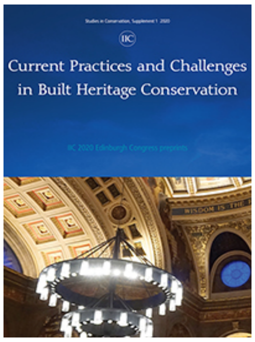

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Assessing the Long-term Success of Reigate Stone Conservation at Hampton Court Palace and the Tower of London

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ABSTRACT
Reigate stone was extensively used in medieval London and is prone to rapid decay. A variety of different conservation treatments has been applied in the past; in many cases, these have not mitigated on-going decay. This paper presents an overview of wax, limewash, silane and ammonium tartrate treatment at the Tower of London and Hampton Court Palace. Documentary analysis and visual inspection indicate that whilst these methods have provided protection to some stones, no single method has resulted in the protection of all stones. Non-destructive and minimally-destructive testing is used to more closely assess the effects of ammonium tartrate treatment. The results imply that inherent stone mineralogy, past decay pathways and/or present environmental factors are a greater influence on on-going decay than treatment histories.

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Historic masonry; built heritage; architectural conservation; non-destructive testing; hydroxylating conversion treatment

Introduction

A wide range of treatments has been used to conserve vulnerable building stones (Doehne and Price 2010). These are frequently tailored to suit particular lithologies: the lime method is a common technique for treating limestone, silanes are more suitable for sandstones. It can be difficult to select appropriate treatment for lithologies which do not fall into standard categories. Frequently such stones represent unique chapters of architectural history. Furthermore, there has long been awareness of limitations and challenges associated with stone conservation (Schaffer 2016). The purpose of active stone conservation is usually to improve water repellence (surface coating) and/or restore fabric strength (consolidation); however, past assessment of field-based experiments has concluded that many attempts are ineffective in the long term (e.g. Clarke and Ashurst 1972; Odgers 2013). Factors such as the penetration depth of consolidants and moisture entrapment due to impermeable surface coats are of on-going concern. The effects of climate change, such as increased intense rainfall, are predicted to put historic masonry under increasing risk of rapid decay (Smith et al. 2011). Furthermore, active conservation protocols are being re-evaluated in response to advances in conservation science and shifts in cultural perceptions of deterioration (Douglas-Jones et al. 2016). As a result of this, assessment of past treatment methods is increasingly necessary.

Reigate stone conservation

Reigate stone has a variable calcite and clay mineral content, an unusual silicate grain structure and is prone to rapid decay (Sanderson and Garner 2001). It was widely used for detailed masonry in South East England from the eleventh to sixteenth centuries and was the principal freestone at sites such as the Tower of London (ToL) and Hampton Court Palace (HCP) (Tatton-Brown 2001). Attempts at conserving Reigate stone are likely to have commenced as soon as techniques became available, however, the scant documentation makes reliable identification and dating difficult. Table 1 provides an overview of past conservation for which documentation or robust evidence is available, focusing on ToL and HCP. Few techniques have successfully mitigated decay; some have accelerated decay. Given its notoriety, stone consolidants may frequently have been trialled on Reigate stone; there is evidence to suggest Roman cement, aluminium hydroxide and barium hydroxide were all used on decaying Reigate masonry shortly after their development; none successfully. Newly-developed techniques continue to be tested against Reigate stone. On-going trials using nanolime at Westminster Abbey await full evaluation. A brief documentary and visual assessment of three widely-used treatment methods applied to Reigate stone follows.

Waxes were widely used surface treatments in late nineteenth- and early twentieth-century England. Much Reigate stone at HCP displays evidence of past

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Table 1. Past Reigate stone conservation techniques. Works for which no reference is given are recorded in the archives of Historic Royal Palaces.

