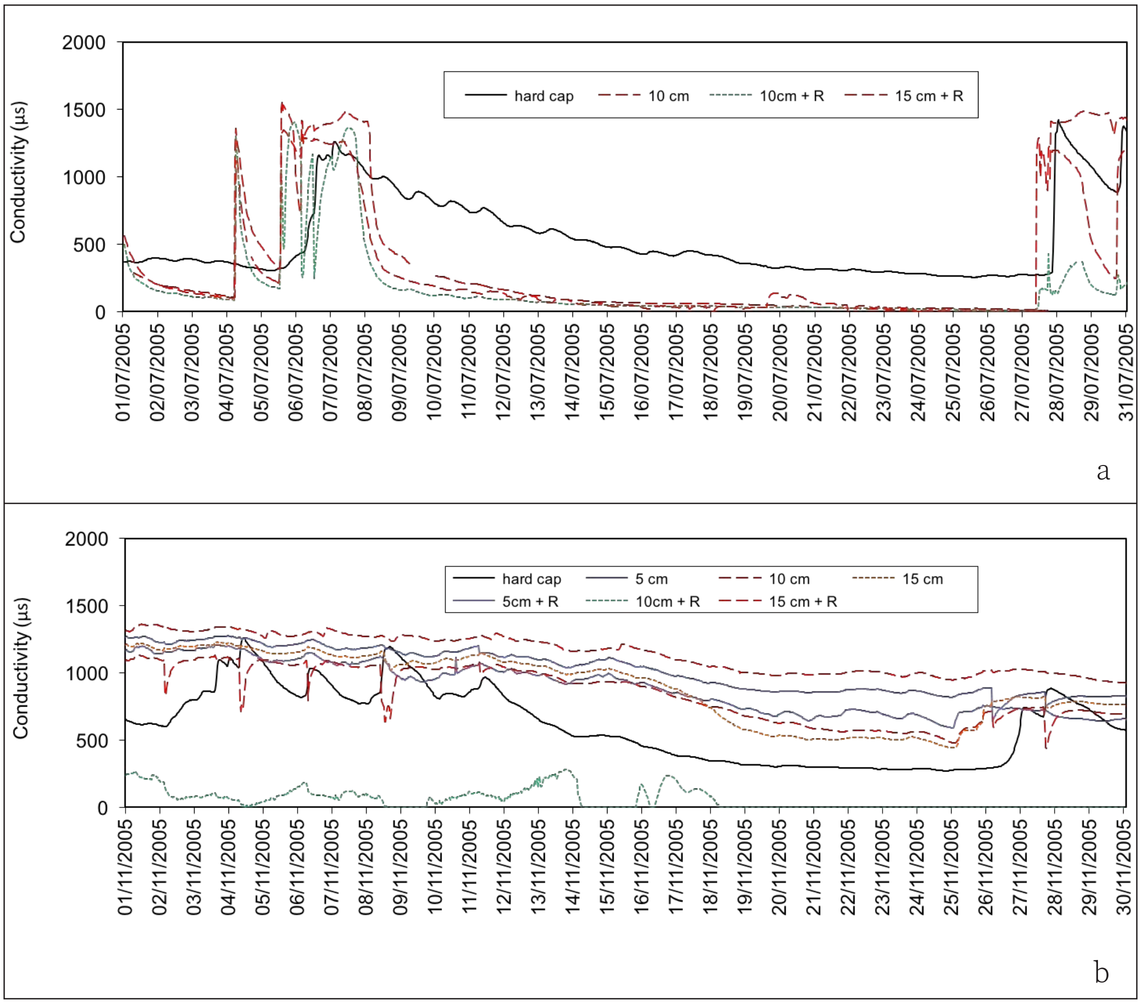

Figure 4.11 Daily moisture fluctuations (measured at 30 minute intervals) for (a) July 2005 and (b) November 2005 for the different thicknesses of soft caps with and without regolith, displaying the hard-capping data for reference (solid black line).

Figure 4.11 illustrates the diurnal moisture fluctuations experienced under the six types of soft cap and hard cap for a summer month (July 2005) and a winter month (November 2005). In July, the responses to rainfall events were complex. There was an increase in the moisture level at the top of the wall-head (and inside the wall-head, in the case of the hard cap) for all measurement sites after a rainfall event on the 6th July. The earlier peaks in moisture on the 4th July recorded by three of the soft-capped sections (10 cm, 10 cm +R and 15 cm +R) may reflect earlier rainfall events. With the exception of the 5-cm soft cap with regolith, the measured moisture response was more rapid in the soft caps than the hard cap. The majority of soft caps also recorded a slightly higher moisture level at the wall-head following the rain event than did the hard-capped section. While the hard cap data showed a relatively simple rise in moisture from *c*.400 to *c*.1200 microsiemens over 2 days, the soft cap responses were characterised by more than one peak in moisture, Figure 4.11a). The drying behaviour was also different. While the hard cap dried out progressively over 20 days, the soft-capped sections dried out more quickly. In response to a second rainfall event towards the end of July, the moisture under the hard cap increased at the same rate as it did under the soft caps (although the 5-cm and 15-cm soft caps with regolith responded more quickly. On this occasion, the maximum moisture level under the hard cap was similar to the maximum reached under any of the soft caps.

In November 2005, (as shown in Figure 4.11b), moisture under the hard cap tended to be lower than under the soft caps (ignoring the 10 cm + R soft cap, which seems to have suffered from sensor problems), with the exception of a few peaks in moisture under the hard cap (e.g. on the 4th and 9th November). It is likely that the lower temperatures in November (as opposed to July) resulted in reduced evaporation and drying of the soft and hard caps and the underlying wall head.

In summary, the data from Byland Abbey show that the wall-head tends to be drier beneath the hard cap than beneath the soft caps in winter, and vice versa in summer. It is important to note, however, that the moisture sensor under the hard cap was located **in** the wall, whereas those under the soft cap were located at the base of the soil – thus the two datasets are not entirely comparable. In addition, the moisture fluctuations beneath the hard cap tend to be muted during summer (as evidenced by the data from July 2005) as compared to the base of the soft caps. This pattern is seen most clearly in the response in early July 2005 of all caps to a rainfall event. The inverse seems to be true during winter (as shown in the data from November 2005) with drier, but more variable conditions under the hard cap.

Building on basic hydrological theory, it was proposed in Chapter 1 (section 1.2.3) that soft capping acts as an effective moisture barrier, reducing the ingress of water from rainfall into the wall head. The magnitude of this effect is assumed to vary according to the pre-existing moisture contents of the soil, rainfall intensity, and so on. It is also proposed that soft capping acts as a humidity blanket, creating a less extreme regime of relative humidity fluctuations at the wall-head. Hard capping is also designed to reduce moisture ingress to wall-heads (as reviewed in section 1.2.8). The results from Byland indicate that soft capping might be more effective than hard capping as a moisture barrier in summer, but less effective in winter. The higher variability in moisture maxima between months under hard capping and soft capping found at Byland gives some support to the proposal that soft capping acts as a humidity blanket, moderating variability in moisture levels at the wall head. However, the results are not in any way clear-cut, largely because of the difficulties of measuring moisture levels under hard and soft capping in a meaningful and easily comparable way. Furthermore, it is important to note that the hard capping here was new and well constructed, and thus not reflective of older, cracked and failing hard capping. It is also important to note that the soft capping was also new, and for most of the measurement period would not have produced a solid mat of roots.

c) Field testing at Wytham Woods: Moisture levels at the base of soft capping

The array of nine watermark sensors deployed in the soft capping soil on one of the test walls at Wytham gives evidence of the moisture conditions over a long period (4 years) within soft capping (Figure 4.12a). This data is not continuous (unlike that at Byland) but represents a series of individual measurement points, as a hand-held reader was used to interrogate the sensors once a month (with a long gap between November 2009 and June 2010). These values are likely to be heavily influenced by meteorological conditions on the day (e.g. whether there has recently been a heavy rain event). The measurement scale is different to that used at Byland, but as with that dataset, high values equal wetter conditions and vice versa. The first thing to note is that all 9 sensors give similar readings at most measurement points, illustrating that even on a small area of soft capping the moisture conditions are quite homogeneous. The only exception is sensor 4 from the SE corner, which shows some tendency to wet up and dry out more dramatically than the others. The second point to note is that there is considerable variability in moisture levels between months, with the highest values recorded in August 2010. Finally, there are some seasonal trends, with generally low values recorded in summer 2011, and generally high values in winter 2012/2013. The soil moisture data and the rainfall data (Figure 4.12b) show broad agreement: wet months are associated with wetter soil moisture conditions in the soft capping. It was not possible to deploy watermark sensors under the hard capping at Wytham, so we have no comparable data for the hard-capped walls.

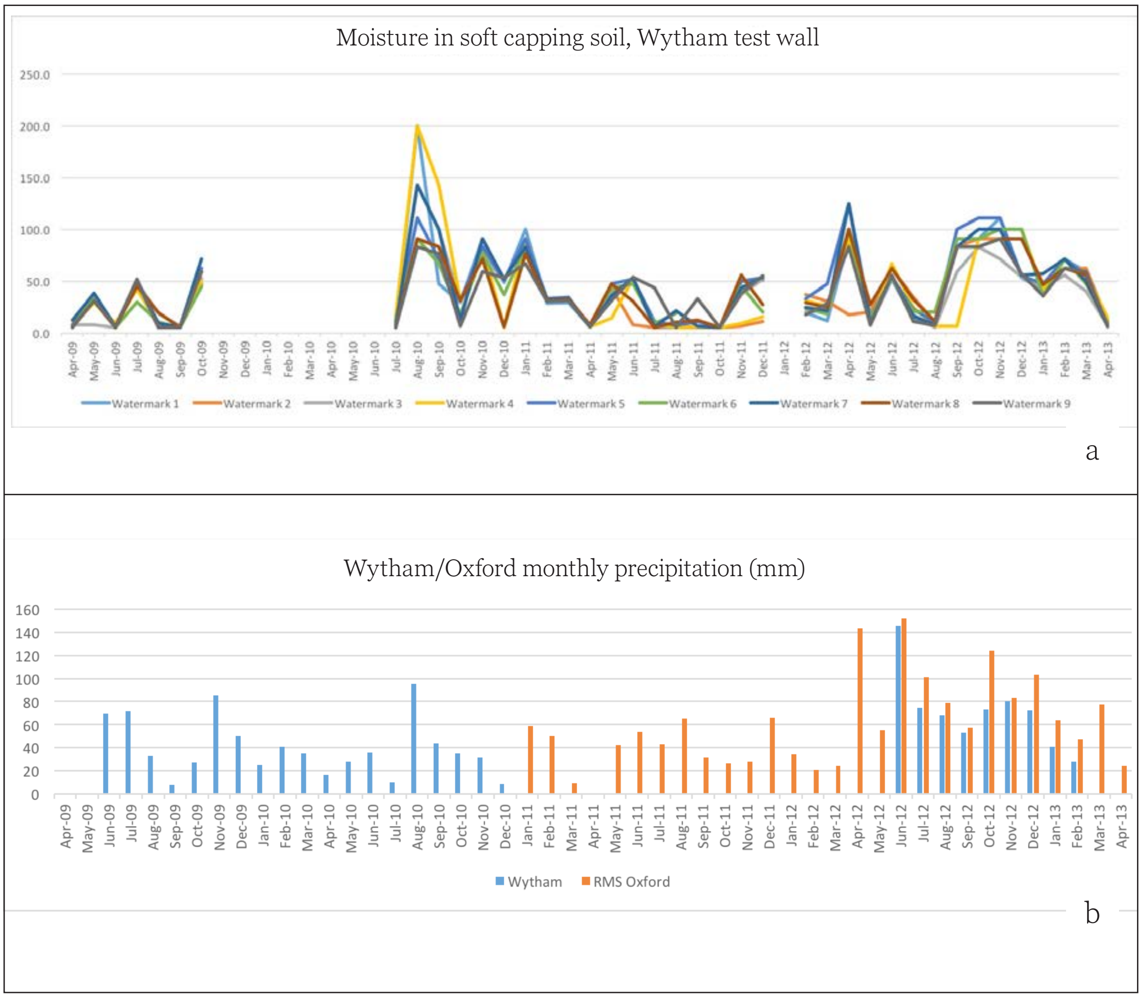

Figure 4.12 (a) Moisture data from soft capping on Wytham Woods test wall 1 from April 2009 to April 2013, (b) monthly rainfall over the same period.

4.3.2 How does soft capping influence moisture levels lower down in the wall in comparison with hard capping?

Different types of capping are likely to influence the volumes, timing and pathways of water penetrating into the heart of ruined walls. Extensive data collection using wooden dowels and 2D resistivity surveys was carried out at Byland Abbey, Hailes Abbey and the Wytham Woods test walls in order to address this research question.

(a) Field testing at Byland Abbey: Dowel and 2D resistivity data

A network of 41 wooden dowels inserted in the long test wall at Byland Abbey between December 2004 and January 2006 (following the methodology outlined in section 3.3.1) provided monthly data regarding moisture levels. The aim of the monitoring was to examine moisture conditions around 20–30 cm below the base of the capping. Sections of wall with different soft cap thicknesses were compared with a hard-capped wall and an uncapped one (control). Because monitoring was carried out on an old wall with largely unknown history and internal characteristics, there may be other more local factors influencing the moisture levels in the dowels as well as whether they are in soft- or hard-capped sections (as discussed by Sass and Viles, 2006).

Figure 4. 13 summarises the data from the Byland dowel network. Each dowel was 40 cm in length. The moisture data were obtained from the full length of the dowel (thus illustrating the moisture conditions within the outer 40 cm of the wall).

The dataset shows high variability over time. The control dowels (in the wall underneath a section of wall which had not recently been capped) provided a comparison for the hard and soft caps, and were the least variable over time (especially on the west-facing side). The control dataset illustrated that the walls are drier in summer and wetter in winter. The dowels from the hard-capped section recorded the highest variability in moisture contents on both east- and west-facing sides of the wall. This variability was most marked in the spring and summer months.

The soft-capped sections tended to show lower levels of fluctuation in moisture levels than the hard-capped section, with generally low levels in summer and high ones in winter 2005/2006. However, conditions in winter 2004/5 and spring 2005 were very changeable in both hard-capped and soft-capped sections.

The data revealed that there is no simple trend in moisture behaviour in walls under soft caps of different thickness. The subset of soft caps that showed the lowest fluctuation in wall moisture contents were the 10-cm soft caps on the west and east-facing walls, and the 5-cm with regolith soft cap on the east-facing side. On the east-facing wall, the soft caps of all thicknesses and compositions showed slightly reduced moisture levels and fluctuations compared to the uncapped section (control dowels) (Figure 4.13b). However, other soft-capped sections exhibited more variability; for example, the walls below the 5-cm soft caps on the west- and east-facing sides.

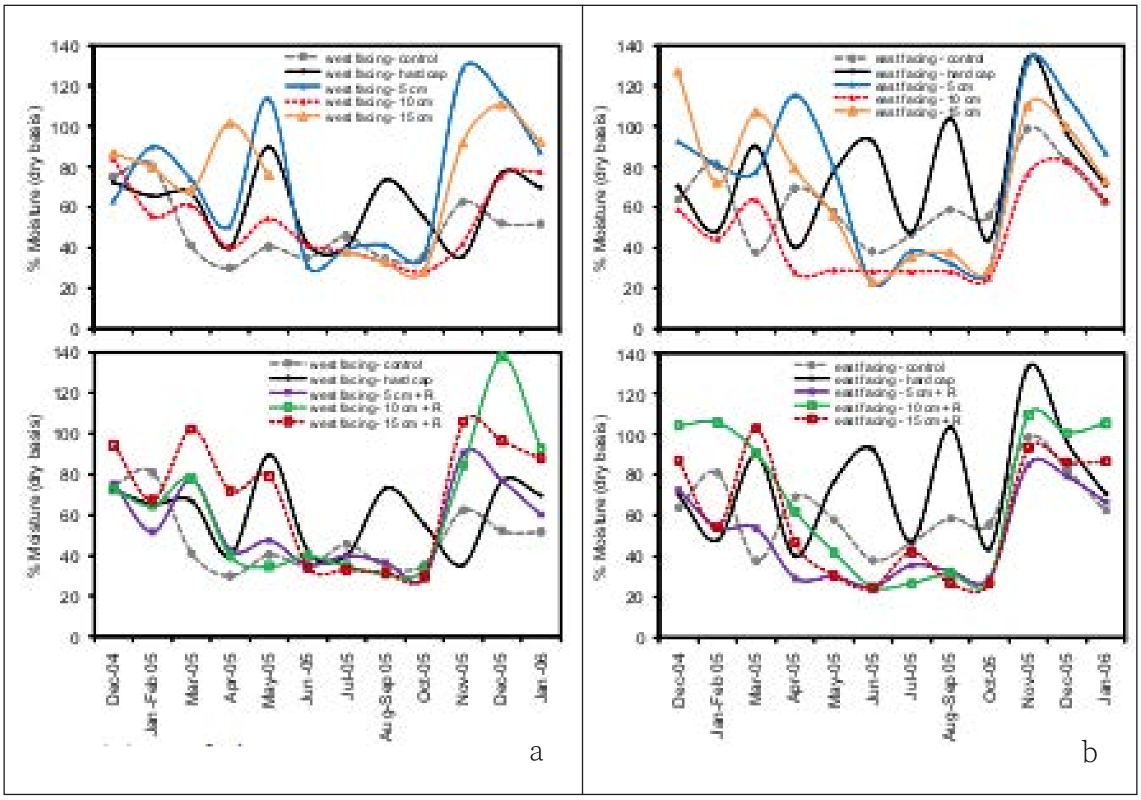

Figure 4.13 Moisture content of wooden dowels inserted in the mortar in the wall beneath the hard capped and soft capped sections (at 15–40 cm below the wall head) alongside a control dowel (at 15–40 cm below the wall head) for (a) west facing, and (b) east facing sides of the Lane wall at Byland Abbey.

Statistical analysis of the data shows that the west-facing control section had significantly lower mean water contents than the east-facing control section. However, no significant differences were found between west- and west-facing values from the capped sections. Furthermore, the west-facing control had significantly lower moisture contents than the hard-capped and 15-cm thick soft-capped sections. Only in the east-facing dowels was there a significant difference between soft-capped sections and the grouped data from hard-capped and control sections.

In conclusion, moisture fluctuations under the soft-capped sections seem to have been more mediated than under the hard capped section, predominantly in the spring and summer months. However, no simple pattern emerges. There was much variability in moisture contents of walls under the different soft-capped sections, and the highest and lowest values recorded both came from dowels under soft-capped sections. Some variability may relate to the dowel method itself, as the values obtained by the dowel method provide a spot value for a small area of the wall (low spatial resolution). In fact, one critique of the method is that the values may depend strongly on the exact location of the dowel (Sass and Viles, 2006). Thus, individual dowels might be more affected by local conditions within the wall than the impact of any capping above.

In order to investigate any differences in inner and outer sections of the walls, data from the innermost 10-cm portion of each dowel was compared with data from the outermost 10 cm. The interiors and exteriors of the dowels were equally dry in the winter. However, the innermost parts of the dowels were wetter than the outermost parts in the summer. This was caused by the reduction in water contents (especially in the outermost section) of the dowels under soft-capped sections. This analysis suggests that soft capping is better than hard capping at reducing near-surface moisture contents during the summer.

Further insights into the influence of different types of capping on wall moisture behaviour comes from the two 2D resistivity surveys undertaken in April 2005 and September 2006 on the east-facing wall at Byland (following the methodology described in section 3.3.1). Results are shown in Figure 4.14. These plots depict a horizontal slice into the wall from the vertical face of the wall (top of each figure), where the widest part of the plot represents the wall face (or surface) and the narrowest part is 47.3 cm into the wall along that horizontal slice. This is in effect a plan view, but taken from 50 cm depth below the top of the wall, rather than from the top of the wall. These were taken along a horizontal transect of just over 5 m in length with the left-hand side, the region under the hard cap, and the right-hand side, the region under the soft cap (a 15-cm soft cap with regolith) (as shown in Figure 3.6). Blues and greens depict lower resistivities (wetter conditions), while oranges and reds record higher resistivities (drier conditions). The two plots show a similar distribution of moisture in the wall in both April and September, although the September surveys reveal generally wetter conditions. In both seasons, there is a distinct contrast between the hard capped (LH side) and soft-capped sections (RH side) of the wall, with higher moisture levels under the hard-capped section. While this could suggest that soft capping is more effective in reducing moisture levels in the underlying wall, the exact nature of the walls (for example, differences in porosity and chemical/salt composition) is not known, and thus the effectiveness of soft capping in this situation unproven.

In summary, there is some evidence from the 2D resistivity surveys at Byland that soft capping is more effective than hard capping in reducing moisture levels at 50-cm depth in walls. The dowel data reveal that it may also be better at reducing the variation in moisture levels during the summer months. However, the patterns are not clear-cut, and there are some contradictions in the two data sets. Without more frequent 2D resistivity surveys or a better spatial coverage of dowel data, it is not possible for firm conclusions to be drawn.

There is no one method that provides unambiguous information on moisture levels within walls, and it is difficult to compare results from different methods. However, moisture data from the wall head (Watermark probes) at Byland Abbey suggest that hard capping may be more effective than soft capping at moderating moisture fluctuations at the wall-head. Lower down on the wall, data 2D resistivity surveys and dowels suggest that the opposite is true: hard capping does not moderate moisture levels and fluctuations as well as both soft capping and uncapped stone.

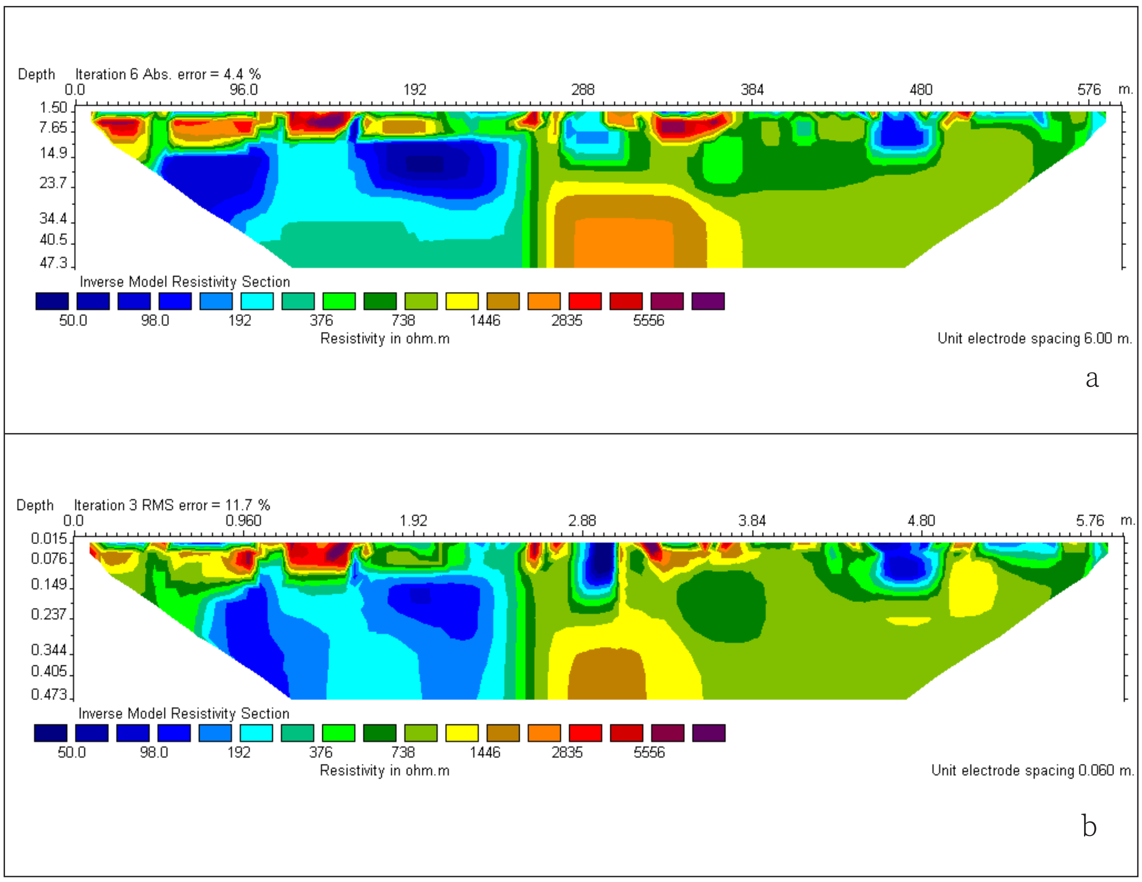

Figure 4.14 2D resistivity graphs showing resistivity in ohm m for hard-capped (left-hand side) and soft-capped (15-cm soft cap with regolith - right-hand side) sections of the wall at Byland Abbey a) April 2005, b) September 2006.

b) Field testing at Hailes Abbey: Dowel and 2D resistivity data

Field-testing at Hailes Abbey employed dowels and 2d resistivity surveys (following the methodology presented in section 3.3.2) both in walls beneath soft capping and walls below bare stone. Sass and Viles reported on this in detail (2006). The key points are summarised here. Figure 4.15 has been created with results from dowels emplaced in east- and west-facing sides of the wall from February to June 2005. Results from each of the 4 10-cm long sections of every dowel are plotted (dots in Figure 4.15) and SURFER used to interpolate between them and produce a contour map of moisture contents. Figure 4.15a has been produced from dowels located up to 30 cm below the wall head, and Figure 4.15b from dowels located lower down the wall (>30 and <70 cm below the wall head). In these greyscale plots, darker tones represent wetter conditions.