Date	Technique	Sites	Outcome
Early C19 (1820)	Roman cement	Bloody Tower gateway ceiling, ToL	Survey in 2002 identified on-going decay of stone beneath plaster.
1840s	Aluminium hydroxide	'experiment made upon a cistern of Reigate stone' (Anon 1844)	Unknown.
1882?	Wax coating	Widespread at HCP	Survey in 2008 linked rapid decay of Reigate stone plaque to impermeable wax coating. Similar decay patterns can be observed elsewhere, however there are also examples of well-preserved coatings.
Early C20	Barium hydroxide	Chapter House at Westminster Abbey (North 1930, 381)	Protective crusts soon delaminated.
1963	Calcium hydroxide (limewater) and various organic polymers	Salt Tower interior, ToL (Experiment including control areas)	Treatment had no significant effect (Clarke and Ashurst 1972, 43)
1984	Brethane (Alkoxysilane)	Upper Wakefield Tower, ToL	Surveys in 1999 and 2003 found that the treated pier, which had since been found to be heavily salt contaminated, was decaying more rapidly than nearby untreated masonry (Price 1993; Church 2003).
1988–1991	Lime method	ToL: Bell (1988), Wakefield (1990), Salt (1991), Cradle (1991) and Wardrobe Towers (1991)	On-going decay in many treated areas. Limewash coats detached rapidly in some areas, mainly attributed to high moisture content of masonry. Other coats still visible now. Casein, pigment and linseed oil variously mixed into limewash and lime mortar.
2001	HCT (solvent based)	Trials at HCP, ToL and Winchester Palace.	Some treated areas have resisted decay. Mineralogy and microclimate likely to be key factors.
2013	CaLoSil (Nanolime)	Trials at Westminster Abbey	Assessment of trials on-going.
2015	HCT (water based) and lime-mortar	Bell Tower exterior, ToL	On-going surface loss noticeable in exposed areas.

treatment. Reference to the restoration of stonework in 1882 provides a possible date for such work at HCP (Colvin 1976, 158). Intended as a water repellent, waxes are prone to adsorb pollution and trap moisture (Odgers and Henry 2012, 136). This can result in accelerated decay patterns, which have been documented at HCP on the Cardinal Wolsey plaque (Figure 1). Coatings do not show uniform signs of decay. In some sheltered areas, coats have partially detached, spalled or eroded to reveal sound stone. In

Figure 1. Cardinal Wolsey Plaque at HCP showing acceleration of decay rate on wax-treated Reigate stone surface.

other sheltered areas, coats have blistered and flaked to reveal flaking stone and gypsum crust. In many exposed areas remnants of coat are isolated, and the stone surface is friable and soiled. Most coats appear discoloured by pollution. Microclimatic stability appears to control the performance of wax treatment.

The lime method emerged in the 1980s as a holistic technique for treating limestone. It consists of consolidation with calcium hydroxide (limewater), plastic repairs with lime-mortar and protective coatings of lime diluted in water (limewash) (Doehne and Price 2010, 36–37). Various additives are added to the limewash in attempts to improve resilience. The technique was widely used on Reigate masonry at ToL in the early 1990s. Initial use of limewater in the upper Bell Tower in 1988 caused concern over the high level of water uptake. There are conflicting accounts of where it was applied after this; contemporary documentation suggests masonry at the Cradle and Wardrobe Towers was also treated with the full lime method (Table 1). Most coats have since detached from Reigate stone at the highly exposed Wardrobe Tower, however, some remain intact. Coats have also largely detached from the lower Bell Tower and the Bell Tower parapet. Rapid decay has been recorded in all three areas, with distinct environmental mechanisms likely to be responsible in each case, ranging from deep wetting of the masonry to rapidly fluctuating conditions (Michette et al. 2019). The more benign environment of the upper Bell Tower has led to longer lasting coats, however recent prolonged moisture ingress in the southern alcove due to defective guttering has rapidly accelerated localised decay. Intact coats are not exclusive to internal masonry; coats applied to the external Cradle Tower have also survived (Figure 2). These observations imply microclimate and stone mineralogy affect the success of limewashing. Despite producing some long-lasting coats limewashing has not been repeated, although lime mortar repairs make up a part of the current conservation strategy at HCP and ToL.