These plots reveal similarly complex spatial patterns in moisture contents as the 2D resistivity surveys at Byland. They also show complex temporal patterns. The upper layer (Figure 4.15a) has higher moisture levels than the lower layer (Figure 4.15b). In general, the wall is wetter and the moisture distribution less uniform in the uncapped section (control) than the soft-capped section. This pattern is most clearly expressed in the lower layer (Figure 4.15b). In the upper layer, there are patches of moister wall in the soft capped region adjacent to the uncapped section Both layers under the soft-capped section show most uniform moisture distributions (and lowest moisture levels) during May and June. A statistical analysis of the data shows that the outermost section of the dowels is significantly drier than the innermost sections in summer and winter, with greatest differences seen in summer in the soft-capped sections. As Sass and Viles (2006) highlight, it is important to exhibit caution in the interpretation of such plots, as they can be skewed by individual sections of dowels, with anomalously high % moisture values. Furthermore, the soft capping was installed in January 2005 on a section of wall that had previously been covered for 18 months during conservation works, and is thus likely to have been initially drier.

Figure 4.16 illustrates the averaged dowel moisture conditions for both the uncapped section (control sections) and soft-capped sections for the east and west-facing sides of the wall over the entire monitoring period. There are no statistically significant differences in moisture conditions between the east and west sides for any of the sections. However clear differences between soft capped and uncapped sections were found between June 2004 and January 2005 (when the soft capping was installed) because of the 18 months of covering during conservation work on the soft-capped section. During the summer of 2005, the soft-capped section was significantly drier than the control section, but in winter 2005/2006 the two sections show similar, variable moisture trends. The soft-capped section started to dry out again relative to the hard-capped section in July 2006.

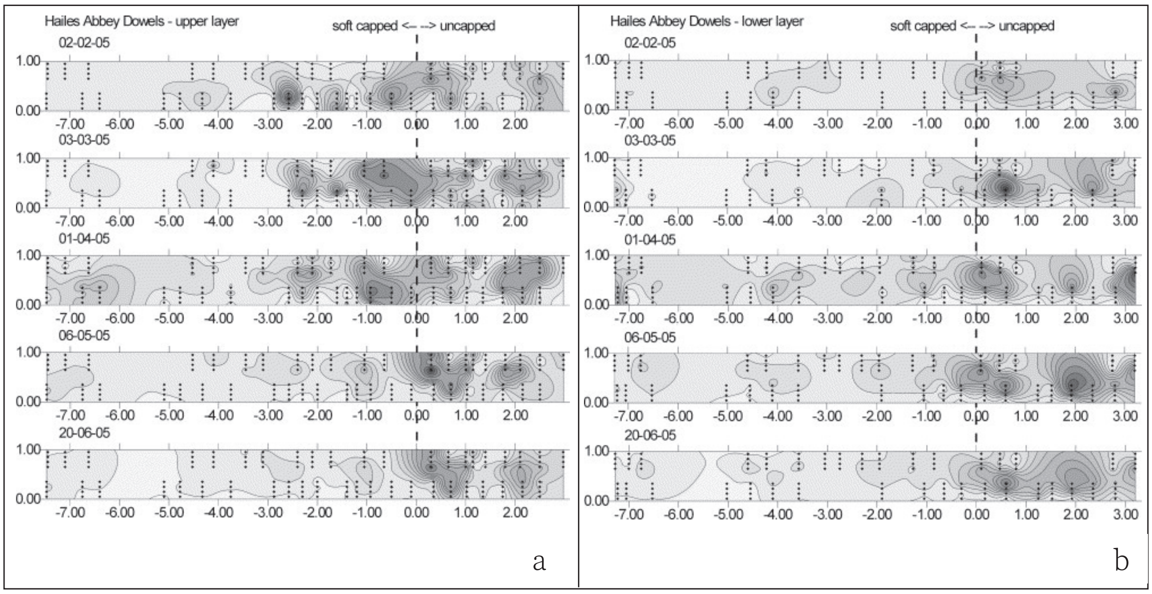

Figure 4.15 Moisture distribution through horizontal 'slices' of the wall using contour plots generated by the SURFER programme for (a) an upper layer (0–30 cm below the wall head) and (b) a lower layer (40–70 m below the wall head). *(reproduced from Sass and Viles 2006)*

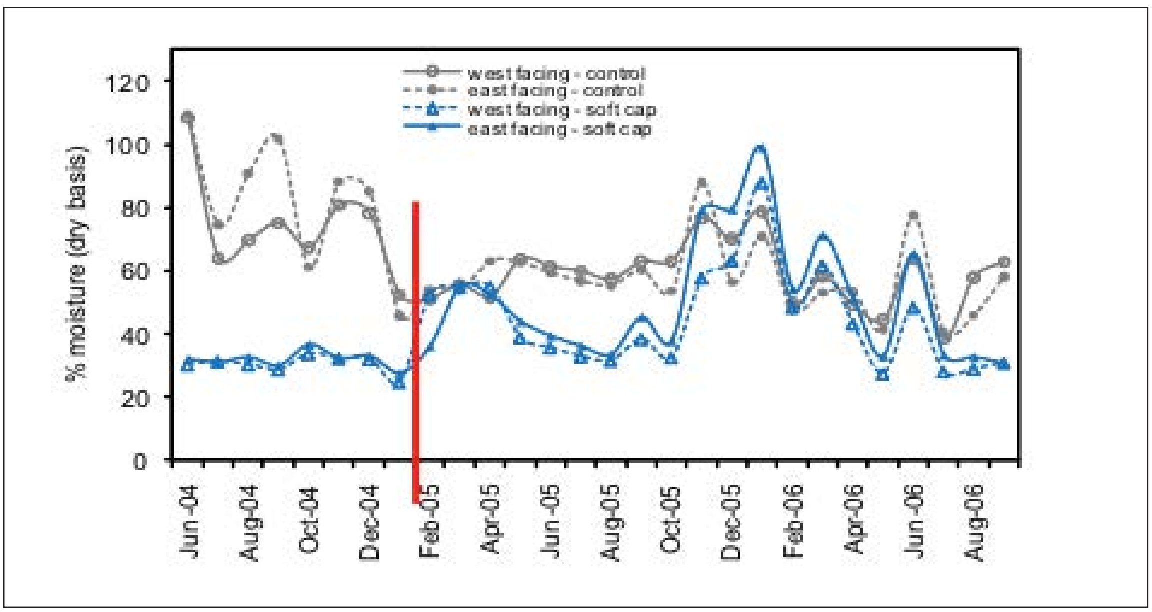

Figure 4.16 Moisture content of wooden dowels (averaged for each set of dowels from all heights within the wall, and across four sections for each dowel), inserted in the mortar in the wall beneath the uncapped (control) and soft-capped sections. The red vertical line marks the date the soft capping was installed.

2D resistivity surveys on both sides of the wall at Hailes were taken in March, April and May 2005, following the methodology outlined in section 3.3.2. Only the results from April 2005 are presented here (Figure 4.17), as there was little change between the measurement periods. Both soft-capped and uncapped sections show a narrow, dry surface zone with wetter patches spreading from *c*.10 to 30 cm into the wall, and drier conditions further in. Figure 4.17 illustrates that the west-facing wall was substantially wetter under the uncapped (control) section than under the soft-capped section, while the east side showed wetter conditions (in two patches) under the soft-capped section. The results of the 2D resistivity surveys of the west-facing wall correlate better with the dowel data (Figure 4.14). The patterns here are less distinct than the ones revealed by the geoelectric surveys at Byland, particularly on the east-facing side of the wall. It would have been helpful to have done further geoelectrical surveys in summer 2005, when the dowel data showed distinctive differences between soft-capped and uncapped sections, but the equipment was not then available.

In summary, there is some evidence at Hailes that soft capping leads to lower levels and reduced fluctuations of moisture in underlying walls. This comes from the data from the arrays of dowels on both the east- and west-facing sides of the wall, although this pattern is restricted to the summer months. The contrast in absolute values is supported by the geoelectric survey on the west side of the wall.

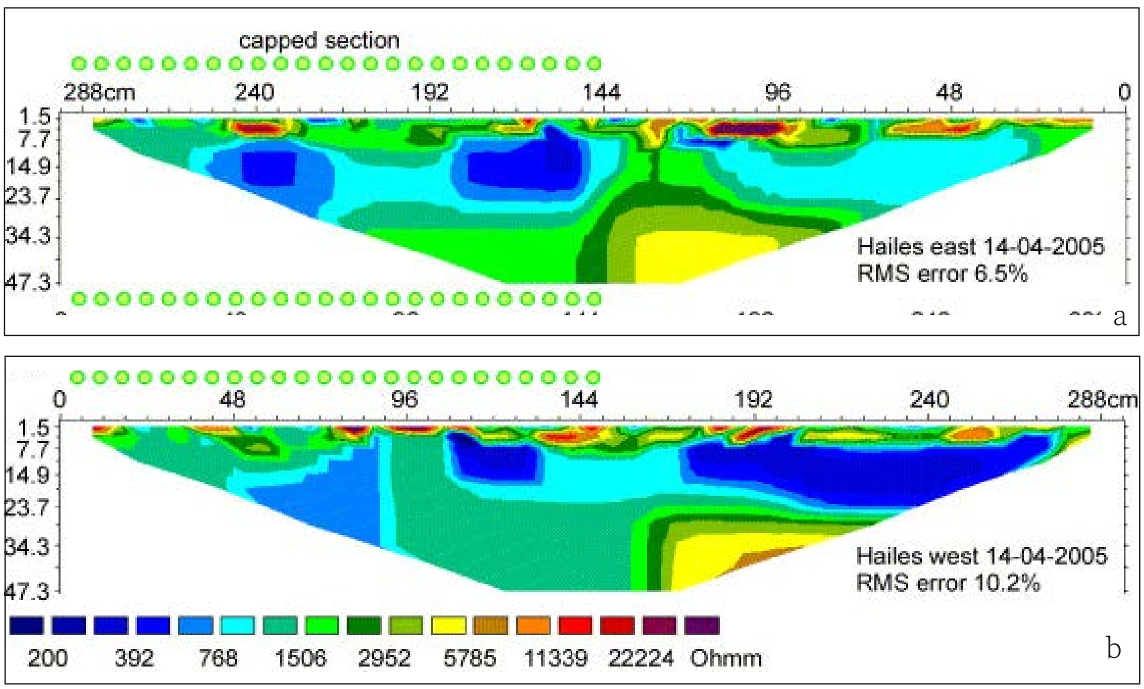

Figure 4.17 Geoelectrics (2D resistivity graphs) showing resistivity (in ohm m) for (a) east and (b) west facing sides under an uncapped (control) section (right-hand side of both profiles) and soft capped section (left-hand side of both profiles) of the wall at Hailes Abbey, April, 2005.

(c) Field testing at Wytham Woods test walls: Dowel and 2D resistivity data

Figure 4.18 shows a summary of the dowel data for Jan to Dec 2011 for all four walls. In this figure, data from 2 dowels have been averaged to produce a single value for each row. Extremely wet conditions were recorded in Jan 2011, including long periods with snow lying on the ground. This may have contributed to the high dowel moisture readings for that month. Figure 4.18 illustrates that moisture contents over the entire year averaged around 30% with little month to month variation, especially for the lower two rows of dowels. More variable behaviour from month to month was observed within the two upper rows of dowels (although still very muted in comparison to the dowel surveys at Byland and Hailes). Highest variability is seen in walls 1 and 4.

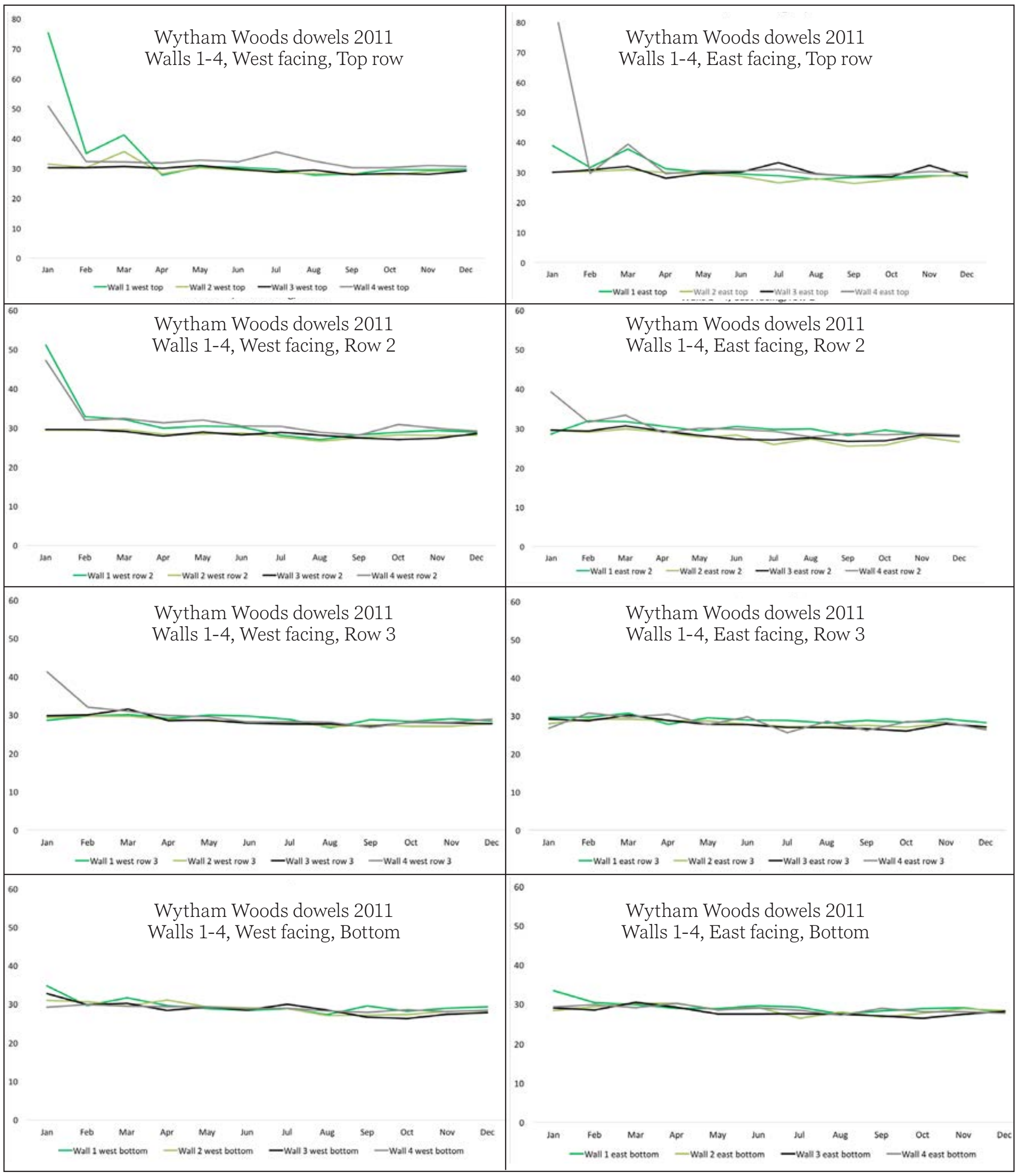

Figure 4.18 Summary dowel data for Wytham Woods test walls, January to December 2011.

Figure 4.19 contains dowel data from rows 1 and 2 over the period from April 2013 to May 2014. Data from 4 dowels have been averaged to produce a single figure for each row (as the dowel network was expanded within these top 2 rows in April 2013 to provide more detailed information of moisture behaviour towards the top of the walls). Wall 1, and to a lesser extent wall 4, shows high variability in monthly moisture levels over the course of the year, with values of 80% and over found in January 2014 within the upper row of dowels. The lower row of dowels shows this behaviour in a more muted way. The other two walls show fairly homogeneous monthly moisture values of around 30%.

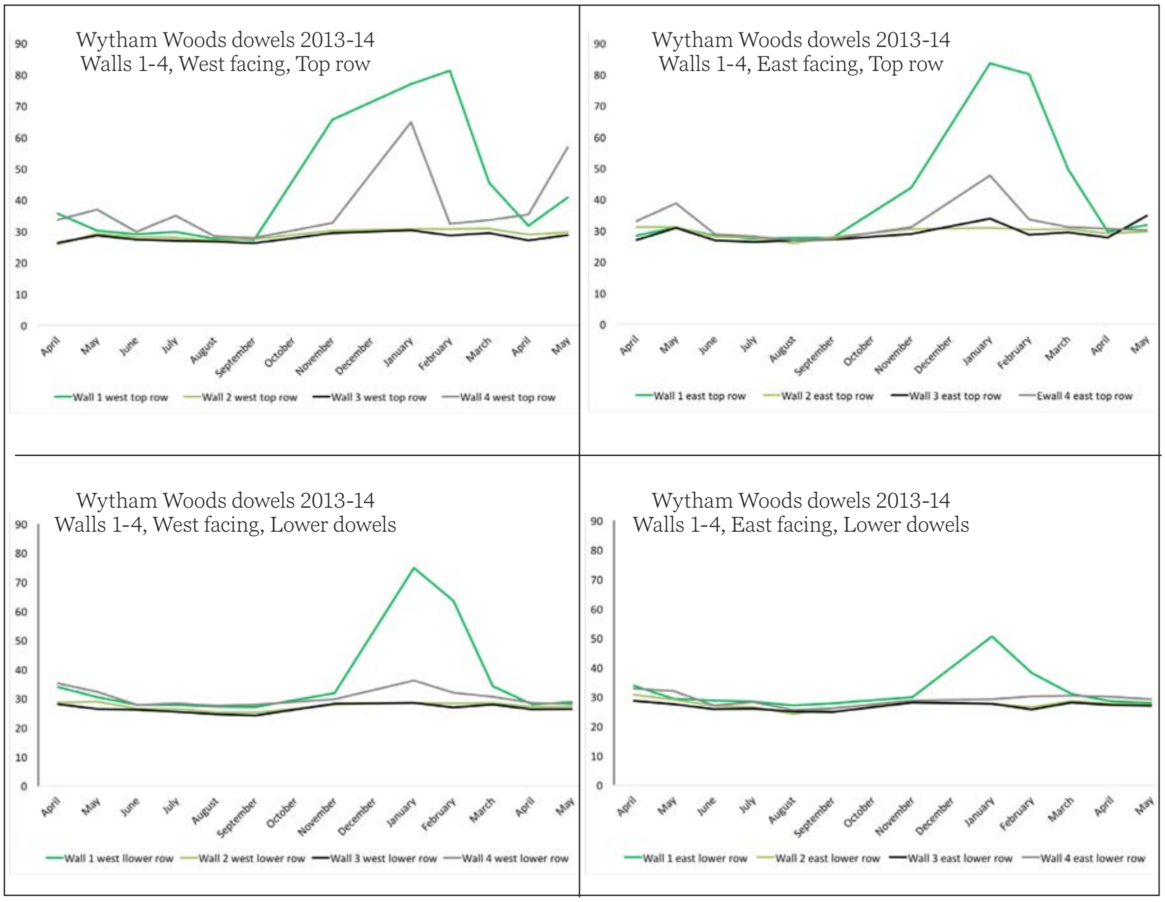

Figure 4.19 Summary dowel data for the upper parts of the Wytham Woods test walls, April 2013 to May 2014.

Monthly rainfall figures compiled in Figure 4.20 from on-site measurements where possible, and data from central Oxford at other periods, provide useful context for the dowel data. The two monitored periods (calendar year 2011 and April 2013–May 2014) are very different in terms of precipitation. 2011 was a dry year with 476.6 mm rainfall and a monthly average of 40 mm, whereas the period April 2013 to May 2014 had a monthly average of 62 mm.

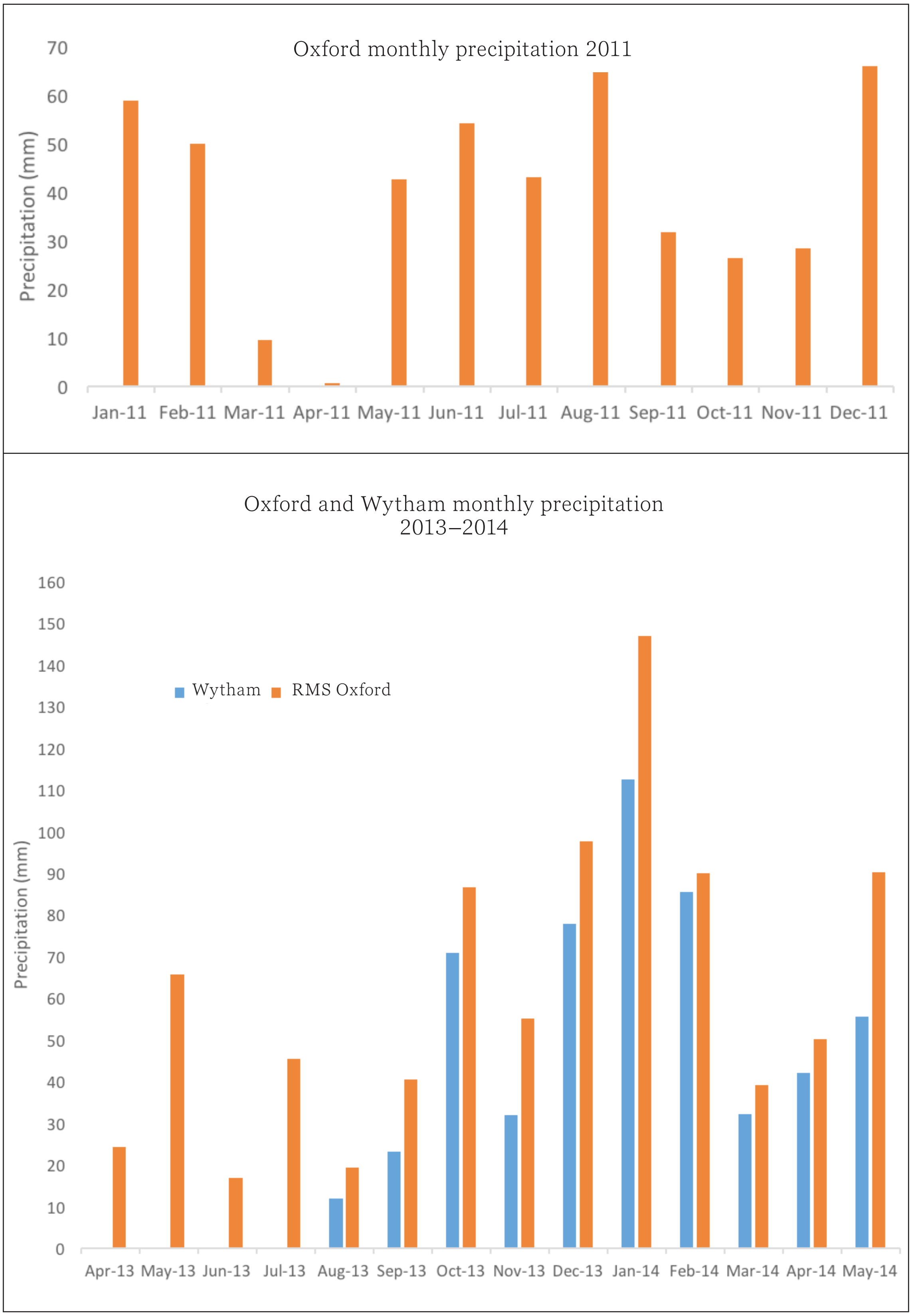

Figure 4.20 Monthly rainfall figures for Jan to Dec 2011 and April 2013 to May 2014 from Oxford (Radcliffe Met Station) and Wytham (on site met station).