Hydroxylating Conversion Treatment (HCT) forms a crystalline deposit of ammonium tartrate on calcite within the pore structure of a stone. It was developed to enhance the adhesion of silanes to calcareous matrices (Weiss, Slavid, and Wheeler 2000). Laboratory testing has shown that use on Reigate stone may be effective even without subsequent application of silanes; treated stone performed positively in freeze–thaw and abrasion tests. Trials were carried out at ToL and HCP in 2001 using HCT and a silane (Conservare OH). Visual assessment of trial areas at the Bell Tower indicates treated stones have become more resistant to decay than an adjacent untreated control (Figure 3). Large areas of Bell Tower masonry were treated with HCT in 2015, however erosion of some treated surfaces has continued. Whilst the trials were carried out with an organic solvent, recent treatment used water as a solvent. Different appearance and decay patterns of stones also suggests various mineralogical compositions. Microclimatic and contextual factors may present a further reason for the varying decay rates within and across the separate treatment phases. Further assessment of the HCT trials on Reigate stone will attempt to establish factors which can determine the success of on-going conservation strategies.

Experimental

An HCT test wall was built at ToL in 2001 (Figure 4). Eight stones were cut in half and separated by an

Figure 2. Left: limewashed Reigate stone at Cradle Tower, ToL, shortly after treatment in 1990 and right: in 2018 showing good state of preservation.

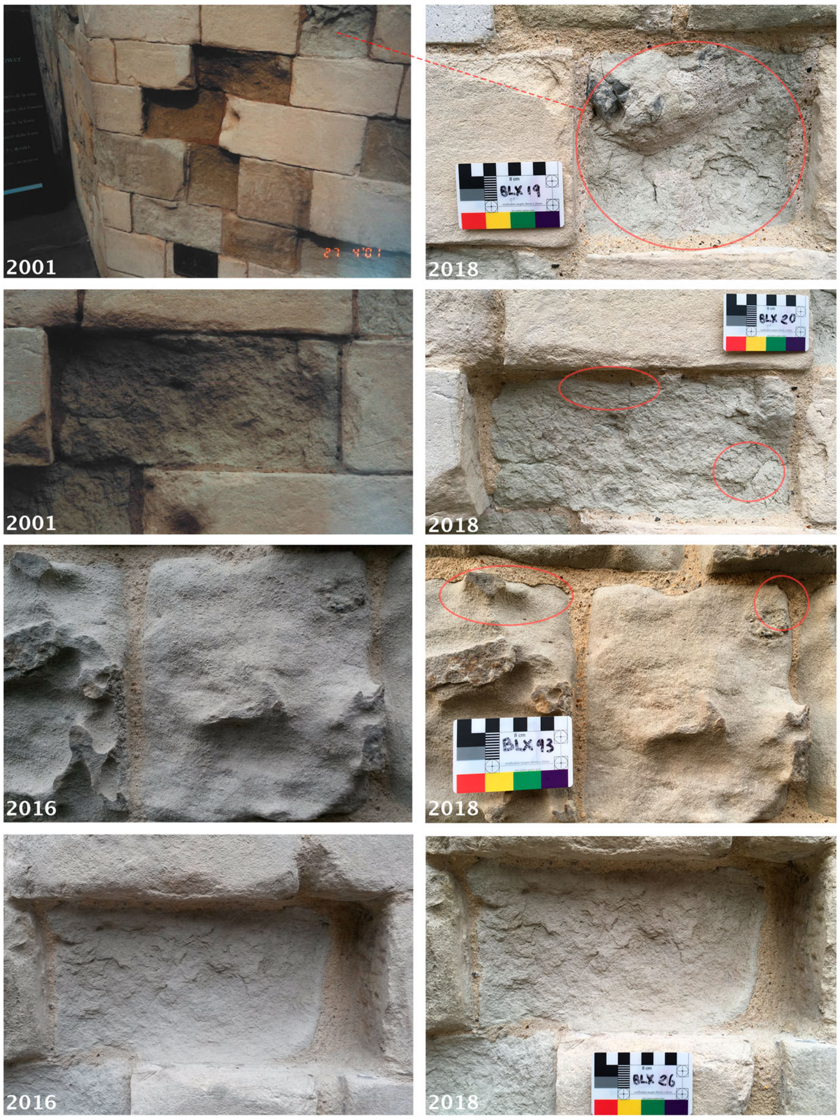

Figure 3. Reigate stone at the Bell Tower, ToL, treated with HCT during the 2001 trials and 2015 conservation work. Greater decay is visible in untreated control (top right), than in stone treated during trial (second row); however, on-going, rapid decay is visible in powdering, darker stones (third row) compared to flaking, lighter stones (bottom row) treated in 2015.