To complement the dowel data, two 'snapshots' of the moisture regimes in all four walls were taken, using two 2D resistivity and Protimeter surveys in contrasting climatic conditions (June 2010 and February 2012). Surveys followed vertical transects towards the centre of both faces of each wall, covering nearly the whole profile of the wall. Both months were characterised by low rainfall totals. Results are summarised in Table 4.5 and the surveys from June 2010 shown visually in Figure 4.21.

In contrast to the dowel survey, the 2D resistivity and Protimeter transect results portray walls 2 and 4 as wet, and walls 1 and 3 as drier. All walls were wetter in the February 2012 survey, although they appeared to contain a dry core around mid-transect level.

Table 4.5 Summary information from Protimeter and 2D resistivity surveys in June 2010 and February 2012 at Wytham Woods test walls

Date	Results	Wall 1 Soft capped	Wall 2 Soft capped	Wall 3 Hard capped	Wall 4 Hard capped
June 2010	Protimeter (mean)	E = 14.2 W = 14.1	E = 15.9 W = 15.9	E = 12.4 W = 12.8	E = 16.6 W = 17.3
	2D resistivity – near surface	Dry (1000–4000)	Medium (500–2000)	Dry (1000–4000)	Medium/wet (50–2000)
	2D resistivity – 10-20 cm inside	Medium wet (30–150)	Wet (30–100)	Medium wet (50–150)	Wet (30–100)
	2D resistivity – > 20 cm inside	Dry core mid transect (1000–2000)	Medium core mid to low transect (150-1000)	Dry to medium core mid to low transect (500-2000)	Medium core mid transect (150-1000)
Feb 2012	Protimeter (mean)	E = 19.2 W = 16.8	E = 19.5 W = 19.4	E = 15.5 W = 15.2	E = 20.7 W = 23.3
	2D resistivity – near surface	Medium dry (1000–3000)	Very wet with dry patches (5 – 2000)	Medium dry (1000-3000)	Very wet with dry patches (5-2000)
	2D resistivity – 10–20 cm inside	Very wet (5–500)	Very wet (5–500)	Very wet (5–500)	Very wet (5–500)
	2D resistivity – > 20 cm inside	Dry core mid transect (1000–2000)	Small dry core mid transect (1000–2000)	Dry core mid transect (1000–2000)	Small dry core mid transect (1000–2000)

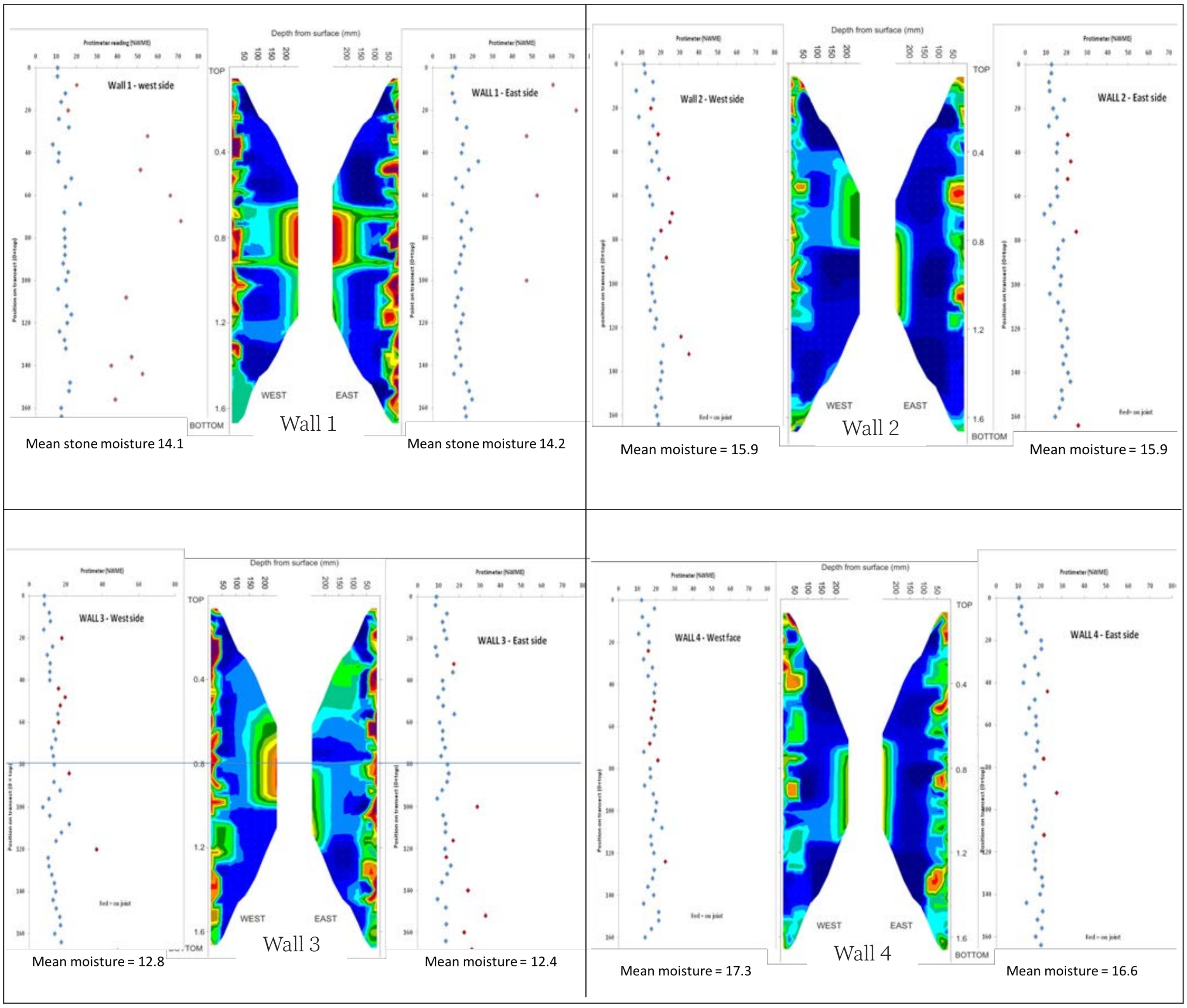

Figure 4.21 2D resistivity surveys and Protimeter transect surveys of east and west facing sides of the four Wytham Woods test walls, June 2010.

The monthly Protimeter survey at the Wytham Woods test walls (see Chapter 3, section 3.3.3 for methodology) can also be used to visualise changes in surface moisture regimes on soft and hard- capped walls. Data for the whole of both west and east-facing sides of the four test walls are presented in Figure 4.22 for the period July 2009 to January 2012 while sample contour plots from February and April 2011 are shown in Figure 4.23, and data for the top four courses (above and below the lead flashing) from July 2009 to January 2012 and April 2013 to January 2014 are presented in Figure 4.24.

From Figure 4.22 it is evident that there was considerable variation in surface moisture conditions across the whole façade, with walls 2 and 4 experiencing the most episodes of 'damp to wet' and 'wet' conditions, especially on the east face. Wall 3 was the driest, with the most frequent episodes of 'dry' and 'dry to damp' conditions, especially on the east face. Wall 1 had the most 'dry to damp' conditions. As Figure 4.23 indicates, the walls also showed high spatial variability in surface moisture contents. Wall 2 often had wetter conditions towards the base.

Whole wall surveys July 2009–January 2012

West facing side

Month	Wall 1	Wall 2	Wall 3	Wall 4
Jul-09	Dry to damp	Dry to wet	Dry to wet	Damp to wet
Aug-09	Dry to wet	Damp to wet	Damp	Wet
Sep-09	Dry to wet	Damp to wet	Dry to wet	Damp
Oct-09	Dry to damp	Dry to damp	Dry to wet	Damp to wet
Nov-09	Dry to wet	Damp to wet	Damp to wet	Wet
Dec-09	Dry to wet	Wet	Damp to wet	Wet
Jan-10	Damp to wet	Wet	Damp to wet	Wet
Feb-10				
Mar-10	Dry to damp	Dry to damp	Dry	Dry to damp
Apr-10	Dry to damp	Damp	Dry to damp	Wet
May-10				
Jun-10				
Jul-10				
Aug-10	Dry to wet	Damp to wet	Dry to wet	Wet
Sep-10	Damp to wet	Wet	Damp to wet	Wet
Oct-10				
Nov-10	Dry to wet	Damp to wet	Dry to wet	Damp to wet
Dec-10				
Jan-11				
Feb-11	Damp to wet	Damp to wet	Damp	Wet
Mar-11	Damp to wet	Damp to wet	Dry to wet	Wet
Apr-11	Dry	Dry	Dry	Dry
May-11	Dry to damp	Dry to damp	Dry to damp	Damp
Jun-11	Dry to damp	Dry to damp	Dry	Dry to damp
Jul-11	Dry to damp	Dry to damp	Dry to damp	Damp
Aug-11	Damp to wet	Damp to wet	Damp to wet	Damp to wet
Sep-11	Dry to damp	Dry to damp	Dry	Dry to damp
Oct-11	Damp	Damp to wet	Dry to damp	Damp to wet
Nov-11	Dry to wet	Damp to wet	Dry to wet	Damp to wet
Dec-11	Wet	Wet	Damp to wet	Wet
Jan-12	Dry to wet	Damp to wet	Dry to wet	Damp to wet

East facing side

Month	Wall 1	Wall 2	Wall 3	Wall 4
Jul-09	Dry to damp	Damp to wet	Dry to damp	Damp
Aug-09	Dry to damp	Damp to wet	Dry	Damp to wet
Sep-09	Dry to damp	Damp to wet	Dry	Damp
Oct-09	Damp	Damp to wet	Dry to wet	Wet
Nov-09	Damp to wet	Wet	Damp to wet	Wet
Dec-09	Damp to wet	Wet	Damp to wet	Wet
Jan-10	Damp to wet	Wet	Damp to wet	Wet
Feb-10				
Mar-10	Dry to damp	Damp	Dry	Dry to wet
Apr-10	Damp	Damp to wet	Dry to damp	Damp to wet
May-10				
Jun-10				
Jul-10				
Aug-10	Dry to wet	Wet	Dry to wet	Wet
Sep-10	Wet	Wet	Damp to wet	Wet
Oct-10				
Nov-10				
Dec-10				
Jan-11				
Feb-11	Damp to wet	Wet	Dry to damp	Wet
Mar-11	Damp to wet	Damp to wet	Damp	Wet
Apr-11	Dry	Dry to damp	Dry	Dry to damp
May-11	Dry to damp	Dry to damp	Dry	Dry to damp
Jun-11	Dry to damp	Damp	Dry	Dry to damp
Jul-11	Dry to damp	Damp	Dry	Dry to damp
Aug-11	Damp	Damp to wet	Damp	Damp to wet
Sep-11	Dry to damp	Damp	Dry to damp	Dry to damp
Oct-11	Damp	Damp towet	Damp	Damp to wet
Nov-11	Damp	Damp to wet	Damp	Damp to wet
Dec-11	Damp to wet	Wet	Damp	Wet
Jan-12	Damp to wet	Wet	Damp	Wet

Figure 4.22 Colour-coded summary of monthly Protimeter surveys of the entire west- and east-facing sides of the four Wytham Woods test walls.

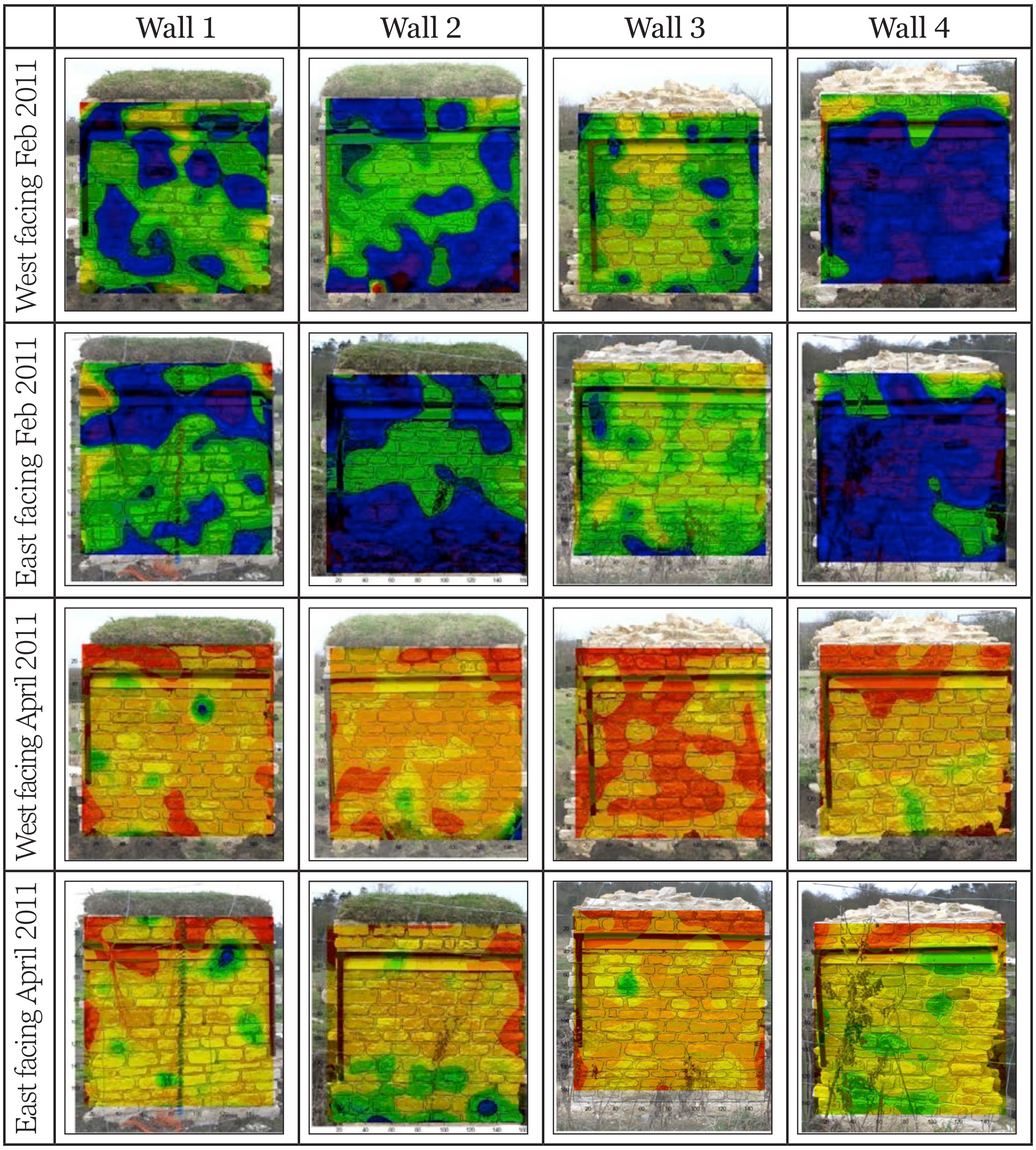

Figure 4.23 Sample contour plots of Protimeter surface moisture survey data from February and April 2011.

WEST facing

Month	Wall 1	Wall 2	Wall 3	Wall 4
Jul-09	Dry to damp	Dry to damp	Dry to wet	Damp to wet
Aug-09	Dry to damp	Damp	Damp to wet	Damp to wet
Sep-09	Dry to damp	Dry to damp	Dry to wet	Damp
Oct-09	Dry to damp	Dry to damp	Damp to wet	Wet
Nov-09	Dry to wet	Damp to wet	Wet	Wet
Dec-09	Dry to damp	Damp to wet	Damp to wet	Damp to wet
Jan-10	Damp to wet	Wet	Wet	Wet
Feb-10				
Mar-10	Dry to damp	Dry to damp	Dry	Dry to damp
Apr-10	Dry to damp	Damp	Dry to damp	Damp to wet
May-10				
Jun-10				
Jul-10				
Aug-10	Dry to wet	Damp to wet	Dry to wet	Wet
Sep-10	Damp to wet	Wet	Damp to wet	Wet
Oct-10				
Nov-10				
Dec-10				
Jan-11				
Feb-11	Damp to wet	Damp to wet	Damp to wet	Damp to wet
Mar-11	Damp to wet	Damp to wet	Dry to wet	Damp to wet
Apr-11	Dry	Dry	Dry	Dry
May-11	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Jun-11	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Jul-11	Dry to damp	Damp to wet	Dry to wet	Dry to damp
Aug-11	Damp to wet	Damp to wet	Dry to wet	Damp to wet
Sep-11	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Oct-11	Dry to damp	Damp to wet	Dry to wet	Damp to wet
Nov-11	Dry to wet	Damp to wet	Dry to wet	Damp to wet
Dec-11	Damp to wet	Damp to wet	Damp to wet	Wet
Jan-12	Dry to wet	Damp to wet	Damp to wet	Damp to wet
Feb-12				
Mar-12				
Apr-12				
May-12				
Jun-12				
Jul-12				
Aug-12				
Sep-12				
Oct-12				
Nov-12				
Dec-12				
Jan-13				
Feb-13				
Mar-13				
Apr-13	Dry to wet	Dry to damp	Dry to damp	Dry to damp
May-13	Dry to wet	Damp to wet	Dry to wet	Dry to wet
Jun-13	Dry to damp	Dry to damp	Dry to wet	Dry to damp
Jul-13	Damp to wet	Dry to damp	Dry to wet	Dry to wet
Aug-13	Dry to damp	Dry to damp	Dry	Dry to damp
Sep-13	Dry to damp	Dry to damp	Dry to damp	Dry to wet
Oct-13	Dry to damp	Dry to damp	Dry to wet	dry to wet
Nov-13	Damp to wet	Damp to wet	Dry to wet	Damp to wet
Dec-13	Damp to wet	Damp to wet	Dry to wet	Dry to wet
Jan-14	Dry to wet	Dry to wet	Dry to wet	Dry to wet

EAST facing

Top 4 courses

July 2009 to January 2014

Month	Wall 1	Wall 2	Wall 3	Wall 4
Jul-09	Dry to damp	Dry to damp	Dry	Dry to damp
Aug-09	Dry	Dry to damp	Dry	Damp to wet
Sep-09	Dry	Dry to damp	Damp	Damp
Oct-09	Damp	Damp	Wet	Wet
Nov-09	Wet	Wet	Damp to wet	Wet
Dec-09	Damp	Damp to wet	Damp	Damp to wet
Jan-10	Damp to wet	Wet	Damp to wet	Wet
Feb-10				
Mar-10	Dry to damp	Dry to damp	Dry	Dry to damp
Apr-10	Dry to wet	Dry to wet	Dry to damp	Dry to wet
May-10				
Jun-10				
Jul-10				
Aug-10	Dry to damp	Damp to wet	Dry to damp	Wet
Sep-10	Wet	Wet	Damp	Wet
Oct-10				
Nov-10				
Dec-10				
Jan-11				
Feb-11	Damp to wet	Wet	Damp	Damp to wet
Mar-11	Damp to wet	Damp to wet	Damp	Damp to wet
Apr-11	Dry to damp	Dry	Dry	Dry to damp
May-11	Dry to damp	Dry to damp	Dry	Dry to damp
Jun-11	Dry to damp	Dry to damp	Dry	Dry to damp
Jul-11	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Aug-11	Dry to wet	Damp to wet	Dry to damp	Dry to wet
Sep-11	Dry to damp	Dry to damp	Dry	Dry to damp
Oct-11	Dry to wet	Damp to wet	Damp	Damp
Nov-11	Damp to wet	Damp to wet	Damp to wet	Damp to wet
Dec-11	Damp to wet	Wet	Damp	Damp to wet
Jan-12	Damp to wet	Wet	Damp	Wet
Feb-12				
Mar-12				
Apr-12				
May-12				
Jun-12				
Jul-12				
Aug-12				
Sep-12				
Oct-12				
Nov-12				
Dec-12				
Jan-13				
Feb-13				
Mar-13				
Apr-13	Dry to wet	Dry to damp	Dry	Dry to damp
May-13	Damp to wet	Damp to wet	Dry to damp	Dry to wet
Jun-13	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Jul-13	Dry to wet	Dry to wet	Dry to damp	Dry to wet
Aug-13	Dry to damp	Dry to damp	Dry to damp	Dry to damp
Sep-13	Dry to damp	Dry to wet	Dry to damp	Dry to damp
Oct-13	Dry to wet	Dry to wet	Dry to damp	Dry to wet
Nov-13	Damp to wet	Dry to wet	Damp	Damp to wet
Dec-13	Wet	Wet	Damp to wet	Damp to wet
Jan-14	Dry to wet	Damp to wet	Damp	Damp to wet

Figure 4.24 Colour-coded summary of monthly Protimeter surveys for the top 4 courses of stone (above and below the lead flashing) for west and east facing sides of the four Wytham Woods test walls.

In summary, the wooden dowel, 2D resistivity and Protimeter data from the test walls at Wytham Woods do not show any significant differences between the soft and hard-capped walls in terms of moisture regimes at the surface and at depth. The dowel data indicate that walls 1 and 4 experienced periods of wetter conditions within the walls; this might be explained by the fact that both walls have lime mortar in the upper layers (cf. walls 2 and 3, which have a cement-based mortar in the cap). However, the 2d resistivity data reveal wetter conditions extending in to the wall along a vertical transect in walls 2 and 4 in both 2010 and February 2012. The monthly protimeter surveys indicate that walls 2 and 4 also experienced the wettest surface conditions.

4.3.3 How does soft capping influence run-off down the wall face?

a) Field testing at Wytham Woods test walls

Installation of the system of guttering and down pipes on the test walls at Wytham Woods provided an opportunity to carry out regular monitoring of the reaction of each wall to rainfall events. After many difficulties were experienced collecting runoff after storms between August 2010 and September 2012, a series of field experiments were carried out in July 2013 (see Chapter 3, section 3.3.3. for the methodology). The results of these experiments have been published in detail in Hanssen and Viles (2014), and are summarised below in Figure 4.25.

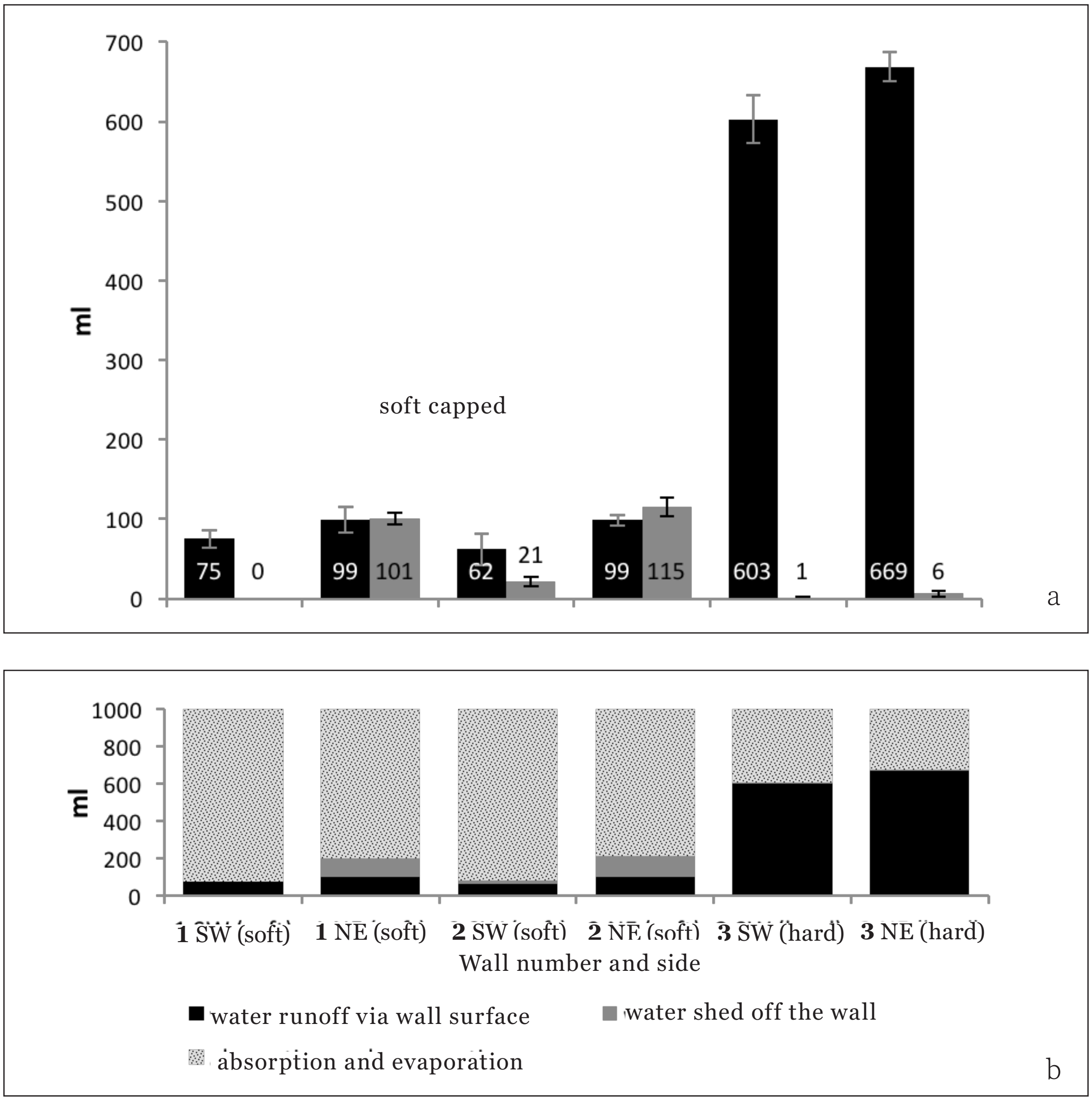

Figure 4.25 Water flows from soft- and hard-capped walls after rain simulation. (a) The amount of water running down the wall surface in comparison with the amount shed off the wall. Error bars indicate the standard error of the mean, (b) Partitioning of the 1 litre of water applied into runoff, shed and absorbed/evaporate pathways.
(reproduced from Hanssen and Viles 2014)

Figure 4.25a compares the water runoff after the simulated rainfall (black bars) with the amount shed (grey bars) from soft-capped walls 1 and 2, and hard-capped wall 3. The most notable finding is the almost 90% reduction in the amount of water running down the face on the two soft-capped walls, in comparison with that running down the hard-capped wall. More water was also shed from the soft-capped walls (up to 115 ml) than the hard-capped wall (negligible amounts). Furthermore, Figure 4.25 b) shows that a much higher proportion of the simulated rainfall was absorbed or evaporated from soft-capped surfaces compared to the hard-capped ones. This was also true of incident rainfall. These results confirm expectations that healthy soft capping should reduce the amount of surface runoff down wall faces. It should also reduce biofouling from algal and other biofilms. Surveys of the walls at Wytham Woods over time illustrate that this has indeed occurred. Dr Vanessa Winchester, a lichen expert, surveyed the lichen flora on the Wytham Woods test walls in August 2012 and found 14 species in all. The top and upper parts of walls 3 and 4 were found to have particularly lush lichen floras, including *Xanthoria parietina, Lecanora dispersa, Caloplaca citrina and Verrucaria nigrescens* (as shown in Figure 4.26).

Figure 4.26 Lichen colonisation on the Wytham Woods test walls.

Clear differences in colouration of the upper two courses of the stonework were observed under the soft capping (light) and hard capping (darker), which reflect colonisation by microbial biofilms and lichens on the hard-capped walls (Figure 4.27).

Figure 4.27 Dark colouration on the top two courses of stonework on hard-capped but not on the soft-capped walls at Wytham Woods.

b) Field observations at Kirkham Priory

The experimental results from the test walls at Wytham Woods are confirmed by observations at Kirkham Priory. As Figure 4.28 indicates, black streaking is a common feature of many of the high-standing ruined limestone walls at Kirkham Priory. The black colouration results from microbial biofilms (probably algal-dominated) that grow preferentially along pathways where water flows frequently down the walls. In one location where soft capping was installed above such black streaking, observations made during a rainstorm illustrate that water flow was heavily reduced. Over time the biofilms should dieback, and the streaking become less apparent.

Figure 4.28 Streaking at Kirkham Priory in (a) 2014 and (b) 2016.

4.3.4. Does soft capping accelerate chemical weathering of the wall head through acidifying water penetrating into the masonry?

a) Field testing at Wytham Woods

Initial tests to determine whether soft capping would cause accelerated chemical weathering were carried out at Wytham Woods, using some accurately prescanned limestone test blocks (see Chapter 3, section 3.3.4 for full details of the methodology). Unfortunately, the scanning method proved not accurate enough in detecting change in topography as a result of chemical weathering over the period of exposure (1 year). A second method was then trialled, using a series of accurately pre-weighed calcite crystals (as described fully in Chapter 3, section 3.3.3.6) to detect chemical weathering. Four sets of calcite crystals were emplaced at Wytham in November 2010, and collected eighteen months later, in April 2012. Two sets of 5 calcite crystals were buried at the base of the soft capping on walls 1 and 2, and two sets of were glued to the top of the hard capping on walls 3 and 4 with bathroom sealant. Before and after emplacement, each crystal was weighed on a high accuracy balance. It was expected that chemical weathering caused by the layer of soil on walls 1 and 2 would result in higher weight loss than that occurring as a result of rainwater impacts on the samples exposed on walls 3 and 4. The data show no evidence of this, indeed the average weight loss from the hard capping was 0.55% (N=3) and the average weight loss from the soft capping was 0.14% (N=10). However, the results are not conclusive, as 7 samples were lost from the hard capping surface during the 18-month period.

b) Field testing at Castle Acre Priory

As described in Chapter 3, section 3.3.5 a fuller array of materials (limestone, calcite and gypsum) was used to evaluate whether or not soft capping enhances chemical weathering of wall heads. Twenty replicates of each type of material were pre-weighed, laser scanned and photographed in detail before exposure. Twelve replicates of each material type were then buried at the base of the soft capping on installation in February 2012 (four under each of the three types of soft capping), and four replicates of each left on hard-capped surfaces. Finally, four replicates of each material type were kept as laboratory controls. The field experiment lasted for 2 years, with samples removed in March 2014. Unfortunately, the samples left on the hard-capped surfaces were all lost (probably taken by crows or other birds). This meant that researchers had to use other data to compare the weight loss from hard-capped surfaces with the weight loss from soft-capped ones, (a) They looked at data from the same material types left out for 9 months on hard-capped surfaces at Wytham Woods as part of a separate project (carried out by Noreen Zaman, University of Oxford) and (b) theoretical calculations based on the known reactivity of the materials, the rainfall total for Norfolk over the same 2-year period, and the average pH of rainfall from the area.

Data is presented here on visual change, weight loss and changes in surface topography and chemistry (using repeat laser scanning, and SEM). Figure 4.29 illustrates the visual changes in samples after 2 years at the base of the Castle Acre Priory soft capping. The gypsum samples were the only ones to show clear change. This is not surprising, as gypsum is a very reactive material. More detailed observations using optical microscopy and SEM showed that some calcite samples had minor deposition of soil particles along cracks, and that some limestone samples had experienced both minor deposition of soil particles in ooid pits, as well as occasional detachment of oolites (see Figure 4.30)

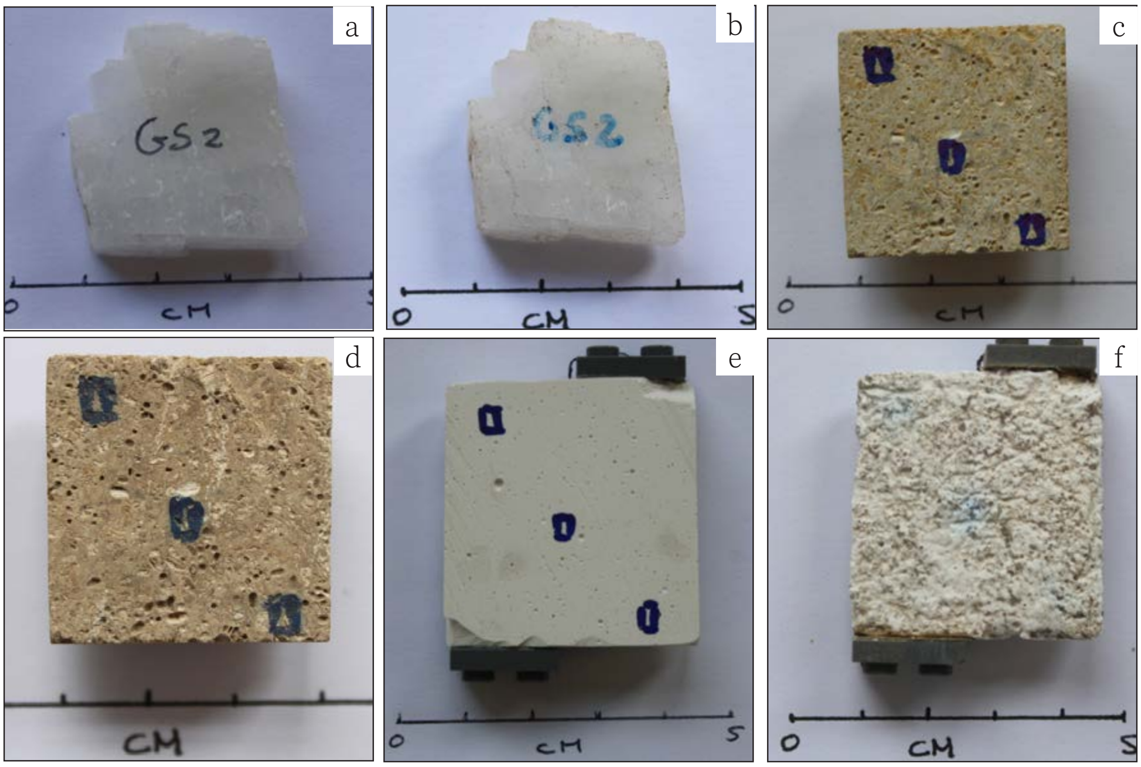

Figure 4.29 Visual changes in calcite crystals (a and b), limestone (c and d) and gypsum (e and f) tablets before and after two years at the base of soft capping at Castle Acre Priory.

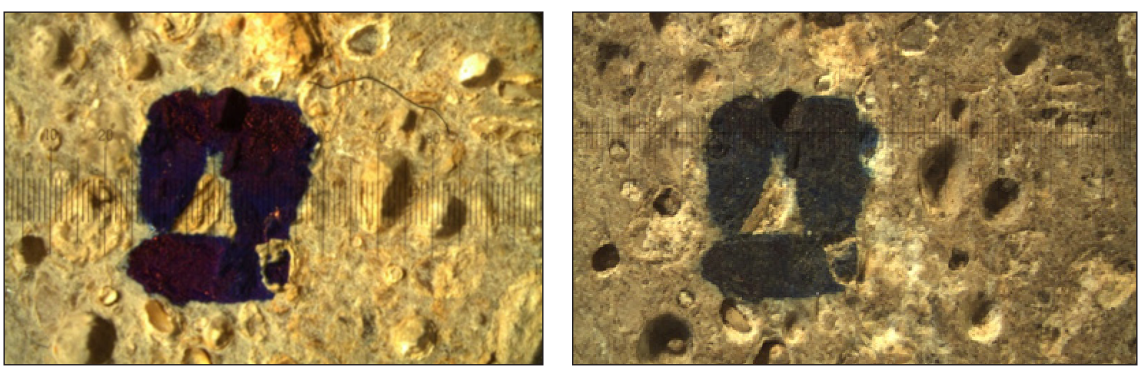

Figure 4.30 Optical microscope images from (a) 2012 (before exposure) and (b) 2014 (after 2 years at the base of grass soft capping – strip 2 – at Castle Acre Priory) illustrating detachment of fragments of ooids.

Table 4.6 Weight loss results (% initial dry weight) afer 2 years' exposure at Castle Acre Priory			
	Calcite	Limestone	Gypsum
Strip 1 (grass + sedum)	Mean: 0.15 Standard dev: 0.07	Mean: 0.38 Standard dev: 0.89	Mean: 23.86 Standard dev: 4.28
Strip 2 (grass)	Mean: 0.27 Standard dev: 0.21	Mean: 0.08 Standard dev: 0.14	Mean: 21.23 Standard dev: 2.99
Strip 3 (sedum mat)	Mean: 0.20 Standard dev: 0.22	Mean: -0.02 Standard dev: 0.18	Mean: 13.42 Standard dev: 7.44
Hard cap (Wytham)	0.27	0.53	
Hard cap (calculated)	0.30		100

Weight loss results are summarised in Table 4.6. Weight losses for all three material types were lower under soft capping than would be expected from exposed surfaces of the ruin (except for calcite crystals from strip 2 (grass) which showed equivalent rates of weathering). These results are not surprising, as soil water pH from the soft capping was around 7.7, whereas the pH of rainfall in this area is around 5.6. Soil waters in soft capping are likely to be less acidic than rainfall in most locations. Furthermore, the soil in particular under the sedum mat in strip 3 was notably dry, which will also retard the rate of chemical weathering.

The laser scanning data back up the weight loss data. Only the limestone blocks were scanned before and after exposure (by John Meneely, Department of Geography, Queens University, Belfast). The accuracy of the Konica Minolta Vi9i scanner used is 0.05mm. Registration errors (which are values in mm of bringing the two scans – pre- and post-exposure – into the same coordinate system) are of the order of 0.018–0.030 mm. The laser scan data show that there has been very little overall change (if any) on the surfaces of the blocks from the soft capping in comparison with the control blocks. Allowing for the registration error and the accuracy of the machine, the only real difference was an increase in the minimum heights of GS3, GS4, (both from strip 1) GSS2 from strip 2, and SS2, SS3 & SS4 (all from strip 3) post-exposure; possibly due to material filling small pits on the surface.

4.4 Research question 3

How does the performance of soft capping alter over time in comparison with hard capping?

4.4.1 How does the appearance of turf-based soft caps alter over time? Repeat photography from Byland, Hailes, Thornton and Wytham Woods

Turf-based capping changes in appearance seasonally (see Figures 4.31 (Byland), 4.32 (Hailes), 4.33 (Thornton) and 4.34 (Wytham Woods). Lush growth in the growing season is followed by dieback during dry periods, when the entire turf cover can go brown. Wetter periods during the growing season lead to renewed, sometimes luxuriant, growth. Drier years result in poorer growth. The edges of turf-based soft capping experience some erosion, as this is the harshest microenvironment for turf capping. At Hailes Abbey and the test walls at Wytham Woods, the addition of sedum plugs to the edges led to greater stability and reduced erosion. The photo sequences illustrate some episodic growth in other flowering plants, but the capping remains dominated by forbs and grasses.

Turf-based soft capping is not always successful. At Howbury Moated site (Figure 4.35), and at triforium level within the nave of the main abbey church at Rievaulx (Figure 4.36), conditions were too harsh to result in the successful establishment of a healthy turf. At Howbury, the narrow wall tops and dry conditions meant the turf never thrived. At Rievaulx, while light levels were adequate, sheltering from the stonework above meant that little rainfall was received, and growth limited. However, even though the capping appeared dead, it has successfully remained in place, and provides some sort of protection to the stone underneath.

Figure 4.31 Byland Abbey soft capping on the Lane wall (Feb 2004–Jan 2016).
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Figure 4.32 Changing appearance of soft capping at Hailes Abbey on cloister arches.
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Figure 4.33 Changing appearance of soft capping at Thornton Abbey.
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Figure 4.34 Changing appearance of soft capping on the Wytham Woods test walls.
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Figure 4.35 Failed soft capping at Howbury moated site (Photo taken in 2010). ©*Heather Viles, University of Oxford*

Figure 4.36 Failed soft capping at Rievaulx Abbey. ©*Heather Viles, University of Oxford*

4.4.2 How does the species composition of turf-based soft caps change over time? Ecological surveys from Byland, Kirkham, Thornton and Hailes

Ecological surveys were commissioned in 2004 and 2007 at Byland Abbey, Kirkham Priory and Thornton Abbey from John Thompson. The original turf flora in 2004 (from the local area where the turf was cut) can be compared with the flora on the wall heads three years later. Species presence was recorded and frequency of occurrence estimated on the DAFOR scale (D=dominant, A=abundant; F=frequent; O=occasional and R=rare).

In 2004, all three sites had turfs composed of up to 10 common and widespread grasses, which was typical of the flora of sites on neutral soils in NE England at low altitude. The principal species found across the three sites were Perennial ryegrass (*Lolium perenne*), Yorkshire fog (*Holcus lanatus*), Common bent (*Agrostis tenuis*) and Red fescue (*Festuca rubra*). Significant changes in the flora of the soft capping were observed between 2004 and 2007, with considerable dieback at Kirkham Priory. Grass species have been lost at all three sites, whilst the diversity of herbaceous species has increased.

At Byland, Red fescue (*Festuca rubra*) continued to be frequent or abundant, whereas Perennial ryegrass (*Lolium perenne*) has gone from being locally frequent to rare, and Yorkshire Fog (*Holcus lanatus*) was not observed at all in 2007. *Dactylis glomerata* (Cocksfoot) has become frequent on the long wall at Byland. Where grasses have died, the bare substrate has been colonised by a wide range of annuals and biennials that have seeds that are wind-borne or carried in by animals (such as birds and ants). The surveys confirm that when the original turf became dry, it was colonised by opportunistic forbs. It seems probable that grasses such as red fescue (*Festuca rubra*) and smooth meadow-grass (*Poa pratensis*) will survive best in the longer term, regenerating from their own seed. Sedum acre was recorded in 2007 as locally dominant in the old soft capping over the vaults at Kirkham Priory, and *Festuca rubra* was the most commonly observed grass in all the soft capping at Kirkham Priory and Thornton by 2007. White clover (*Trifolium repens*) was frequent to abundant in 2004, but absent in 2007.

In October 2007, English Heritage commissioned a more in-depth survey of species composition at Hailes Abbey. It compared the species present in the turf of the soft capping on the long wall along the east cloister (capped in January 2005) with the species in the adjacent field, from which the turf had originally been extracted. An unpublished report for English Heritage by Lush and Garnett (2007) provides detail of the results.

A modified version of the Common Standards Monitoring methodology was used which involved sampling 20 points each on the wall-head and in the field. The survey also employed 5 quadrats (25 x 25 cm) on the wall head and in the field to provide more detailed data. Within the quadrats % cover of all vascular plants was recorded, and the results used to determine the National Vegetation Classification (NVC) type. The vegetation was classified as MG6a *Lolium perenne–Cynosurus cristatus* grassland, which is commonly found in semi-improved grasslands. Perennial rye-grass (*Lolium perenne*) was less common on the wall head than in the field (an average 29% cover compared with 43%), whilst Cocksfoot (*Dactylis glomerata*) and Red fescue (*Festuca rubra*) were both more abundant on the wall head (17% and 28%) than in the field (3% and 12%). The authors of the report propose that it is likely that the soft capping at Hailes Abbey will continue to see declines in perennial rye-grass, and a gradual reduction in turf height as plant growth becomes inhibited through the washing out of nutrients and minerals. However, at the time of the survey, the wall head turf was higher than the turf in the field (over 22 cm vs. 8 cm on average), probably because it was not subject to grazing.

In September 2011 another vegetation survey was carried out at Hailes Abbey by the same authors. Their research showed that the vegetation capping was still intact with little evidence of erosion, but there had been considerable changes in the flora (as they had predicted in 2007). The authors ascribe these changes to rapid leaching of nutrients and lack of moisture in the soft capping soils. The community in 2011 had altered from MG6a to MG11a (*Festuca rubra–Agrostis stolonifera–Potentilla anserina grassland*) *Lolium perenne* sub-community. Vegetation heights averaged nearly 15 cm at the time of the 2011 survey, and *Lolium perenne* numbers had continued to decline, whilst dicotyledons were largely absent, and bryophytes completely absent.

4.4.3 How do more complex designs of soft capping perform over time? Repeat photography from Godstow Nunnery and Castle Acre Priory

At two sites, a range of different soft capping types was trialled. At Godstow Nunnery commercial turf, sedum mat and seeded mats were compared with the usual locally cut turf. The soft capping types were trialled with and without water-retaining gels. At Castle Acre Priory, local turf-based capping (with and without sedum plugs at the edges) was compared with the same type of sedum mat used at Godstow. Figures 4.37 and 4.38 illustrate how the different cappings evolved visually over time. At Godstow the seeded mat did not perform well, with little growth of the seeds within the mat. The commercial turf also performed poorly.

At Castle Acre Priory, all three cappings performed well, showing clear visual changes with seasons and as a response to wet and dry periods.

Figure 4.37 Changes in appearance to grass and sedum soft capping at Godstow Nunnery. *©Heather Viles, University of Oxford*

Figure 4.38 Changes in appearance to grass and sedum soft capping at Castle Acre Priory, 2012–2015. ©*Heather Viles, University of Oxford*

4.4.4 How does hard capping perform over time?

Hard caps were installed at Byland Abbey, Kirkham Priory and Thornton Abbey in the course of the soft capping research project. All these sites suffer from harsh environmental conditions. At Byland Abbey, the relatively weak mortar mix used on the lane wall was affected by frost damage the second winter after installation. Once the friable material damaged by frost was removed, this hard cap has performed well. At Kirkham Priory, a stronger mortar mix was used, and appears to have performed well. However, there is a lush growth of moss at the interface between the mortar and the underlying stone. This indicates a concentration of moisture in this zone, perhaps because of the development of micro cracking in the mortar. At Thornton Abbey – a very damp, cold and frost-prone site – a stronger mortar mix was used both in the hard capping and as a render. For the first 4–5 years, both capping and render performed well, but observations in 2016 show that neither have successfully withstood the harsh conditions in the longer term.

5 DISCUSSION

This chapter addresses the questions posed in Box 1.4 in Chapter 1, and provides an assessment of the value of soft capping as a conservation strategy for ruined buildings and monuments. Box 1.4 provides a summary of some of the common concerns and issues raised by professionals and those involved in the care and maintenance of ruined sites.

5.1 How well does soft capping protect underlying stonework in comparison to hard capping?

Research carried out in the laboratory clearly demonstrates that soft capping provides a better thermal blanket for wall heads than hard capping or bare stone. Chapter 4, section 4.2.1, Figures 4.1 and 4.2). Soft capping insulates stonework, reducing the threat of freezing events. It also decreases daily temperature ranges, thereby protecting stonework against the threat of thermal expansion and contraction. The laboratory data is confirmed by similar results obtained from over one year of field exposure in Oxford (Chapter 4, Figures 4.5 and 4.6) and 20 months of monitoring at Byland Abbey. It is thought that soil and turf are better buffering agents against temperature fluctuations than stone and mortar because of differences in thermal conductivity.

However, when it comes to moisture conditions within walls, the picture is more complex. Laboratory experiments (Chapter 4, section 4.3.1, Table 4.4) revealed that soft-capped walls dry faster than uncapped walls. Monitoring at Hailes Abbey showed evidence that soft capping is associated with lower levels of moisture and less extreme moisture fluctuations than walls that are uncapped. (Chapter 4, section 4.3.2.b). The results of field trials at Byland Abbey, however, were more diverse. On one hand, the wall head tended to be drier and more variable than under hard capping in summer (with the reverse true in winter). On the other hand, dowel and 2D resistivity surveys showed that lower down the wall moisture levels were lower and fluctuations more muted under soft as opposed to hard capping in summer. Furthermore, wooden dowel monitoring revealed that older hard capping (the control section) was characterised by the lowest seasonal variation in moisture, and similarly dry conditions to most of the soft capped sections. (Chapter 4, section 4.3.2.a. Different trends emerged at Wytham Woods, where 2D resistivity, Protimeter and wooden dowel surveys showed no clear difference in moisture regimes between hard and soft-capped walls.

There is no confusion, however, about the impact of soft capping on the outside of walls. The installation of soft capping at Kirkham Priory reduced water running down the face and thus stopped the replenishment of microbiological streaking on the wall (Chapter 4, section 4.3.3.b). (It will take some time for the pre-existing streaking to disappear.) Monitoring rainfall hitting the Wytham Woods test walls clearly demonstrated the effectiveness of soft capping. It absorbed and shed more moisture than hard capping, thus reducing runoff down the wall.

5.2 What sort of soft capping design is most effective?

Different thicknesses of soft capping (5, 10 and 15 cm, both with and without slate regolith), were evaluated for this project. Different types of capping – local turf, local turf + sedum plugs, commercial turf, sedum mats, seeded mats, and on site seeding – were evaluated. Different capping techniques were also assessed: such as water retention gels and bamboo pins to hold turf sections together.