impermeable membrane. The right half of each stone was treated with HCT, the left acted as an untreated control. Photos taken shortly after construction of the test wall show that individual stones displayed a range of different textures, colours and pre-existing decay features. This suggests various sources. HCT.1, HCT.2 and HCT.4 had a yellow-brown discolouration of varying density but covering most of the surface area, probably related to a previous surface treatment, possibly linseed oil or wax (Odgers and Henry 2012, 136). HCT.3 and HCT.5 had rough surfaces. HCT.6, HCT.7 and HCT.8 had smooth, pale grey surfaces with localised damage.

Individual stones were investigated in 2018 using non- and minimally-destructive techniques (NDTs). Measurements were taken on treated and untreated surfaces of each HCT stone; for comparison, measurements were taken on a single stone treated with wax or limewash.

Surface hardness (SH) was measured using an Equotip rebound hammer (Proceq). 20 scattered measurements were taken on each surface. Leeb hardness (HLD) is given as an average of these readings.

Water uptake was determined using Karsten tubes sealed against each surface with putty and filled with distilled water. The amount of water absorbed by the stone was recorded at intervals of 5, 10, 20, 40 and 80 s. The absorption coefficient *wp* (g/m^{2}s$^{0.5}$) was calculated using the formula

$$wp = \frac{\frac{[m(1) + m(2) + \ldots m(5)]}{A}}{\left[\sqrt{t(1)} + \sqrt{t(2)} + \ldots \sqrt{t(5)}\right]}$$

where *m(n)* is equal to the mass of absorbed water in g weighed at the interval *t(n)* in s. *A* is equal to 5×10^{-4}, the area of the surface in m^2 that is in contact with water.

Drilling-resistance measurements (DRM) (SINT Technology attached to Makita drill with 3 mm bit) were

Figure 4. HCT trial wall at ToL. Top: shortly after treatment in 2001 (dark surfaces due to residual moisture following treatment). Middle: individual stones in 2018 (each stone treated on right hand side only). Bottom: micrograph taken with Dinolite USB microscope, showing consolidation of treated surface.

made to investigate depth of consolidation and crust formation. Two measurements were taken on each surface, with the drilling velocity set to 1 cm/min and the penetration depth set to 25 mm. Resistance (N) is given as an average of these measurements for outer (1–4.9 mm depth) and inner (5–25 mm) parts of the

Table 2. Results of NDT (*due to deterioration of drill bit, values measured on separate stones are not calibrated).

	Surface hardness (HLD)				Absorption coefficient (g/m^{2}s$^{0.5}$)		Drilling resistance (N)*			
	Untreated		Treated				Untreated		Treated	
	Mean	SD	Mean	SD	Untreated	Treated	1–4.9 mm	5–25 mm	1–4.9 mm	5–25 mm
HCT.1	477	26	451	48	921	-	18.6	20.3	18.1	19.4
HCT.2	465	30	446	55	1021	620	7.4	9.4	7.4	7.2
HCT.3	451	51	426	62	1499	663	10.2	17.1	15.6	17.7
HCT.4	516	111	447	73	43	773	49.6	28.6	36.3	28.7
HCT.5	440	20	411	39	1496	1130	16	16.9	14.5	15.1
HCT.6	442	63	528	39	156	223	7	9	9.6	8.8
HCT.7	362	71	520	46	482	904	43.1	42.8	36.7	43.9
HCT.8	464	35	419	25	673	2179	23.3	26.9	19.8	17.3
Wax	345	47	422	57	526	91	-	-	12.7	7.4
Lime	-	-	314	83	-	1170	22.5	25.3	3.3	25.2

stone. Before and after the measurements a reference block was used to calibrate the instrument. DRM has been used in previous assessments of stone consolidants (e.g. Odgers 2013) and is being used to assess the nanolime trials at Westminster Abbey, making it a useful technique for this study.