All thicknesses of grass and turf capping (from 5 to 15 cm) proved to be effective thermal blankets at Byland Abbey. The best performance was obtained where sedum plugs were used with local turf to protect the edges from erosion, as was demonstrated at Byland Abbey and Wytham Woods. Results from the research at Godstow Abbey and Castle Acre Priory demonstrate that local turf and sedum mats are both effective, although the long-term viability of the edges of sedum mats may be a problem (see Chapter 6.1.3). Local turf is also cheaper and easier to handle than sedum mats. Seeded mats and commercial turf were trialled at Godstow Abbey and found not to perform as well as local turf or sedum mats (although after seven years, the capping was still *in situ* and growing). Monitoring here also demonstrated that the addition of slate regolith had no significant effect on the thermal blanketing performance of the capping. However, because the moisture results from the wall head and lower down the walls at Byland Abbey were highly variable, it is not possible to draw any clear conclusions about the influence of either thickness of capping or presence of slate regolith on moisture control performance.

A trial of on-site seeding at Howbury Moated Site failed. This method of soft capping is not recommended unless the wall heads can be watered and protected while the seeds germinate and become established.

Water-retaining gels were evaluated at Godstow Nunnery and not found to significantly improve the growth of soft capping. Split bamboo pins were used at all sites and found to be effective at holding turf sections in place when they are first installed. Observations from the extensive soft capping at Hailes Abbey indicate that the use of longer bamboo pins on low walls might be good practice, as they discourage people and animals from walking over the capping. However, their removal for site presentation reasons may be necessary once the turf has established (see Chapter 8.4).

5.3 How can we maximise the benefits of soft capping and minimise any damaging effects?

One of the largest benefits of soft capping is its ability to reduce water runoff down the wall face. The best way to maintain and encourage this is to ensure the healthy growth of soft capping, especially towards the edges. Research at Wytham Woods test walls, Godstow Abbey, Hailes Abbey and Castle Acre Priory demonstrated that sedum plugs added to the edges of local turf reduced edge erosion and maximised growth in a range of English climatic conditions. The sedum plugs used in this research were designed to mimic the growth of naturally occurring sedums observed growing along the edges of long-established soft caps at Kirkham Priory.

Figure 5.1 Naturally occurring sedums forming stable edges on older soft caps at Kirkham Priory. ©*Alan Cathersides*

There has been some concern that water might infiltrate soft capping and become acidified, thus leading to the accelerated deterioration of vulnerable materials (such as limestone). However, research has shown no evidence that this occurs (Chapter 4, section 4.3.4). In fact, soft capping generally reduces the amount of water reaching the wall head, and produces neutral (rather than acidic) conditions. Maintaining healthy growth of a soft cap should not lead to any detrimental effects from acid water infiltration. Another concern is that soft capping might lead to the deterioration of underlying stonework by plant roots. This too is unlikely. Grass and sedum do not produce woody roots, and so even if the roots reach through the soil and connect with underlying stonework, they will not cause serious deterioration. During the course of this research project, no woody species were observed growing in the test strips of soft capping at any of the sites. Occasionally, taller herbs such as thistles were found, but while these have bigger roots than grasses, they are mostly biennial, and unlikely to pose any threat to wall heads. Furthermore, it is easy to eliminate the potential for damage any woody plants might pose: simply remove them if they establish themselves in the soft capping.

Specifiers often ask whether pre-consolidation of ruined walls is necessary before soft capping is installed in order to maximise its benefits and minimise any damaging effects. In this project, pre-consolidation was not required or attempted on any of the trial sites, but is recommended in some situations (see Chapter 6.1). However, such pre-consolidation is not necessary to enhance the performance of soft capping. Soft capping is also a good interim conservation solution for ruined sites, as one of its advantages is that it can be installed and removed relatively quickly and easily.

5.4 What are the soft capping requirements for different wall material types? Such as limestone, sandstone and brick?

A range of material types have been soft-capped in this project, including different types of limestone, sandstone, brick, and flint. There are no specific requirements for any of these different materials.

5.5 Is the height and structure of the walls important to the success and design of soft capping?

The research carried out for this project has demonstrated that height and composition do not seem to influence the success of soft capping, and have no implications for its design. Across the range of different walls studied, the success of soft capping has not been influenced by height. However, this is not the case with wall thickness. In general, soft capping is more successful on thicker walls than on thinner ones. In fact, thin walls under 30 cm thick should probably not be soft-capped. When soft capping was trialled at the Howbury Moated Site it failed (although this might have been exacerbated by dry climatic conditions). If the walls are thicker, however – between 30 and 60 cm – soft capping can be successful, but only if sedum plugs are added to the edges. Soft capping on walls over 60-cm thick functions successfully in all English climatic conditions. Sedums appear to be beneficial for all soft caps, and critical for the success of those on narrow walls.

The geometry of wall-heads (flat, rough or sloping) also plays an important factor in the success of soft capping. In this project, flat wall-heads or those with a slope of less than 20 degrees were capped successfully. Rough wall-heads can be problematic (especially for sedum mats which are heavy and quite rigid). One solution might be to add extra soil (or hard capping) to level the surface before installing soft capping.

There are other design factors that influence the success of soft capping. For example, local turf caps at Rievaulx did not thrive on the flat bases of window openings at triforium level in the main church. The walls above prevented enough moisture from reaching the capping.

5.6 Does soft capping need to be varied for different climates?

The performance of soft capping was tested across a spectrum of dry and wet climatic conditions in Yorkshire, Gloucestershire, Oxfordshire, Norfolk, and Greater London. No significant difference in the performance of soft capping was found, even at Whitby Abbey which is located on a windy, coastal promontory.

Some care needs to be taken when installing soft capping in dry sites, as drier sites are characterised by more frequent apparent dieback of grass. However, once established, soft capping will survive periods of drought. Its protective functions will remain intact even when it appears to be dried out. Sedum plugs implanted along the edges of turf-based soft capping have been found during this research project to be a successful way of preventing edge erosion and enhancing the growth of soft capping in drier English climates.

Careful installation of soft capping is crucial to its successful establishment and growth under all climatic conditions. Ideally, soft capping should be installed between October and February so it does not dry out during its establishment phase. If soft capping needs to be installed at other times of year, it is critical to water it regularly so that it does not dry out during the first few weeks.

5.7 Does the performance of soft capping change over time?

Soft capping is a living system. It adjusts seasonally to changing climatic conditions, and its balance of species evolves over time. While this project has demonstrated seasonal changes in the performance of soft capping (such as drier conditions under soft capping in summer at Byland Abbey and Hailes Abbey), seasonal drying of soft capping can be a good thing, as it discourages the growth of woody species. Drying out can also lead to the edges of soft capping eroding (as has been observed at some sites during this research), but the addition of sedum plugs can successfully mitigate this problem, as was seen at Wytham Woods, Hailes Abbey and Godstow Nunnery. It has also been seen that when soft capping is made with local turf – as is the case at Byland and Hailes Abbeys – the grass species mix sometimes begins to change, with species that are more tolerant of drought conditions becoming dominant.

At both sites rabbits have also dug small burrows in soft caps which can enhance erosion. Burrowing is likely to be very limited in soft capping, because the soils are so thin. Older soft caps on very low walls at Kirkham Priory have recently (2016) been observed to have been colonised by ants creating visible ant mounds in the soils, but this is a rare occurrence. Such biological disturbance and mixing of soil may destabilise soft capping, but this is unlikely to be more than a very localised problem.

5.8 What is the best maintenance and monitoring strategy for evaluating soft capping?

Maintenance

This research has demonstrated that soft capping is generally a low maintenance conservation strategy. In essence, once successfully established, soft capping is a self-maintaining system. This is especially true on high wall-heads that are well away from human interference and trampling, and also are stressful environments for plant growth (thus keeping woody plants in check, and grass relatively short). Low walls can occasionally be damaged by animals, or by people walking or sitting on them. In situations like these, some maintenance might be required to repair eroded areas. In other cases, grass capping may grow exuberantly on low walls and require trimming for presentational reasons.

Monitoring

Monitoring soft capping is a relatively simple task. Quinquennial inspections should be sufficient to check for any edge erosion. A landscape manager or similar professional should inspect for the growth of woody species on an annual or biennial basis. If any woody species has established in the soft capping, it can be quickly identified and removed before it reaches a size that could be damaging.

On sites where staff regularly change, or are only staffed at certain times of year, it could be useful to have a folder with a regular photographic survey of the soft cappings from strategic points. This would enable staff to become familiar with the ways the capping changes with the seasons.

5.9 How might future climate change affect soft capping?

As a self-maintaining natural system, soft capping will adapt and change if climatic conditions alter significantly. This research project has demonstrated that it can thrive across the spectrum of current English climatic conditions. It is likely to be able to continue to do well if and when the climate changes, with anticipated warmer annual temperatures, drier summers and more variable conditions (e.g. larger storm events). However, regional differences are likely. In areas where hotter and drier conditions dominate, turf-based soft capping will become more difficult to maintain, and sedum-based designs more likely to thrive. In contrast, in areas where warmer and wetter conditions are found, grass-based soft capping will thrive. If winters become colder and stormier, soft capping should not be seriously affected. Over time the species mix in soft capping will evolve in response to the changing climatic conditions, and sedum-based capping is likely to become more successful.

5.10 Does soft capping keep the core of ruined walls dry?

The difficulties of reliably monitoring moisture contents and the complexities of moisture movements in old ruined walls mean that it is as yet very difficult to answer this question. The research carried out for this project has shown varied results from which general conclusions cannot be drawn.

5.11 Does soft capping damage the wall-head?

Many professionals working on the conservation of ruins worry that both roots penetrating through soft capping, and water acidifying as it passes through soft capping, can cause damage to the underlying masonry. Anecdotal reports of trying to lift soft capping and finding the plants firmly rooted into the stonework cause concern. However, grass roots are not anatomically capable of rooting into stone and causing damage. Furthermore, root growth of other species can actually enable soft capping to function more effectively. At Myross Church ruins, for instance, a substantial root matrix has developed over centuries, and has proved to be very effective at securing the soft capping, and protecting the wall below. Indeed, the research carried out for this project shows no evidence at all of damage from soft capping. In fact, field experiments at Wytham Woods and Castle Acre Priory demonstrate that walls under soft capping should experience lower rates of chemical weathering than exposed wall heads. The thermal blanketing effect also reduces other weathering processes, such as freeze-thaw and thermal expansion and contraction.

5.12 Does soft capping require a membrane to separate the cap from the stone below?

In this research project, all soft caps were installed without a membrane. While some experts recommend the use of a membrane to isolate the capping from the underlying stonework, our experience shows this is not necessary and is actually counterproductive.

5.13 Are naturally occurring soft caps beneficial?

While this research project did not investigate the performance of any natural soft caps, it seems likely that they would provide the same benefits as installed capping, as long as (a) they are thick enough and provide consistent enough cover to provide the same service; and (b) do not contain large, woody species which could do damage.

5.14 Will grass roots damage the wall?

See answer to question 5.12 above.

5.15 How does a soft cap become successfully established?

Chapter 6 of this report provides detailed information about how and when to install soft capping to ensure that it survives and thrives. The key considerations are:

- Timing: installation between October and February is best.
- Design: ensure that the best materials and methods are used, bearing in mind the nature and climatic location of the wall to be capped.
- Vigilance: keep an eye on the capping for the first few weeks – watering as necessary – in order to ensure that it becomes well established.

5.16 Will soft capping stay in place in high winds?

This research project established a test site on the top of an exposed wall at Whitby Abbey, Yorkshire, specifically to address this question. The soft capping there is now well established and thriving. It is important to use bamboo pins or other methods to keep the turfs in place when soft caps are installed (before they root into the soil) in such windy locations to ensure that they are not blown out of position before they have had a chance to take root.

5.17 Will a soft cap help conserve wall flora?

As this research project has demonstrated, one of the benefits of soft capping is that it reduces runoff down the wall face. This has implications for wall flora. There were clear differences in the microbiological staining and lichen flora on the soft and hard capped test walls at Wytham Woods after a few years, with more luxuriant lichen growth and darker microbiological staining on the hard capped walls. On older walls, such as at Godstow Nunnery, there are no clear differences in wall flora under soft-capped and uncapped wall-heads, but fragments of sedum plants have become detached from the main sections of soft capping and are now established in crevices on the wall face below. This is also true at Hailes Abbey and Castle Acre Priory. At Rievaulx Abbey, trials were carried out to brush away lichen and mosses from below one of the window ledges before soft capping was installed, in order to evaluate whether it would re-establish once the soft capping was in place. The findings so far have been inconclusive.

5.18 Will a soft cap reduce fabric loss from the wall below?

The indications from this research project are that soft capping reduces fabric loss, as it moderates temperature and probably, moisture regimes, as well as temperature fluctuations at the wall head and runoff down the wall face. On ruins with no previous history of conservation treatments, soft capping is an effective way of 'sealing off' the most vulnerable and possibly weakest face of the wall (i.e. the broken wall head), thus stopping rainwater ingress. Soft capping is therefore extremely effective where the main agents of deterioration come through the wall head. In other situations, where the main focus of damage is at the base of walls (as in flooding, for example) soft capping is unlikely to make a major difference. However, most English ruins have been subjected to a range of conservation interventions over the last century or so, often including extensive consolidation of hard capping constructed of cement-based mortars. In these cases, the ruined walls today are a complex composite of old and newer fabric. They can be subject to significant movement and decay, partly through natural ageing, but also as a result of past treatments. In such circumstances, soft capping should stabilise conditions at the wall head, and slow down the rate of deterioration of the wall below.

6 CARRYING OUT SOFT AND HARD CAPPING

The installation of soft capping is a simple process. However, since walls differ substantially in terms of size, shape, location, materials, aspect, and so on, it is inevitable that modifications will often be necessary. This chapter first discusses the steps for installing soft capping on different kinds of walls, as well as possible complications and limitations. It then goes on to discuss hard capping. At the end of the chapter, the two techniques are compared.

6.1 Practical guidance: building soft caps

The guidance below has been derived from experience gained from installing soft capping on 12 test walls during this research project, as well as observations of other sites. For the current research, it was agreed that no repair work would be carried out on the existing hard caps, as it might be beneficial to compare the wall head surface before and after installing the soft capping. It was also a research aim to develop repair methods that are very practical and can be easily implemented at a reasonable cost.

The existing wall top must be thoroughly assessed. The surface will have often been hard-capped during earlier repair programmes. It is not necessary for these hard caps to be removed, thus avoiding considerable expense, as removal can be a costly procedure. However, it is best to repair any major cracks (over 5mm wide), as these may become conduits to water, a serious weathering agent. It is also sensible to repair/reset any loose stonework, especially near the edges. Generally, the easiest sites to cap have walls with a regular, straight edge and a flat or slightly convex profile.

The installation of a membrane beneath soft capping is unnecessary, and may be harmful to its effectiveness in the longer term. Membranes stop fine grass rootlets from getting established in a stone surface. These rootlets eventually grow into a dense mass, just like the tangle of roots which has proved so successful at resisting water penetration at Myross Church in County Cork, Ireland (Figure 1.4). Moreover, the undulating nature of most wall tops means that installing membranes effectively and finishing the edges neatly is difficult. When grass roots cannot connect to a wall top, the soft cap can roll up like a carpet. Membranes and barriers often tend to separate slightly from surfaces. This both looks conspicuous and concentrates the flow of water.

The successful installation and establishment of soft caps on the test walls within this research project has shown that membranes are not needed. Examples of the types of problems encountered with membranes can be seen in Figures 6.1a to 6.1d taken at a site where an early use of soft capping did include a geotextile.

Figures 6.1 (a-d) showing the problems with using membranes on both even and uneven wall-heads. *(all ©Alan Cathersides)*

6.1.1 The process

1. Remove any loose material, and consider making repairs to any previously installed hard capping.

2. Lay the ends of several turf sections upside down along either side of the wall top. The ends of each turf section should be left to hang down the wall (Figure 6.2b). This may need to be done in conjunction with the next step in order to prevent the turfs from slipping off the wall.

3. Build up soil evenly over the wall top and turf ends to cover the whole surface area (Figure 6.2c). Firmly compact the soil by hand to the desired depth. Do not over-compact the soil. It should not be so wet that it cannot compact properly, which would lead to significant problems later on in the process and after installation. Rather, the particles should be just moist enough to bind together , thus reducing soil loss on the lower part of the wall.

4. Fold the sections of turf hanging over the wall up over the soil (Figure 6.2d). Firm the turf down onto the soil to ensure good contact between the root mass and the soil; any air pockets will inhibit growth, as roots growing into them dry out and perish. The edges of the soft cap are especially important. When the turf sections have been folded over, press them down firmly with a slight camber, back from the edge. A slight bulge over the wall face is acceptable, but any more should be avoided. Overhanging bulges are problematic, as the turf on the underside is likely to die, causing it to dry up and disintegrate, causing soil loss and erosion of the edge. (Figure 6.2d)

5. On narrower areas of wall-head, trim the edges from one of the sections of turf to prevent any overlapping. Alternatively, on wide areas of wall head, fill in any gap between the ends of each turf, using additional pieces of turf cut to the appropriate dimensions (Figure 6.2e).

6. Finally, pin down the turf using biodegradable pins (split bamboo canes or similar) to ensure individual turf sections do not slip off before they take root (Figure 6.4).

Sites that have irregular edges, steps, or uneven or steeply sloping profiles can be more difficult to soft cap, and problems can arise. Irregular edges should be soft-capped, using the same process as outlined above. Extra care should be taken to ensure that overlapping turf is kept to a minimum, as this causes the turf underneath to die out due to lack of exposure to sunlight. The roots of the turf on top will then have difficulties growing through the layer of dead material, and they too may dry out and die.

Figure 6.2 The main stages of the soft wall-capping process.
(a) Repairs should be made to the existing hard cap (if appropriate, see 6.1)
(b) Turf sections should be hung over the edges of the wall.
(c) Soil should be built up over the wall-head.
(d) The turf should be folded over the built up soil and firmed down.
(e) Additional turf should fill in any gaps and the turf pinned to keep in place until rooting takes place.
(f) The underside of a bulging turf is likely to die and disintegrate.
(all ©Alan Cathersides)

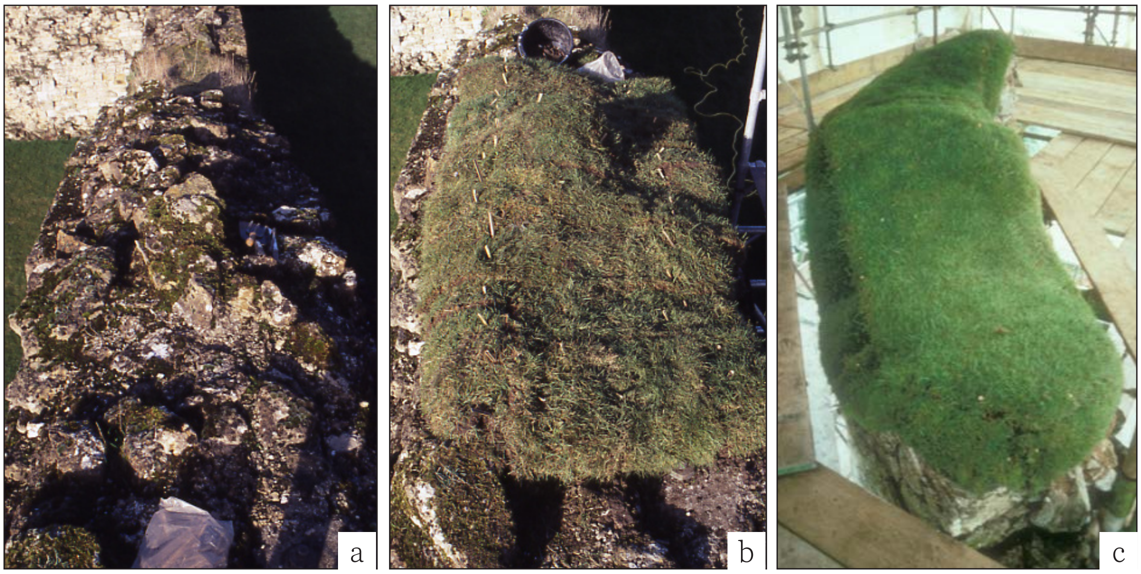

Figure 6.3
(a) Typical uneven wall-top before soft capping. ©*Alan Ctahersides*
(b) After soft capping, using a consistent depth of soil so that the finished appearance reflects underlying topography. ©*Alan Cathersides*
(c) A similar wall-head soft capped using varying depths of soil to provide a consistent surface level. Note that this particular example uses turf from a local supplier and is different from (a) and (b). © *Chris Wood, Historic England*

If the surface of the existing wall head is uneven, a decision must be made about the desired appearance of the finished soft cap (Figure 6.3). Principally, there are three options. Firstly, soil may be used to level off the wall surface, which evens up the finished surface after turfing. Secondly, keeping the depth of soil constant over the whole of the wall top will enable the finished appearance to closely resemble the masonry surface profile (before soft capping). Thirdly, the soil depth can be kept relatively constant, but not built up over larger projections. The finished appearance is relatively even, but will be punctuated by the larger stones, which are left uncovered.

There are only two options for dealing with an uncapped surface with a distinctly stepped profile (Figure 6.4). It is impossible to replicate a step exactly using soft capping because turf will never establish properly on a vertical surface. One is to cap the horizontal surfaces above and below the vertical face, which is left exposed. This will initially retain the stepped appearance (see Figure 6.5 (i)). However, when the grass grows, this profile will be hard to see. Furthermore, this leaves some of the historic fabric exposed. The other option is to 'ramp' the soft cap over the step (see Figure 6.5(ii)). This protects the fabric more fully but loses the definition of the step. The height of the wall may be an important consideration, as soft caps on lower walls are much more visible than those at higher levels.

Figure 6.4 When capping steeply profiled edges it is critical to peg the turf in place until it can properly root into the mass of soil beneath. ©*Alan Cathersides*

Figure 6.5 (a) soft capping above and below the step initially retains its appearance (right hand side), but this will be lost to some extent as the grass grows, (b) ramping over the step means a loss of definition but increased fabric protection. *(both ©Alan Cathersides)*

6.1.2 Edge treatment

The edges of soft caps are invariably the most exposed, and are prone to drying out, followed by dieback and erosion. This was particularly noticeable in this research project on south and west-facing edges that are more liable to drought stress, but east and north-facing edges also suffer in particularly dry periods. One possible solution to this problem is the use of drought tolerant stonecrops (*Sedum sp.)*. The root system of sedum does not form a fibrous mat that holds together, as grass does when undercut (although see section on sedum mats below). This does not make it a good choice to be used as turf. However, it can easily be grown as a 'plug' – a small, individually grown plant (see Figure 6.6a) – that can be inserted into soft caps.

During this project, sedum plugs were initially trialled on existing soft caps where the edges had died back and were beginning to erode away. They were inserted at approximately 50-mm intervals and were found to establish rapidly and stabilise the edges (see Figures 6.6b and 6.6c). When an additional trial area was installed at Castle Acre Priory, it provided an opportunity to test the effectiveness of plugs on new soft capping (see Figure 6.6d). The wall was orientated from east to west and so had a south-facing edge and a north-facing edge. Plugs were inserted in both. After 15 months, it was clear that on the south-facing edge the grass had suffered serious dieback, but the sedum plugs had responded very well, expanding considerably and stabilising the edge (see Figure 6.6e). On the north face, the grass had not died back, and the sedum plugs remained much the same size as when planted (see Figure 6.6f). However, by November 2016, the sedum plugs on both sides were much less healthy. Longer-term observations are needed before any confident statements can be made.

One potential problem with sedum is that due to its brittle nature and extreme drought tolerance, small pieces frequently break off and fall down the wall. When these pieces land on a ledge, they almost inevitably take root and establish a new plant (see Figure 6.6g). However, this is a presentational issue, not a building conservation one. The root systems of sedum are very small and fine and do not cause damage. If necessary, these rooted 'cuttings' can be easily removed. On high walls, for which scaffolding is required, it is better to add sedum plugs to soft capping on installation, rather than return to add them at a later stage.

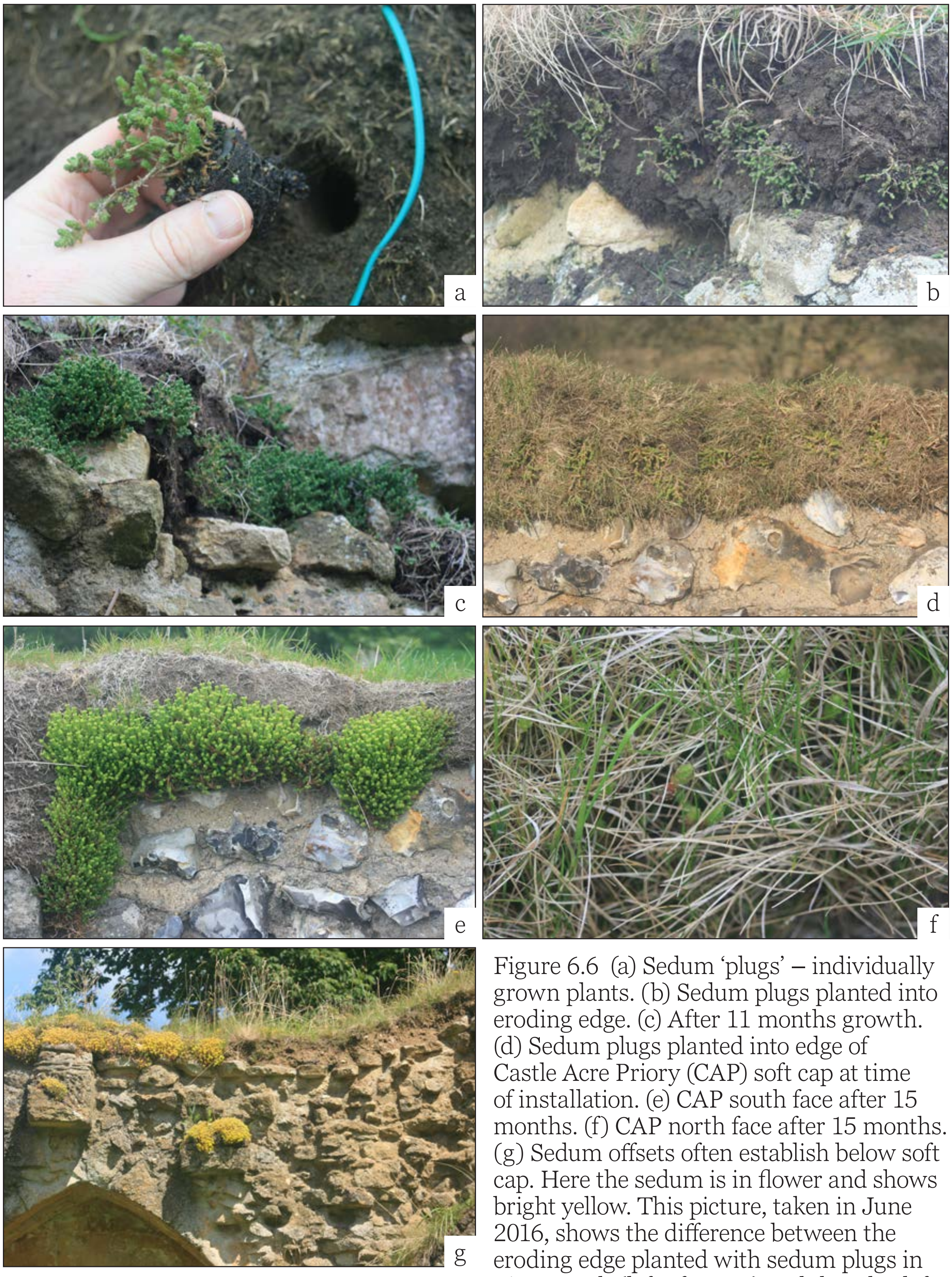

Figure 6.6 (a) Sedum ‘plugs’ – individually grown plants. (b) Sedum plugs planted into eroding edge. (c) After 11 months growth. (d) Sedum plugs planted into edge of Castle Acre Priory (CAP) soft cap at time of installation. (e) CAP south face after 15 months. (f) CAP north face after 15 months. (g) Sedum offsets often establish below soft cap. Here the sedum is in flower and shows bright yellow. This picture, taken in June 2016, shows the difference between the eroding edge planted with sedum plugs in Figure 6.6b (left of centre) and the edge left unplanted (right of centre).
(all ©Alan Cathersides)

6.1.3 Alternatives to turf

Other options to turf for soft caps have been trialled (see Figure 6.7) and include the following.

Seed

The advantage with seed is that it is very easy to get a mix of exactly the right sort of drought-tolerant grasses. It is cheaper than turf, and even small amounts of a mix are usually easy to obtain. Seeding has some serious disadvantages, though, and is therefore not recommended. The three main disadvantages are:

- It is difficult to build up the required 100–150mm of soil on the wall-head without a turf to hold it in place, especially at the edges. It has to be tapered down to a very thin layer. Otherwise it simply crumbles away.
- It takes 10–14 days for the seed to germinate, so any strong wind or more than gentle rain tends to wash the seed down to lower points (or off the wall entirely).
- It takes approximately 8–10 weeks to form an initial cover of grass, so any heavy rain tends to wash parts of the capping completely off the wall-head.

Seeded Mats

These mats are often used on embankments, and consist of two layers of hessian (or similar material) with grass seed in the middle. They are laid over a prepared surface where the seed germinates, forming a grass cover. The hessian eventually rots away. Seeded mats did not prove to be a good option for soft capping. The amount of handling and trimming needed to fit them as a soft cap led to the loss of some seed. Like turf, they could maintain the required level of soil on the wall top, but they were difficult to peg into place. Eventually an extra layer of soil was used to hold them. On the level centre of the wall, germination was reasonable under the layer of soil, but at the edges (where no covering soil could be placed), there was no germination at all.

Sedum Mats

As mentioned above, sedum roots do not enable it to be cut as a turf. However, mats of living sedums growing within a soil-filled plastic matrix are readily available, as they are frequently used by the green roof industry. These were trialled at Godstow Nunnery and Castle Acre Priory. The mats are very heavy, and installing them as soft caps in the standard 'turf' fashion was difficult work. Furthermore, it is also difficult to trim these mats to fit uneven areas. However, once installed, they did work very well, and at least initially provided a very effective soft cap. Unfortunately, the soil appears to wash out of the plastic matrix at the edges over time, and vegetation cannot grow, which leaves the unattractive matrix on show. The mats are also much more expensive than turf.

Figure 6.7 (a-d)
(a) Using seed makes it difficult to establish a suitable depth of soil, especially at the edges.
(b) Soil and seed wash away in rain.
(c) Seeded mat installation.
(d) Sedum mat showing plastic matrix used to maintain soil and root.
(all ©Alan Cathersides)

Figure 6.7 (e-h)
(e) Sedum mat during installation – the heavy weight of the mat makes it difficult to manipulate.
(f) Sedum mat after installation
(g) Edges of Sedum mat after.
(h) Sedum mat after 7 years showing loss of soil and Sedums at edges.
(all ©Alan Cathersides)

6.1.4 Water-retaining gel

Developed for the horticultural market, water-retaining gels are readily available from many outlets, and are widely used for hanging baskets to cut down on watering. The dry gel is mixed with soil, and when watered, absorbs a substantial amount of fluid, holding it against gravitational drainage, thus making it available to plant roots.

We trialled water-retaining gels at Godstow Nunnery to see if they could prevent turf used in soft capping from drying out. Half of the soil used in the four different soft caps in the two-metre stretch (locally-cut turf, commercial turf, sedum mat and seeded mat) was untreated, while the other half was mixed with gel.

During the first year, the soft caps were regularly checked. The only noticeable difference was that seedlings of Fat-hen (Chenopodium album) were prevalent during the summer on the halves with soil + gel, but not on those with just soil. No obvious explanation for this is known. However, Fat-hen poses no particular problems (nor provides any real benefits) to soft capping. It is likely to appear only in dry years when there is bare soil, and disappear once grasses and forbs re-establish a good cover.

Overall, it was felt that the use of water-retaining gel offered no benefit to establishing soft capping.

6.1.5 Operational advice

a) Site logistics

Soft capping from ladders is impractical and unrealistic, and should not be attempted. Instead, if walls are high, all soft capping should be done from scaffolding. Scaffolding should be erected on both sides of the wall so that operatives can have full access to the wall-head at about waist height. Both turf and soil are heavy, so an electrical hoist should be fitted even on relatively low scaffolding. It is important to make sure that the scaffold is designed to take the weight and size of materials.

The necessity of lifting heavy materials to the top makes soft capping high walls difficult. In contrast, while it might be easier to soft cap low-walled sites, they pose another kind of problem: animal damage after the cap has been installed. During our field research, rabbits damaged one of the soft caps at Byland Abbey, and a fox (probably scrambling up to sit on the wall top, Figure 6.8) damaged one at Howbury. The damage, however, was not that serious, as rabbits soon learn that burrowing is pointless in shallow soft caps and stop doing it (as was the case at Byland).However, feeding scrapes can be a problem on heavily populated sites. If animal damage is anticipated, the use of a large number of split cane pegs (which stick out by 150 mm from the soft capping) can discourage the animal from climbing onto the wall until the turf has become properly established.

Figure 6.8. (a) A rabbit's trial burrow at Byland Abbey; and (b) damage to the newly installed soft cap at Howbury caused by a fox scrambling up the side of this low wall. *(both ©Heather Viles, University of Oxford)*

b) Timing

Due to the restricted soil depth, absence of moisture from below, and the greater air turbulence experienced on high walls, turf in a soft cap can easily dry out, especially during the first three to four weeks after it has been laid. Thus, the ideal time for installing soft capping is between October and February, as generally temperatures are cooler, and there is often more rainfall than at other times of year. It is important that facilities for watering are provided if soft capping is undertaken in the spring or summer. Keeping turf moist is very important, because when it dries out, it shrinks and gaps appear between turfs. It is then impossible to close these gaps up again, leaving the soil exposed and vulnerable to being washed out.

c) Materials

Trials have shown that locally grown, mechanically cut turf is better than commercial turf for soft capping purposes. Local turf contains a wide range of species, many of which can tolerate the climatic conditions experienced at the site. Generally, this is not the case with commercial turf. If commercial turf must be used, it should contain the minimum possible percentage of Ryegrass (*Lolium sp.*) and the maximum of Bents (*Agrostis sp.*) and Fescues (*Festuca sp.*). In dry years, there is a strong chance that the soft cap will appear to die back during the summer months (Figure 6.9). However, it will usually grow back once the weather conditions become wetter again. This happens more effectively on established soft caps, or those installed using local turf, because there is a bank of seeds within the soil. Commercial turf is grown on sterilised soil and does not contain this seed bank. Consequently, it takes longer to recover following drying.

Table 6.1 Comparison of commercial turf and locally cut turf			
Commercial Turf		Locally cut turf	
Advantages	Disadvantages	Advantages	Disadvantages
Readily available	Cut thinly to reduce transport costs. Some growers will provide thicker cut turf, but this needs to be ordered in advance and will attract a premium and extra transport costs	Can be cut to ideal ½ - ¾“ thickness (thus keeping maximum amount of root)	May not be possible to cut on some scheduled monuments, although adjacent land may potentially be used
	Thinly cut turf has minimal root and very prone to quickly drying out in adverse conditions	Thicker cut contains more root which aids establishment and gives some buffer against adverse conditions	
	Grown on sterile soil so no built in seedbank for regeneration	Soil will contain natural seedbank so regeneration after dieback will be quicker	May need some advance preparation such as cutting (lifting and using turf with long grass is difficult)
	May be difficult to obtain ideal mix of grasses (unsuitable Ryegrasses predominate in commercial turf) although different mixes should be obtainable Specially grown turf with chosen grass mix can be obtained but needs advance ordering and may attract a premium	Wide mix of grasses and forbes, usually native to the area, some of which will thrive and multiply in the soft cap	Re-instatement of area needed after turf is cut and removed
	On larger jobs delivery may need to be staggered to avoid rolled turf sitting too long and drying out/starting to die	Sufficient turf can be cut and left in situ then taken up an used as needed. Any unused turf can be left in-situ to regrow	
	More expensive	Cheaper	
	Thinly cut turf are lighter and easier to flip up in high winds, before new roots grow, if not securely pegged down	Increased root and soil on thicker turfs make these heavier and less likely to move. Pegging down is still necessary but not so critical	
		Minimal transport necessary	
Note: Any area for turf-cutting should be short grass, or given a cut in advance of starting turf cuttings.			

There will always be a certain amount of wastage caused by overlapping and trimming of the turf. A useful rule of thumb is to cut/order 2x the area of the wall head to ensure that the amount of turf is sufficient. If the area where the grass is to be grown has a lot of stone near the surface, and useable turfs of a suitable size are relatively scarce, it is worth cutting a larger area than planned while the turf cutter is on site. In that way it will not be necessary to rehire the machine. Any unused turf can simply be left in place to re-root.

The advantages and disadvantages of both commercial and local turf are summarised in Table 6.1. It should be noted that cutting turf from within a scheduled monument would require SMC and this could be considered at an early stage of planning. If the site is within a SSSI, turf cutting may also require permission from Natural England.

Soil quality is not as critical as turf composition. Natural soft caps, which have built up over decades or even centuries, contain a wide range of elements derived from natural soil formation and whatever broken pieces of masonry that were originally on the wall-head. The grasses and other plants that form the best soft caps are all tolerant of drought, and can survive on a low amount of nutrients, so there is no need to provide a rich soil or to add nutrients. Soils that are high in clay will tend to bake hard when very dry, causing them to crack. They will then be difficult to re-hydrate. Therefore, it is best to avoid using soil with a high clay content, particularly in the south and east of the country, where it is more frequently dry. Using *BS 3882:2015 Textural classification,* soil with less than 15% clay is recommended, with the ideal division between sand and silt being roughly equal (but this is less important). A sandy silt loam soil is ideal, but silt loam or sandy loam is acceptable.

d) Long-term considerations

Once the soft cap has been established, it should be relatively maintenance-free, although periodic assessment is advisable. Establishment will take approximately three months when it is still quite prone to drying out. It is perfectly normal for the established soft capping to dry out after prolonged periods of dry weather during the summer months, and may even die back completely (see Figure 6.9). However, as already stated, established soft caps should be resilient enough to recover over the autumn/winter, when water availability is again increased. Cutting back the soft cap because of excessive growth should not normally be required, as the wall top location restricts water, nutrient and soil supply. On lower walls where conditions are usually more benign, periodic trimming may be necessary to ensure that the cap looks neat if that is the desired presentational style for the site.

On ground level or very low walls that are frequently walked on by visitors, compaction and subsequent erosion may occur, and periodic repairs may be necessary (see Figure 6.10). Low walls may also suffer periodic attacks of burrowing by rabbits (see site logistics above). These are rarely widespread or frequent but the caps may need occasional repair. On heavily populated sites, feeding scrapes may become excessive, and the caps may also require repair.

Figure 6.9 A soft-capped section, at Byland Abbey completely dried out in in August 2006 (a), greening up a few weeks later in September 2006 (b) and completely recovered by June 2007 (c). *(all ©Heather Viles, University of Oxford)*

Figure 6.10 Low walls which are soft capped may need periodic repair because of erosion resulting from compaction. ©*Alan Cathersides*

e) Concerns

All woody species can damage turf by constantly growing thicker. However, since soft capping consists of non-woody species such as grasses and herbaceous plants, this is not a great concern. While it is possible that soft caps can be invaded by woody plant species, this is unlikely. Grass swards are competitive, and the water supply limited. Woody species are likely to die out during dry spells, unlike the more drought tolerant grasses. However, trees can frequently be found growing directly on the walls, rather than in the naturally established soft caps. Figure 6.11 shows damage to uncapped walls caused by tree roots.

Wind, especially at particularly exposed sites, or on very high walls, is another concern. It is important to ensure that the turf is pegged into position for the first 3 to 4 weeks while rooting takes place, as a precaution. After this initial period, the soft capping becomes quite stable, and the risk of it being displaced by wind is minimal, as shown by the trial at Whitby Abbey (see section 2.6), chosen specifically as a very windy site. The best way for the turf to be pegged down is by using short sections of bamboo cane, which can be easily pushed into the soil, as seen in Figure 6.4. These can be left to rot away naturally. They will keep the turf pinned down for much longer than is necessary (for rooting) as an additional precaution.

Figure 6.11 Damage to the moat wall at the Tower of London (a) caused by the secondary thickening of tree roots; and a tree growing on an uncapped ledge on a wall at Wigmore Castle (b). *(both ©Alan Cathersides)*

6.2 Practical guidance: building hard caps

New hard caps were constructed for comparative purposes in this research project. They were built on wall-heads at the test sites that had previously been repaired and consolidated with cementitious mixes. An additional justification for this was that virtually all of the monuments that are maintained by the English Heritage Trust have been consolidated at some time in their history (Figure 6.12b).

a

b

Figure 6.12 (a) An example of a 'natural' site where there has been no previous consolidation and (b) an example of a site where there has been extensive consolidation. *(both ©Colin Burns)*

Traditionally, decaying wall-heads in ancient structures were consolidated with materials stored in stone piles at the sites, the result of archaeological clearance of fallen masonry. They were therefore from the original construction. Great care was taken to match the colour and textures of new mortars with those of the ruined structure. From the earliest consolidation of Ancient Monuments, cements were employed for grouting and deep tamping works. In those early days cements were less strong than modern cements. For other works of rebuilding, deep pointing, and so on, hydraulic limes were used.

Such considered techniques gave way in the 1950s to the use of cements for all consolidation works, as cements require less expertise and time to cure. However, cement mortars have become stronger over time, and thus today are generally inappropriate and damaging when used in the conservation of structures built with lime mortars. It is important to note that even though cement mortars might not be regarded as the best choice for wall head consolidation today, historically their use has helped preserve ruined structures that might otherwise have been lost to continued decay.

The main problems with using cement technologies on structures built with lime mortars relate to their differential thermal expansion (see section 4.2.1.d, which looked at thermal expansion properties of different materials) and permeability characteristics including those of stone. Lime mortar has a much greater coefficient of expansion and permeability than modern cements. Cement capping can in effect create a solid, continuous beam at the wall-head, and thermal movement over an extended period of time will produce shearing between cement and lime, together with cross fracturing of the wall cap. Pointing of faces with cement mortar has a similar effect, which is usually exhibited by fracturing near wall ends/corners, as seen in Figure 6.13. Such fracturing allows rapid rainwater penetration to the softer lime core of the structure and can hasten deterioration. For these reasons, consolidation techniques are increasingly making use of modern lime mortars to better match those used in the original construction.

Figure 6.13 Cracking in the wall due to consolidation using cement mortars. © *Chris Wood, Historic England*

6.2.1 Hard Capping: The basic process

1. Before commencing any practical work on a site, it is important to conduct a records' search to understand what has previously been carried out. Uninformed wall clearance and consolidation can destroy important archaeological and historical evidence. Photogrammetric methods, rectified photography and/or drawings should be used throughout the wall clearance to record and assess the initial state of the wall head, unless it is very recent and of limited historical value. At all stages of the hard capping, it is essential that photography is used to record the procedure, and where possible, a detailed written record of the materials and technologies used should be kept.

2. The exact positions of all face stones and any notable archaeological features on the wall-head should be recorded on a planning frame. This consists of a simple wooden frame on which clear plastic sheeting is attached. This frame must be positioned on pins in the masonry to ensure that it can be realigned precisely into the same position at any given time, and every individual stone and the skyline of the broken wall head traced onto the planning frame to enable an accurate rebuild (Figure 6.14).


a

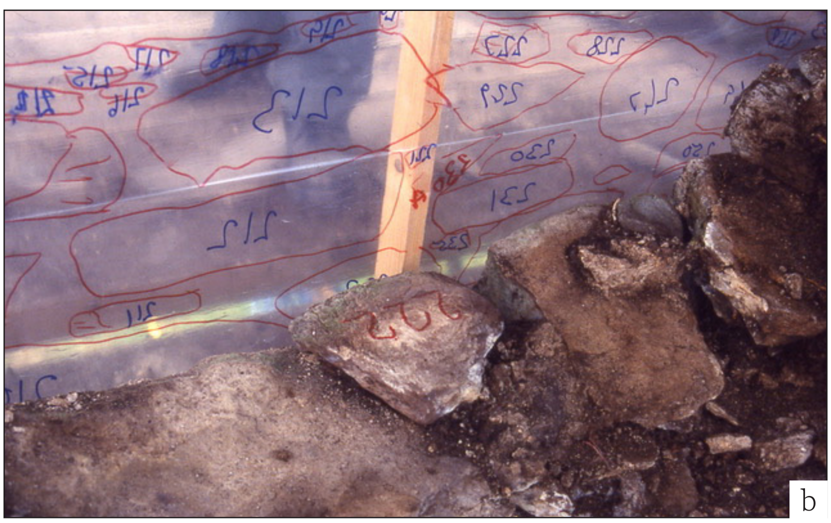
b

Figure 6.14a-b Using the planning frame to trace the outline of individual stones. ©*Colin Burns*

3. Dismantling of the wall can now take place. As each face stone is removed, it is numbered with indelible marker or paint in accordance with the planning frame (Figure 6.15). The number is usually written on the top bed of the stone prior to its removal. The only exception to this general rule is the top course, which should be marked on the bottom bed so that the marking is hidden once the wall is rebuilt. This is an important procedure, as it allows the mason to be able to identify the correct stone and its orientation from the pile during the rebuilding process. The removed stones must be cleaned of any residual mortar or soil, washed and then stacked away from the wall, ready for later rebuilding.

4. As the face work is dismantled, the core is removed. These stones must be cleaned of residual mortar and soil before being stacked separately for use in rebuilding the wall (Figure 6.15). It is often virtually impossible to remove all the residual cement from the core work without causing damage to the stones, and consequently, it is often necessary to discard the majority of the core material. During this dismantling process any roots or soil within the walls are removed. It is not necessary to remove all traces of root material, and fine roots can remain deeply buried in the wall, as they are unlikely to survive because of a lack of sunlight. Substantial root systems, however, should be traced down the wall by unpicking the masonry until they are no longer deemed to be a problem.

Figure 6.15 (a) Numbering and labelling the face work stones as they are removed from the wall, and (b) removal and cleaning of the core work. ©*Colin Burns*

Figure 6.16 (top) (a) Cleaning the surface to prepare it for rebuilding, and (b) starting to rebuild the wall in levels across the wall.
Figure 6.17a,b (bottom) The wall near completion, showing good continuity with the rest of the structure. *(all ©Colin Burns)*

5. When taking down consolidated stonework from wall-heads, previous consolidation is often found to be between 400 and 600 mm deep. Exceptions to this were found at Byland Abbey, where the depth was between 200 and 300 mm below the wall head, and Kirkham Priory, where the original core mortar was found at 1 m below the surface. In any event, it is essential that all the cement be removed from the wall head, which can be a time-consuming procedure.

6. Once dismantling is completed, the exposed wall-head should be prepared for the resetting of the face stones by brushing or hoovering off loose material and washing with clean (potable) water. Rebuilding can then commence, starting with the face work, which should be positioned in accordance with the planning frame. On completion of each facing course, the core work should be installed, thus building across the wall in lifts. This process continues until the final course of face work, at which point the broken wall-head is constructed (Figure 6.16).

7. The relationship between the face work and the core work is critical, especially for the construction of the broken wall-head. It is important that its final formation shows good continuity with the rest of the structure (Figure 6.17). It is generally accepted that the finished wall-head may be modified from the original 'as found' position to avoid rainwater ponding. It is important, however, not to compromise any archaeological features that exist within the masonry. Occasionally, the reintroduction of reclaimed fallen masonry into a wall increases the height of the wall head. A black line, galleting, or similar arrangement can then be introduced to indicate the height of wall before consolidation of the added masonry.

6.2.2 Operational advice

a) Site logistics

A scaffolding platform will be required for all but very low walls (below approximately 1.5 m). It is essential that an independent access mason's scaffold is used, and that it is not affixed in any way to the wall. Any contact with scaffolding tubes and the wall must be cushioned with plastic end caps. The scaffolding must also be suitably load bearing, as once a section of wall has been dismantled a considerable weight will be placed upon it. In addition, an electrical or mechanical hoist may be fixed to the scaffold to raise and lower the materials.

When working on long stretches of wall, it is important that it is dismantled in short sections of approximately 3 m. This is the most suitable approach for a number of reasons. Firstly, if the whole wall is dismantled at the same time, then an unsafe load may be placed upon the scaffolding. Secondly, it is safer to work in sections along a long wall, as movement along the scaffold may be impaired by a lack of space caused by the loose stones. Thirdly, it is useful to dismantle the wall in sections so that the masons may better recall its previous form when reconstructing it.

b) Materials

It is often impossible to separate the cement from the stone without causing considerable damage. Consequently, significant amounts of stone may need to be discarded, and replacements sourced. At Kirkham Priory, approximately 15–20% of the face stonework had parallel fractures 100 mm from the face. A large quantity of replacement material was required. Traditionally, such replacement blocks were sourced from the stone heaps held on site. Unfortunately, many of these sites have been cleaned up, and such stone heaps are now seldom available.

In cases like this, stones must be sourced from suitable quarries. However, freshly quarried stone does not always match the existing weathered stonework. In addition, newly quarried stone is likely to be stronger than older stonework, and therefore more resistant to weathering and decay. This can place additional localised stresses on the very fabric that it is intended to assist. This should only be of concern, though, in walls where the original masonry is in very poor condition. Advice from a geologist/petrographer is strongly recommended so that the most appropriate geological match is obtained (see the Historic England guidance, Sourcing Stone for Historic Building Repair, 2016). As well as resisting the elements, mortar should protect masonry without creating new problems. When designing a new mortar, it is important to match the colour, texture and weathering of the old one. But the first consideration should always be the type and condition of the stones used in the wall. Generally, mortar should be more permeable and sacrificial than the masonry units. This will allow moisture movement through the wall.

The colour and appearance of mortar is normally derived through aggregate choice. However, the traditional 'like for like' approach may need to be adjusted in order to distinguish new work from old. Samples of unweathered mortar should be taken for analysis and historical records.

6.3 Conclusions: soft Capping vs. hard Capping

It is difficult to be conclusive about the practicalities of soft capping as compared to hard capping. Context is all-important. The approach and degrees of complexity will vary, and both alternatives will not necessarily be acceptable to the owners of the site and the consent providers. Nonetheless, the research outlined in this volume has given some clear indications of various practical differences that are likely to be found in most cases.

Hard capping done well calls for skill, experience and ingenuity. It is best carried out by masons experienced in this type of work. Unexpected problems invariably arise as the old capping and core are dismantled. While every effort should be made to reuse masonry, there will inevitably be a shortfall, so a source of suitable stone will need to be found. Both an adequate amount of time and the services of an experienced geologist will be needed.

Nowadays, hard capping is usually carried out using a hydraulic lime as a binder, either in the form of natural hydraulic lime (as used in the research tests at Byland, Kirkham and Thornton) or as a non-hydraulic (putty) lime gauged with pozzolans. When mixed with well-graded aggregates and water, both limes will produce a chemical set. But they also contain a significant non-hydraulic lime content, which hardens slowly by reacting with carbon dioxide in the air. Reaching full strength can take time. Therefore, good protection and care of finished work is essential if the hard cap is to resist frosts, rains and harsh exposure. Successful results were achieved at the test sites because protection was kept around the walls for a minimum of three weeks afterwards. The work was tended daily. For anything other than low walls, a substantial scaffold was needed in order to accommodate a considerable weight of stone. It also required sheeting around the sides and a roof to help protect the finished work. Hard capping therefore requires good preplanning, experienced and skilled personnel, and a work programme that in total could take a few weeks.

In contrast, soft capping is relatively straightforward. The biggest practical task prior to the work is selecting and securing a suitable source of local turfs, but once done, the stripping usually takes less than a day (depending on the size of the site). A stout scaffold and hoist are required for higher walls, but there is no need for the scaffold to be roofed nor left up once the work is finished. Most of the test walls capped in this research required little work to the masonry, merely a brushing off of loose debris prior to the soil being spread on the top. All works were completed in a matter of days.

Soft capping does not call for great skills, although experience of carrying it out is a big advantage, as is a horticultural background. Like hard capping, soft capping is best carried out at the optimum time of year. In this case, it is the winter months that may be better, because amongst other things, there are fewer visitors.

6.4 Costs: comparing soft and hard capping

Comparing the costs of hard and soft capping incurred during this research project will only offer relative differences, as our aim was to develop ‘model’ ways of achieving successful results, not commercial ways. We spent time getting it right, recording what was done and ensuring that all the monitoring equipment was successfully accommodated. The capping done on the sites as part of this research project was also quite small in scale, and scaling up costings so they would be appropriate for much larger areas of ruins is difficult.

There were a great many variables at each site that makes it difficult to be precise about the differences in cost. For example, the unexpected difficulty in removing the concrete capping at Kirkham Priory substantially delayed completion of the new hard capping; it indicated the often unknown, greater complexity of hard capping which makes realistic costings in advance quite challenging. What this section aims to do is firstly, show the range of costs encountered for the hard and soft capping trials which were undertaken in 2004, and secondly, list the variables which need to be considered when estimating the cost of a capping project.

6.4.1 Range of costs

The cost per m^2 of the two options ranged between £39–£75 for soft capping, and £567–£991 for hard capping (2004 prices). These costs do not include the cost of the scaffolding needed for higher walls regardless of whether soft or hard-capping was being installed. It is important to note, however, that hard capping required scaffolding to be used for a longer amount of time, and to be sheeted and roofed.

The soft capping costs are for installation on top of existing hard caps with minimal repair (see section 6.1.1). They would be higher if the existing hard capping needed to be removed, although this is seldom required. The hard capping costs include removal of the existing cementitious hard cappings. The highest end of the range reflects the situation at Kirkham Priory where this proved particularly difficult and time consuming.

6.4.2 Variables to consider when costing projects

Labour

These costs are based on an estimated average labour cost of £300 per day master mason, £200 a day mason/soft capping installer, £150 a day labourer. No imported stone was required, and all turf was cut on site.

Size of Project

Common to both operations. Larger sites and higher walls will require more time spent in moving material around the site.

Scaffolding

Common to both operations. Usually necessary on any walls over 1.5 m tall to provide comfortable working level. Electric hoists necessary for moving materials on taller scaffolds. Increased time to move materials as working height increases. Likely to be required for longer with hard capping than for soft capping.

Turf

Cutting on site requires machine hire (see 6.1.5), so sufficient turf should be cut at start of project. Special mix or thickness commercial turf will require notice and may attract a premium.

Soil

Brought-in soil can be delivered in tote bags, which can sometimes be dropped directly onto the scaffold to save later movement. If available on site, it will require machine or labour to move.

Sedum plugs

Advisable for at least south- and west-facing edges. Ideally placed every 50–100mm along edges.

Mortar

Type and restrictions on use (timing, for example). Need for storage/working/mixing area off of scaffold. Must be protected from weather.

Stone

If available on site, may need sorting. If bought in, appropriate type needs sourcing.

Power tools

Drills, pneumatics, and hammers may be required for removal of existing hard capping. Generator or other sources of power required.

7 TO SOFT CAP OR NOT TO SOFT CAP?

7.1 Introduction

Research results clearly indicate that soft capping has substantial technical and practical benefits. It is effective, less invasive than hard capping, comparatively cheap, easy to maintain and usually self-sustaining. It also can be easily reversed, which makes it an effective temporary solution, pending decisions on future consolidation works. Furthermore, soft capping enhances biodiversity. In fact, one could say it is nature's way of protecting uncovered wall-heads.

Technical issues are of course only part of the decision-making process. Judgements on the suitability of treatments also have to take into account their impact on the significance of the heritage asset. English Heritage's *Conservation Principles, Policies and Guidance for the Sustainable Management of the Historic Environment* (2008) describes a range of heritage values (evidential; historical; aesthetic; communal) that should be considered when assessing the effects that proposed changes will have on the significance of a heritage asset. While installing soft capping entails only minimal disturbance to masonry, it will alter the appearance of the monument to some degree and might affect values and significance. For instance, on very low walls, soft capping may create the impression of an apparent floorscape of unrelieved grass. The impacts of installation of soft capping on heritage site values should be considered on a case-by-case basis. This issue was not included in the current research.

Certain procedures must also be followed. If the walls are part of a scheduled monument (which is the case with most English Heritage properties), scheduled monument consent will be needed from the Secretary of State at the Department for Digital, Culture, Media and Sport (DCMS), with advice from Historic England. Besides the budget-holder (who will fund the work), the key adviser for an English Heritage site will be one of its building curators. He or she will consider the effect of the proposed changes on the significance of the monument, and whether they will enhance or impair visitors' understanding. The other key stakeholder will be the Inspector of Ancient Monuments (Historic England), who will provide an independent assessment of the proposals on behalf of/for the Secretary of State.

7.2 Historical performance

Hard capping has been used as a conservation technique in a range of situations for the last 100 years. However, this technique has many limitations. Even apparently good hard caps that appear to be quite intact will often have minor cracks or crazing. These can let moisture in and keep the stonework below quite damp. As many of the sites examined in this project are located in fairly hostile environments, there was a tendency to use very strong cementitious materials, which led to further problems with the underlying fabric. Furthermore, the work required for reversing hard capping is extremely demanding and equally invasive.

In contrast, the procedures involved in the establishment and removal of soft capping are much less invasive, and are consequently much less damaging to the historic fabric. One of the most important objectives of the Ministry of Works was to 'conserve as found'. It can be argued that soft capping better implements the concept of 'conserve as found' than hard capping (Figure 7.1).

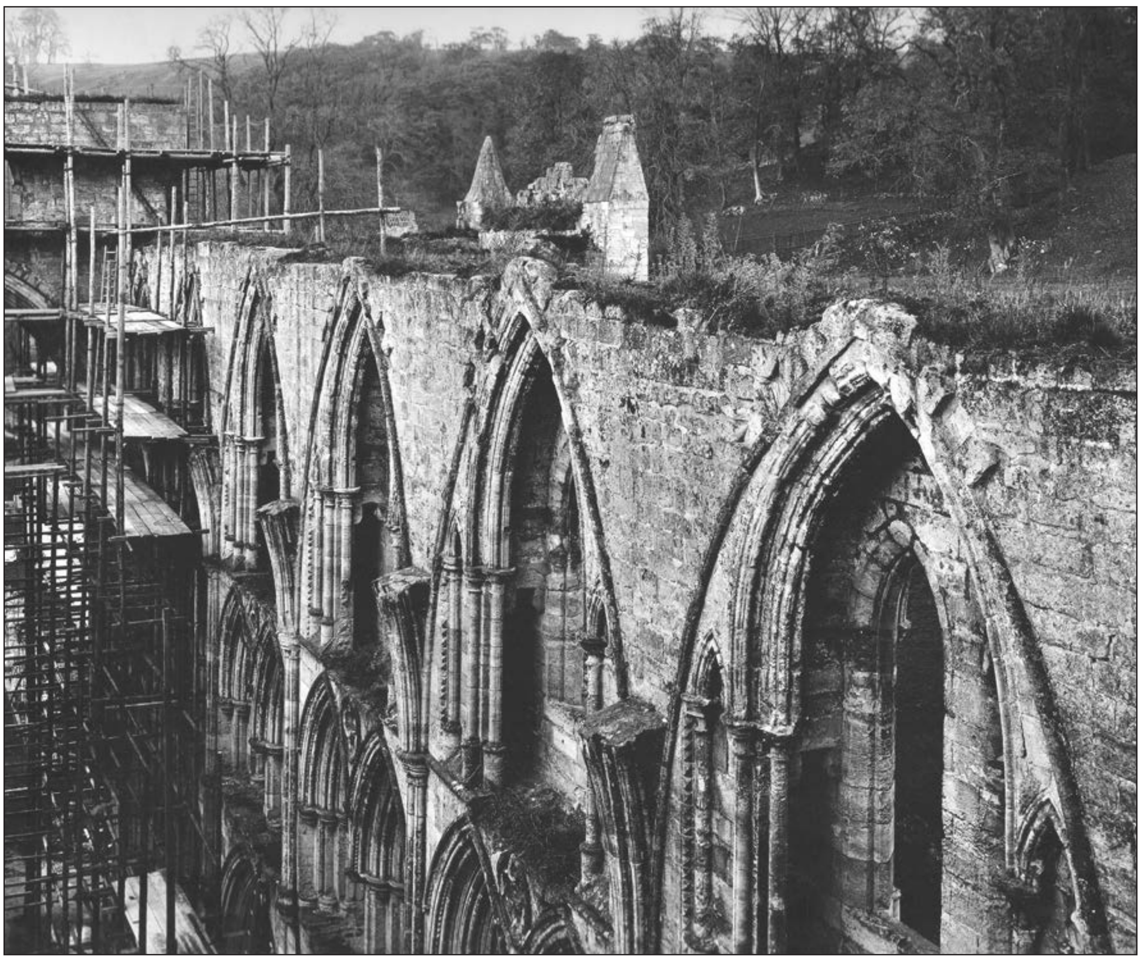

Figure 7.1 An early photograph showing the Church at Rievaulx before the Ministry of Works began consolidation in the early 20th Century. A natural soft capping had developed over the previous 350 years and seems to have provided good protection for the masonry below. *Source: Historic England Archive (AL0876_011_01)*

Figure 7.2 (a) The Kirkham Priory laver site in the 19th century, covered with extensive natural vegetation growth and (b) in recent times, where past conservation techniques have led to the removal of the protective vegetation cover (© *Chris Wood, Historic England).*

A number of examples of the efficacy of soft capping exist, both in England and other countries. For instance, there are a significant number of ruined medieval structures in Eire protected by natural soft caps. The former church at Myross in County Cork is one. Its roof was removed in the 16th century, and grass colonised the wall-heads. Although the church overlooks the Atlantic Ocean and often experiences extreme weather, these natural soft caps protected the walls so that they are still in good vertical alignment, despite hundreds of years without maintenance. And in the 1990s, English Heritage took over the care of Wigmore Castle (see Figure 1.3). Its walls had been built from a locally sourced mudstone, a material not known to be robust. However, its wall-heads were covered with a luxuriant growth of grass, ferns and other plants that had provided protection for centuries. It was decided to conserve this cap, and it was taken off, stored, and watered before being returned to the consolidated walls. The walls would almost certainly have been rendered to help protect it from the elements.

Figure 7.3 (a) Kirkham Priory refectory wall in the early 20th century before consolidation, showing clear coursing lines of the facework and a very flat walltop with a grass cover, and (b) in recent times, without a grass cover and significant alterations to its profile (© *Chris Wood, Historic England).*

19th- and early 20th-century photographs show other examples of natural soft capping on ruined monuments. Vegetation might even have been encouraged to grow in order to enhance a ‘picturesque' appearance, as was possibly the case at Kirkham Priory (Figure 7.2a). This 19th-century photograph reveals that the wall was in relatively good condition, especially considering that it had very likely been neglected for four centuries. The medieval tracery too was in very good condition, so the wall-head (including its organic growth) must have conferred protection from the elements. Further along from the laver at Kirkham Priory is the wall of the refectory. Figure 7.3a shows this section of the wall in the early 20th century, prior to the Ministry of Works consolidation programme of the 1920s. The wall had a flat, regular top with a grass cover.

In comparison, Figure 7.3b shows the same location in the first decade of the 21st century. Most of the rubble walling is still intact, although the distinctive coursing is not clear. More significantly, the wall top has been consolidated, leading to significant alteration in its profile, and a significant amount of rebuilding had been carried out. There is considerable black streaking on the wall face in the later photograph; on the earlier photograph there was none. It is likely this streaking is algal colonisation along preferentially wetted flow-paths that have become the focus for runoff after the natural soft capping was removed from the top of the wall.

Figure 7.2b shows a recent (*c*.2003) photo of the same location just prior to soft capping. Most of the vegetation has been removed, and only mosses remain on small patches of the wall. The two photographs reveal the significant changes that have occurred in the facework. Some time after the removal of the natural soft capping, the ashlars and heraldic emblem in the spandrel were lost. Frustratingly, there is no documentary evidence to show whether deterioration was caused by the removal of the vegetation.

7.3 Experimental data

The laboratory experiments, field experiments and field monitoring reported earlier in this report (Chapter 4) have focussed on identifying the thermal blanketing and moisture barrier roles of soft and hard capping, as well as evaluating the changing performance of soft and hard capping over time.

7.3.1 Thermal blanketing

The laboratory experiments and field monitoring have shown that soft capping provides an excellent thermal blanket for wall-heads, regardless of the thickness of the soil. It has been found that the soil thickness only becomes important in especially hostile conditions, where a soft cap is exposed to a number of freezing events; a thick soil bed then becomes beneficial.

Field observations have shown the effectiveness of soft capping as a thermal blanket, such as at Thornton Abbey (Figure 7.4), where freeze-thaw processes have been highly damaging to exposed brickwork. As part of the soft capping field trials, fragments of decaying brickwork were removed from a low wall-top before capping. After 18 months, the brickwork under the capping showed no evidence of fresh decay (Figure 7.4d), whereas the exposed brickwork adjacent to the soft-capped section showed considerable ongoing deterioration.

Figure 7.4 Photographs from Thornton Abbey showing:
(a) decaying brickwork just before soft capping
(b) newly installed soft capping (May 2004)
(c) established soft capping (April 2010)
(d) detail showing fresh damage to exposed brickwork, with inset (e) showing stable state of brickwork underlying soft capping (April 2010).
(all ©Heather Viles, University of Oxford)

7.3.2 Control of moisture ingress and runoff

The laboratory and field research has not produced conclusive results on the role of soft capping in reducing moisture ingress into wall-heads. This is partly because of the difficulty of finding suitable techniques to measure moisture flow, and partly because of the unknown internal structure of many ancient ruined walls. Some of the evidence suggests that soft capping reduces the amount of moisture entering the walls, but there is also evidence that the effectiveness of soft capping varies seasonally.

The installation of soft capping at Kirkham Priory gave us an opportunity to monitor its role in reducing damaging water runoff down the face of the walls. At Kirkham, as shown in Figure 7.5, there are notable black streaks down parts of the wall face, which reflect algal and other micro-organic growths on runoff prone areas. Some visual evidence of reduced soiling (Figure 7.5b) indicates that soft capping may indeed be effective at reducing this runoff, but further research is needed to confirm this.

Figure 7.5 Streaking on the wall of the frater (refectory wall) (a) before and (b) 18 months after soft capping was installed. Streaking appears less noticeable after 18 months underneath the soft capped section (black line, image b, just after heavy rain), whilst there is no difference between the hard-capped section and the uncapped areas. *(both ©Chris Wood, Historic England)*

By applying water to new soft capping at Byland Abbey, its potential for water shedding can be seen (in Figure 7.6). While this was not a strictly scientific test, using a watering can and observing the pattern of runoff showed that even short tufts of grass can be effective at shedding water away from the wall face, thus reducing the threat of algal colonisation and unsightly black streaking.

The field experiments at the Wytham Woods test site (Chapter 4, and Hanssen and Viles, 2014) have provided more conclusive evidence of the shedding role of soft capping. Lichens have colonised wall faces below it, as it provides a stable environment for their growth (see Figure 4.26 of the Wytham Woods test walls). In contrast, the walls under hard capping exhibit no lichen growth, although they are abundant on top. Although lichens have a negligible effect on the longevity and performance of stonework, they are redolent of the natural patina that historic masonry acquires over time. Many observers view this as a quintessential feature.

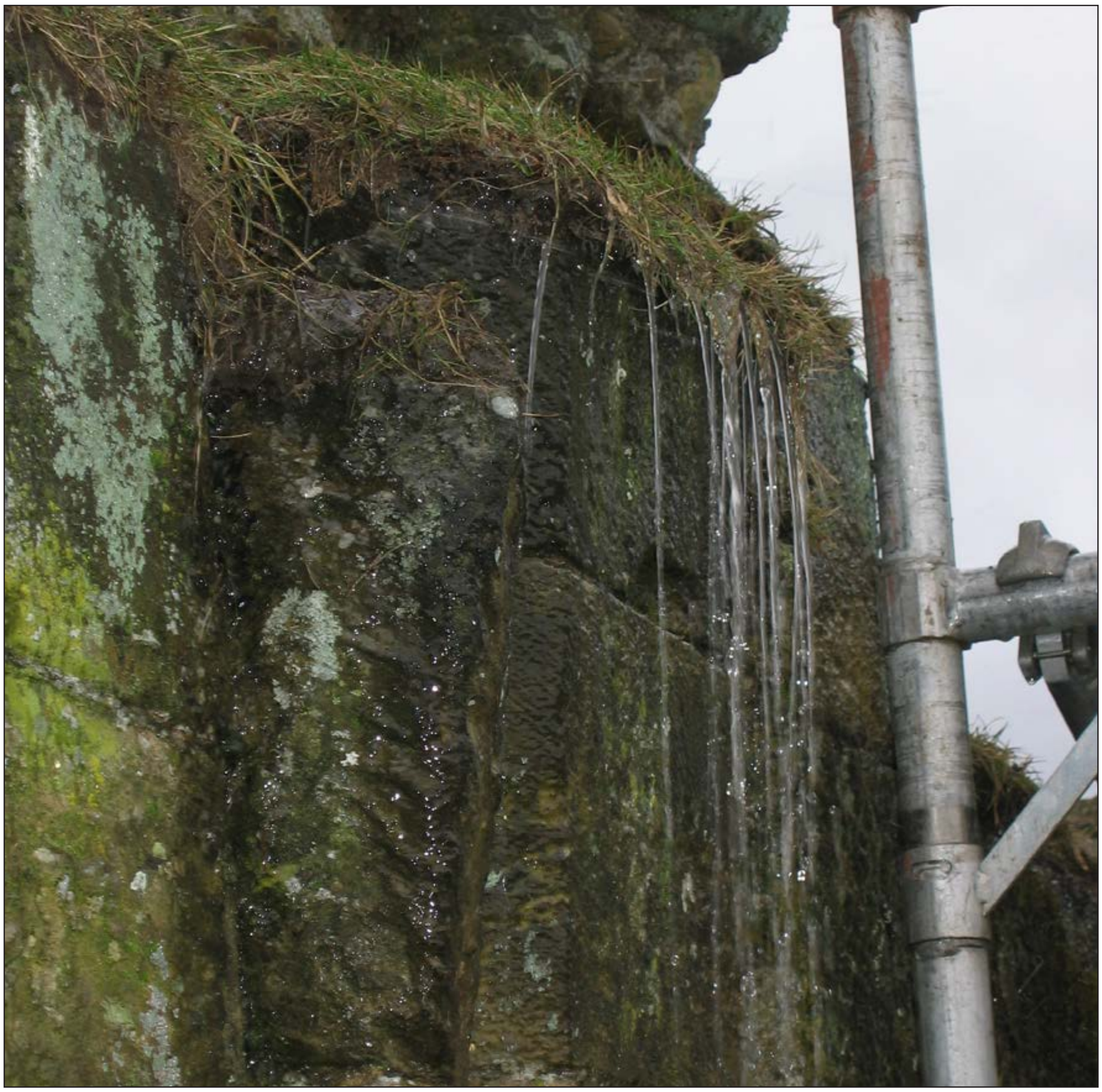

Figure 7.6 The effects of watering newly installed soft capping at Byland Abbey illustrated the water shedding role of even, short turf. ©*Chris Wood, Historic England*

7.3.3 Practical considerations

Our field trials have illustrated that soft capping is fairly easy to install (particularly in comparison with hard capping), although it still needs to be done carefully and with thought. Each situation/site will require some individual modifications to a general approach, depending on: the local climatic conditions, the nature of the walls, the availability of materials and the personnel. As Figure 7.7 illustrates, the soil can get washed off the wall if the grass dies back and forms bare areas. In addition, animals can dislodge turf and soil. Water-retaining gels have not been found to improve the performance of soft capping – if anything, they have had the opposite effect. Turf cut from nearby seems to perform much better than commercially cut turf.

Figure 7.7 One of the soft capped areas at Thornton Abbey, (a) at the time of installation, (b) 18 months after installation, and (c) in November 2016. *(all ©Chris Wood, Historic England)*

Particular care must be taken at the edges of soft-capped sections, as here the soil can dry out most easily and it is harder for grass to grow. Sedum plants may be particularly good at growing under these edge conditions (Figure 7.8), as observations of natural soft capping have shown. Our field experiments at Wytham, Godstow, Hailes Abbey and Castle Acre Priory all demonstrate the value of sedums (both in the form of mats and plugs along the edges of turf capping) in making soft capping more resilient to drought. In the longer term, seasonal drying out of turf capping is to be expected. Our research shows that soft caps recover well in autumn and winter as long as water can reach them effectively. As with all conservation approaches, maintenance is required. But this has been shown to be relatively minor, at most involving only the removal of woody species whose roots might penetrate the stonework. (In fact, no woody growths have been observed at any of our test sites). Sedum mats are robust but harder to install than turf caps, while seeded mats have been found to be easy to install but short-lived and prone to erosion.

Practical issues have also been raised during our research of whether or not wall-heads need to be consolidated before installing the soft caps. In general, it appears that no consolidation is needed apart from filling major cracks (over 5 mm in width) and re-bedding loose edge stones.

Figure 7.8 Soft capping in a highly exposed position at Whitby Abbey showing decay at the edges (a); and older soft capping at Kirkham Priory showing exuberant growth of sedum along the edges (b). *(both ©Chris Wood, Historic England)*

7.3.4 Hard capping and other alternative strategies

The research has also thrown light on the usefulness of hard capping as an alternative conservation treatment. While we have not provided a robust and detailed comparison of the two techniques at every site, it is clear that hard capping with appropriate lime-based mortars is a useful method in some circumstances. At Byland Abbey, Kirkham Priory and Thornton Abbey, for example, hard capping was installed successfully. It currently looks good and has proved to be resilient. However, eventually hard capping will crack and decay. The cost of repairing and replacing it is likely to be much higher than the cost of the small-scale routine maintenance needed for soft capping. Furthermore, as we found during this research project, hard capping is a lot more expensive and time-consuming to install than soft capping. Finding a suitable source of stone for hard capping can also be difficult, and designing and providing an appropriate and effective mortar also relies on good workmanship and sound protection. On a more philosophical note, hard capping also usually involves creating a new profile, and thus does not fulfil the 'conserve as found' principle, even if face stones are recorded and replaced in their original positions.

Other conservation options exist, but have not been directly investigated during this research. For example, building roofs over deteriorating structures, as illustrated in Figure 7.9 from Sherborne Old Castle. We propose that in such situations, soft capping could work just as effectively and look far less intrusive.

Figure 7.9 A flat zinc roof built at Sherborne Old Castle to tackle problems of water ingress.
(both ©Chris Wood, Historic England)

7.4 Decisions to be taken before choosing to soft cap

Four key issues need to be considered before deciding to use soft capping. Firstly, it is important to address the philosophical issues. Principles of reversibility, minimum intervention, the use of authentic materials, like-for-like repairs and 'conserve as found' must all be thought about in relation to its effect on the significance of the structure. As our research has illustrated, soft capping is often less invasive and more easily reversible than other harder conservation strategies. However, soft capping may not always be most appropriate because of the perceived value of a monument. Reacting to a proposal to introduce soft capping to Hadrian's Wall (Figure 7.10) in the early 1990s, the Ancient Monument Inspector wrote:

> *"I remain totally against any sort of green alternative to the traditional way these lengths of Hadrian's wall in the guardianship of the State have been consolidated and are currently being maintained. The remains of the wall, albeit very fragmentary in places, should continue to be conserved free of vegetation of any sort. Hadrian's Wall, as one of the great frontier works of any period in man's history is now designated a World Heritage Site. It is also monument to one of Rome's greatest emperors, one who actually visited the wall at its inception and is considered to have taken a personal interest in its construction. Its inspired design is no less a piece of architecture than Tivoli, Castel Sant'Angelo, the Pantheon and the many other monumental buildings which Hadrian caused to be erected in provinces throughout the Empire. The wall in our case has already been consolidated with hard capping and should not now be allowed to gather vegetation and thereby blend into the Northumberland landscape like a common field wall. It should stand out as far as possible as a piece of Roman architecture of unparalleled grandeur..."*

Figure 7.10 Hadrian's wall: an example of a ruined monument, which may be unsuitable for soft capping for philosophical reasons. ©*Heather Viles, University of Oxford*

Secondly, it is important to understand the fabric of the monument and how it is decaying. Soft capping may be particularly beneficial where there is a risk of surface erosion from runoff from hard capping and if there is the threat of frost damage or differential thermal expansion. Under other regimes of deterioration, soft capping may be less effective. It is certainly not a panacea for all ills.

Thirdly, the climatic and microclimatic conditions of the monument must be understood. Drought-prone areas may not be suitable for turf capping, although other plant communities may thrive even under very dry conditions (e.g. sedums).

Fourthly, it is important to consider a monitoring and maintenance regime before taking any conservation action. Simple photographic monitoring, coupled with inspection through binoculars for high and inaccessible walls, can provide good evidence of the state of soft capping. Seasonal changes will occur, and thus monitoring should take place at the same time each year.

7.5 Implications for future conservation practice

Adopting soft wall capping as a conservation technique has potentially huge implications for the appearance and management of historic sites. Soft capping can lead to a major change in the appearance of sites (as shown in Figure 7.11). It is also potentially a much less disruptive intervention than hard capping, and requires much less invasive maintenance and monitoring. The use of soft capping might secure more historic fabric as it is relatively easy to install, and should also contribute to enhanced conservation and biodiversity at heritage sites. Finally, soft capping has proved to be a highly cost effective solution to many conservation problems. And evidence clearly shows it is the natural way to protect walls.

Figure 7.11 North Leigh Roman Villa (near Oxford), showing recent installation of soft capping on half of the site to the right of the roofed building (May 2009). ©*Alan Cathersides*

8 SOFT CAPPING AN ENTIRE SITE – HAILES ABBEY

8.1 Background

This Cistercian Abbey, which dates from the mid 13th to the 16th century, contains a wide range of standing remains constructed from Cotswold limestone and rubble. It is managed by the National Trust and looked after by English Heritage. The site was extensively excavated in the late 19th century. The remains are vulnerable to freeze-thaw activity and have suffered serious deterioration in many places. Hard capping had been carried out in the past to address these problems, and some small sections of low wall were soft-capped in the 1990s. A full description of the site is provided in Chapter 2, section 2.7.

During the early stages of this research project, those responsible for the care and management of Hailes Abbey expressed interest in further soft capping, and it was chosen to be one of the experimental test sites. Promising results during the early phases of this project encouraged the English Heritage South West Regional team to consider soft capping as a larger scale option for ongoing deterioration problems. The possibility of completely soft capping the whole monument offered not only a conservation solution, but also the opportunity to evaluate its effect on appearance and its reception by visitors and professionals.

This research project focussed on the performance of soft capping, and not on aesthetic issues and how they might affect the significance of monuments. However, these issues could not be totally ignored, as they are often paramount in the minds of visitors and others with an interest in the sites. Testing at other sites only utilised relatively small sections of wall tops so it was not easy to make aesthetic judgements, or answer the following questions which were posed during the research, including:

- How does soft capping change the appearance of a site?
- Is the change perceived by visitors as being better, worse or neutral?
- Does soft capping make the physical remains on a ruined site more difficult to interpret and understand?

In order to address these questions, the research team looked for a suitable monument that could be entirely soft-capped. Hailes Abbey was chosen because it had particular and serious problems with fabric decay resulting from a high water table, regular flooding and severe winter frosts. Even if soft capping ultimately proved unacceptable, it would at least provide a holding operation that could reduce the ongoing damage at the site.

Once all masonry surfaces were soft-capped, the plan was to monitor regularly and review its performance, as well as its perception by the public.

8.2 Work undertaken

Full drawings, specification and schedules of work were required because of the scale of the project, so funding was not confirmed until late in 2012, when prices were received from competing contractors. The work was undertaken between 28th January and 15th March 2013.

Soft capping should ideally be installed before the end of February, as the weather in March, particularly in the southwest of England, can often be warm and dry, and occasionally even quite hot (see Chapter 6). This can lead to the turf drying out and dying before it can become established if it is not watered. Fortunately, the weather was mostly cloudy, cool and frequently wet during the installation process. Arrangements for watering were put in place in case it changed after the soft capping was installed. However, since the weather in the three weeks following completion was predominantly inclement, the soft cap established very well.

The walls required preparation before they could be soft-capped. This included some consolidation of loose wall tops, the pinning of individual stones, localised grouting, and mortar and plastic repairs. One hard cap built up during earlier works was removed, and the corework below consolidated. Then virtually all of the masonry was soft-capped, from surfaces at ground level to the highest standing masonry (the walls around the cloister which stand approximately 4-5 m tall). Even small ledges and column tops were capped. This was done to give the fullest possible idea of what a ‘completely’ soft-capped site would look like, and to see how small areas of capping would perform over time.

Only one exception was made (see Figure 8.1a). It was felt this particularly badly

Figure 8.1 Deterioration in small sections of stonework which were not suitable for soft capping. *(both ©Alan Cathersides)*

Figure 8.2 Area of adjacent field, from where turf was removed, (a) at completion of works in March 2013, and (b) 9 months after restoration works in January 2014. *(both ©Alan Cathersides)*

eroded section needed substantial repair work before soft capping could be done. Unfortunately, this work was not part of the research project, and funds were not available to complete it before it finished. Figure 8.1b shows the deterioration of this area since 2013. A better alternative strategy would have been to soft cap it as a holding operation until funding for repair was confirmed. Then the masonry could have been repaired – ideally when the weather is warm, during the spring or summer – and re-soft-capped.

Turf for the soft capping was taken from a field adjacent to the monument. Approximately 2,300 m^2 was used in the works. Following completion of the work, the cleared area was lightly rotovated and seeded. Recovery was very good, as can be seen in Figures 8.2a and 8.2b

BEFORE 3RD SEPT 2012	IMMEDIATELY AFTER 21ST MAR 2013	6TH JUNE 2016	4TH OCT 2016

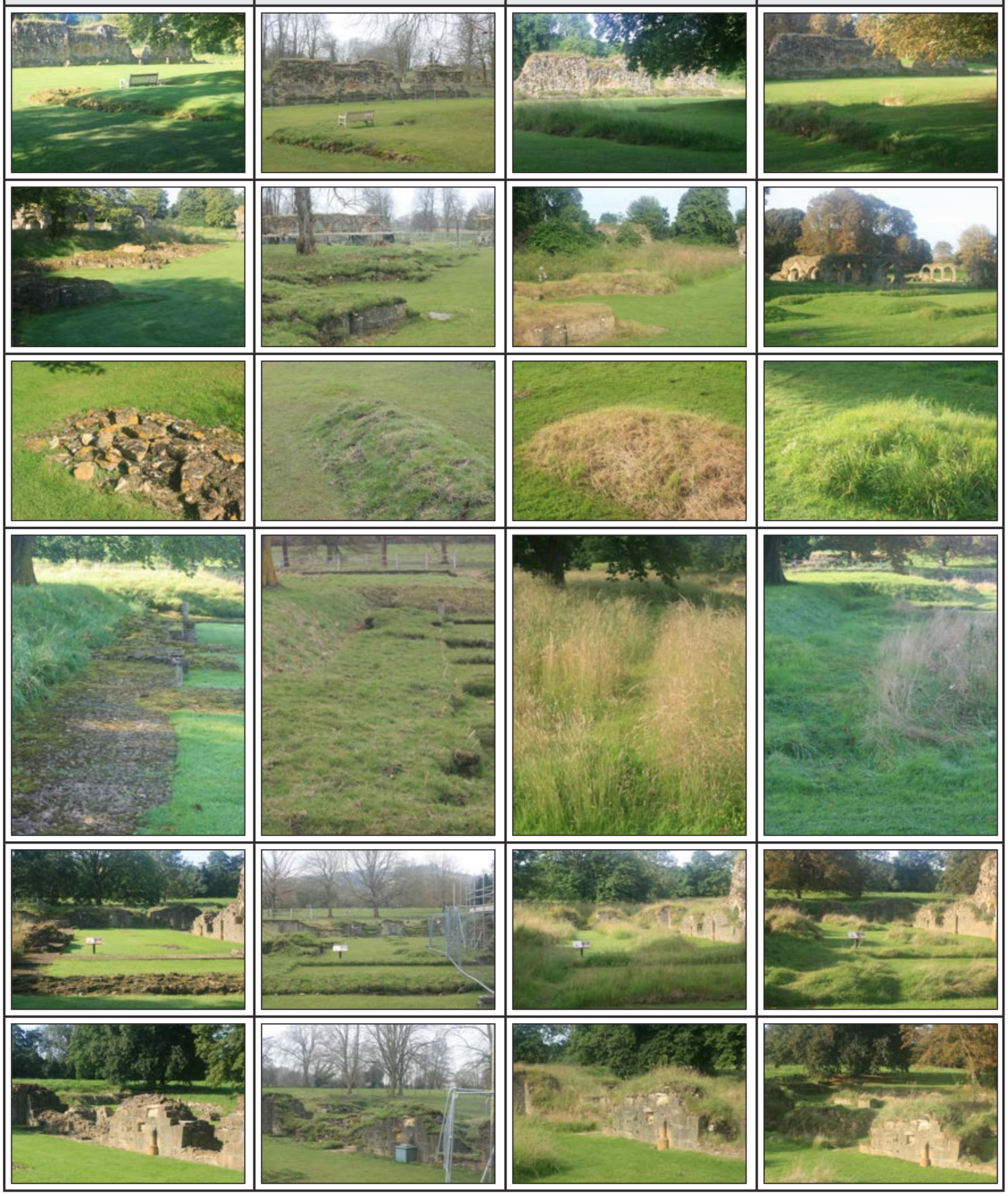

Figure 8.3 Before and after images from around Hailes Abbey showing the immediate visual impact of soft capping. *(all ©Alan Cathersides)*

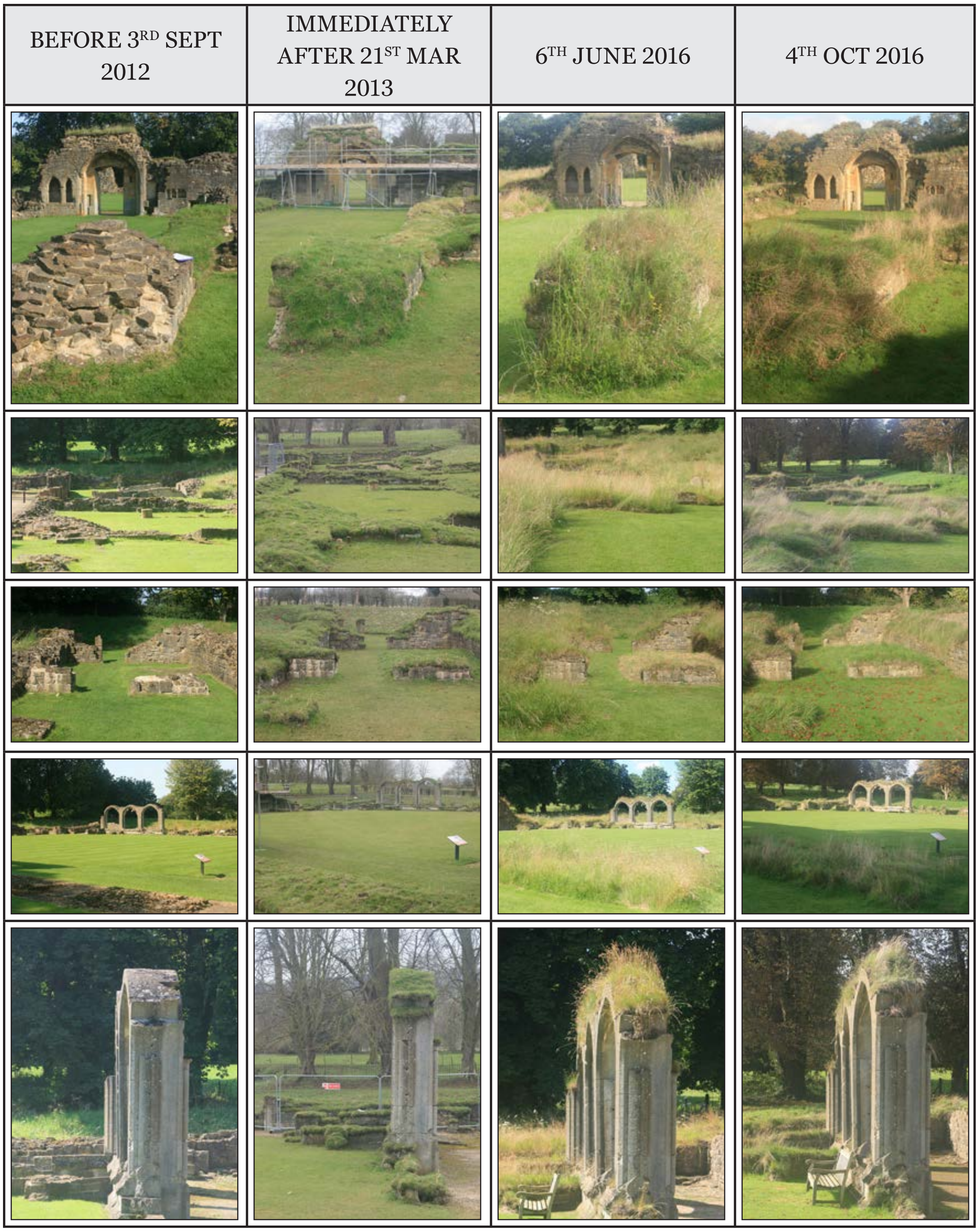

Figure 8.3 Before and after images from around Hailes Abbey showing the immediate visual impact of soft capping. *(all ©Alan Cathersides)*

8.3 Public Perception

Visitor perception of the work on this site was also assessed. This was done in three ways. Firstly, through reports from on-site staff who have daily contact with the public. Secondly, by monitoring written and email feedback received from visitors, and thirdly, by direct survey, using questionnaires completed by visitors, as well as some in-depth interviews with a selected few.

8.3.1 Visitor Operations Staff

Members of the research team regularly received verbal reports from the English Heritage Visitor Operations Staff who run the site and are the first line of contact. When time permitted (when the site was not too busy), they were able to brief visitors about the soft capping trial. The response was generally interested and positive.

When the soft capping was first installed, bamboo canes were put in place to stop turfs from blowing or falling off before they had established. They also prevented animals from burrowing and people from sitting or walking on the newly laid turf. As the beginning of the spring was cold, the grass grew slowly, which did little to conceal the canes. Many visitors found the ‘forest of split bamboo canes’ to be visually very intrusive, particularly at lower levels (see Figure 8.4). However, after the turf had rooted, the canes were removed from the lower level caps. Then most of the visitors, especially those who had not visited the ruins before, found nothing untoward about the appearance of the ruins. Some, particularly those who had visited the site previously, questioned the changes, but most were satisfied when the reasoning behind soft capping was explained. The general consensus was that over all, the protection of the fabric warranted the change in the appearance of the site.

Figure 8.4 (a-d) showing bamboo canes considered to be intrusive. *(all ©Alan Cathersides)*

8.3.2 Complaints from Visitors

To date (June 2016) English Heritage has received only two written complaints about the appearance of the soft capping. Following a detailed response from the research team explaining the reasons for the work, the complainants felt their concerns had been addressed and would continue to visit the site to see how it developed.

8.3.3 Visitor Perception Research

A detailed visitor perception research project was carried out by Ellen Sleight, an undergraduate student at the University of Oxford (Sleight 2014 unpublished). Using a key word test, questionnaires and in-depth interviews, this work aimed to draw out people's feelings about the appearance of the site.

Participants were initially asked whether they had noticed the soft capping before the introduction of the research drew their attention to it. Two thirds (67%) of the participants had noticed the soft capping, and one third (33%) had not. 78% of visitors had a positive perception of the soft capping, while just under 16% had a negative view (the remainder being neutral). Where perceptions were negative, the vast majority said that once they understood the conservation benefits, they could accept the aesthetic appearance. 17% of the participants who hadn't noticed the soft capping used the word 'natural' to describe the ruin in the key word test. They were also more likely to describe the ruin using phrases unrelated to the vegetation.

For the key word test, visitors were asked to describe the ruin in three words. The majority (84%) used three positive words, while only 5% used three negative words. The other 11% had a mixed response. The most commonly used words were 'grand', 'striking' and 'beautiful', and while these are not direct comments about the soft capping, they are about ruins which have been soft-capped. Over a third of those questioned (39%) used at least one word that was directly related to the soft capping. These included visitors describing Hailes Abbey in positive terms as 'natural' (9%), 'overgrown' (6%), 'vegetated' (8%) and 'grassy' (6%). Negative words, used less frequently, included 'neglected' (5%), 'unkempt' (4%) and 'hairy' (1%).

Questionnaire responses were collected on both weekdays and weekends. 55% of the responses were from women, and 45% from men. The over 50s age group predominated (almost 73%), but that is probably a fair indicator of the demographic visiting such sites. Nearly 72% were visiting for the first time. Over half of the repeat visitors had visited once or twice before. The rest of the repeat visitors had visited three or more times, including 2% who had visited over 40 times!

As part of the questionnaire, participants were asked to rank a series of statements about the soft capping. They were asked whether they agreed strongly, agreed, felt neutral, disagreed or disagreed strongly. The statements were:

- 'Vegetation enhances the look of the Abbey'
- 'This Abbey appears neglected'
- 'The soft capping is aesthetically pleasing'
- 'This Abbey looks as though it is actively being conserved'
- 'Vegetation conceals too much of the Abbey'
- 'Vegetation looks as though it belongs on the walls'
- 'The soft capping detracts from the aesthetics of the Abbey'

These responses were then coded for their perception of soft capping between 2 (strongly positive) to -2 (strongly negative). Overall, 78% of participants had a positive perception, 15% a negative perception, and 7% a neutral score.

At the end of the questionnaire, visitors were shown three images of the ruin and asked which one they preferred. The image showing the ruin after the soft capping was the most popular image, with almost half of participants (47%) selecting it. A further 12% selected an image showing natural vegetation growth on the ruin (taken in 1937). Although only 20% chose an image that showed the exposed stone with no vegetation, this represents a fairly significant number of visitors.

Finally, in cases where participants felt that the soft capping resulted in a loss of authenticity, they were asked to evaluate whether this outweighed the conservation benefits. Most thought no. One participant stated that 'the conservation benefits are more important at the end of the day, and you can't expect ruins to be completely authentic anyway because they have been here for so long'. Almost two-thirds (64%) of visitors indicated that there was not enough information on-site about the conservation of the Abbey, and 45% thought this should be displayed on notice boards.

8.4 Presentation of ruins

There is no single accepted professional view on how ruins should be presented (Ashbee 2009). Even the most widely accepted conservation mantra – 'Conserve as found' – is open to wide interpretation, as indicated earlier in this volume.

Site managers want to both impress and educate visitors about a monument and its place in history. A key element in this is the 'readability' of the site: the ease with which visitors can look at the remains and understand and visualise what the site had originally been like. Concerns have been expressed that the use of soft caps, particularly on low walls, can make this process more difficult. This is especially so when low or ground level walls with a vigorously growing soft cap are close to areas of long grass managed for other reasons (ecological and/or visitor management). There the definition of the 'wall' could be lost. Adjustments at Hailes to make these divisions clearer include maintaining short grass immediately adjacent to all soft-capped walls and the occasional trimming of vigorous growth on low-level soft caps.

The visitor perception research work carried out at Hailes (Sleight 2014 unpublished) gives some substantiation to this concern. 40% of participants mentioned specific parts of the soft capping as being more concealing than others. One thought that the turf had a positive aesthetic effect over all, but "on the little lower pillars in the middle of the Chapter House they look comical because they are so maintained and trimmed to fit the shape of the stone." Two other participants noted that the soft capping concealed too much of the lower walls of the ruin, with one commenting "On the lower walls I can't tell in some places what is just grass and what grass has stone underneath it." On the other hand, one participant thought that the grass concealed too much of the high walls, because it "makes it look like the top of the arch was the full height of the building."

Some concerns were more complex and indicative of the difficulty of presenting ruins to a varied audience. When asked if soft capping affected how the participant imagined the original building, a visitor said that he had tried to imagine the ruin, and thought that the grass "gives the impression that the ruin has been neglected so moves it further away from being a building in my mind. It makes it look even more aged so makes it feel like even longer since it was inhabited, it is harder to picture people here." However, another noted that while the vegetation made it harder to think about the building as a whole, "it is hard to imagine the actual building anyway, even without the vegetation."

All visitors approach and interact with heritage sites in a different way. This makes it difficult to present a site in a way that suits everybody. Thompson (1989) condemned the visitors that did not want to make the concentrated effort that appreciation of a ruin requires. This condescending attitude is now unacceptable. Professionals need to find new ways of engaging visitors so that they understand the importance of soft capping in conserving sites.

8.5 Conclusion

Although the change to the appearance of the site is substantial, it has not caused a great deal of adverse comment. Indeed, a third of visitors did not even notice the soft capping until it was pointed out. Over all, a large percentage of visitors had a positive perception of the soft capping, while a relatively small number (<16%) found it detrimental to the appearance of the site. We believe this gives a strong mandate for site managers to consider extensive use of soft capping where this would be beneficial to fabric preservation.

The site has been monitored on a regular basis by English Heritage staff, including those concerned with maintenance, preservation and presentation. This group is pleased with the overall outcome of the soft capping and the visitor response to it, but will continue to consider a number of issues that might need to be adjusted to assist visitor interpretation. These include:

- **Ensuring that where low or ground level soft-capped walls are located next to areas of long grass, a strip (+/- 1 metre wide) is maintained as short grass.** In that way, a clear distinction will be retained between the long-grass areas and the soft-capped wall.
- **Experimenting with different mowing regimes** for the soft capping on low and ground level walls to assist interpretation and prevent the soft caps from becoming too ragged.
- **Removing the four capped pillar bases** in the Chapter House (South Transept) where the soft capping could not establish.

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