Results and discussion

Visual inspection of the test wall reveals that HCT.6 and HCT.7 have become noticeably more resistant to decay following treatment (Figure 4). In both cases, granular disintegration has affected large parts of the untreated area, but only small parts of the treated area. Decay has progressed most rapidly around pre-existing decay features, which were more evenly spread across the surface of the untreated areas. Whilst decay was visible in other stones, there was no apparent difference between the decay rates of treated and untreated areas.

Results of the NDT support the visual observations (Table 2). HCT.6 and HCT.7 are the only stones to show an increase in SH following treatment. There is no clear correlation between water uptake and treatment, suggesting that HCT does not have a water repellent effect. Absorption was lower in treated areas on fewer than half the stones. Instead, factors such as individual stone composition or position appear to control water uptake. Environmental and mineralogical factors also appear to influence DRM more than treatment. Only HCT.3 and HCT.6 required a slight increase in force to penetrate the initial subsurface of the treated area. Where DRM does indicate a consolidating effect, profiles suggest a penetration depth of at least 5 mm (Figure 5). Comparison of resistance across stones should be treated with caution due to rapid deterioration of the drill bit: HCT.2 and HCT.6 were measured on a different day from the other stones using a new drill bit and appear accordingly less resistant. Nevertheless, HCT.7 was significantly more resistant and more heterogenous than any other stone (Figure 5). This could reflect a higher calcite content, which would explain effective treatment. HCT.4 displayed crust formation or case hardening of the outer 3-4 mm of both treated and untreated areas. HCT.4 sits on the lowest course of the test wall and showed signs of salt contamination. Regardless of any effect treatment may have had, inherent mineralogy and environmental stresses appear to exert a greater control on on-going decay.

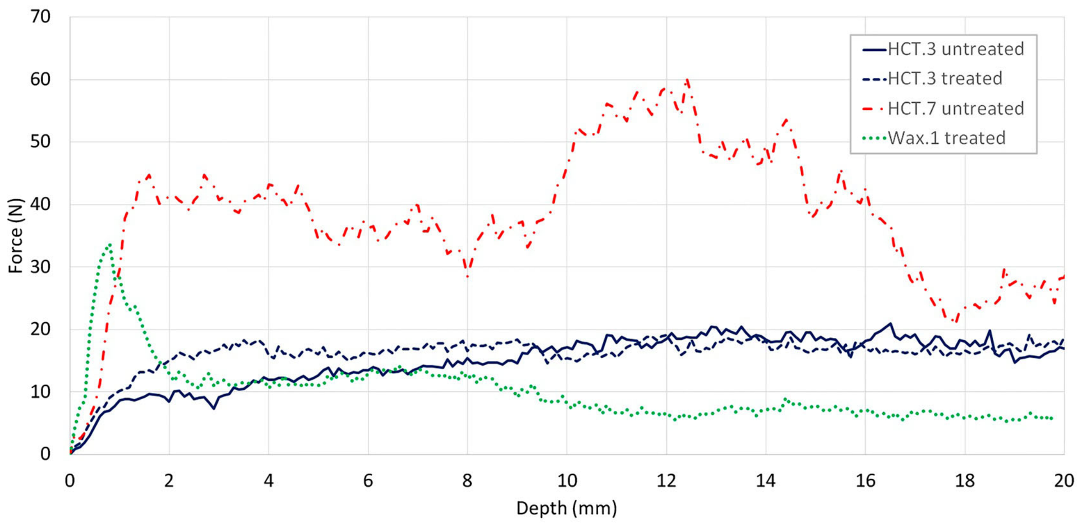

Figure 5. DRM profiles of selected stones.

Similar measurements taken on wax-coated and limewash samples highlight characteristics of both treatments. DRM and SH suggest that limewash produces a softer outer layer, whilst the high absorption coefficient indicates the coating is moisture permeable. The wax coating is noticeably harder and less permeable than the underlying stone. DRM indicates that the coat forms an outer case of several mm thickness with significantly different properties from the underlying stone. This can explain the decay patterns seen at HCP, with moisture entrapment behind the coating eventually leading to blistering and spalling to reveal the decayed surface. Limewash offers a more benign protective coat, which is also prone to decay but unlikely to damage underlying stone.

These findings support documentary and anecdotal evidence that indicate specific treatment methods are only suitable in certain circumstances. This supports previous assessments of stone consolidants, which have failed to identify an overwhelming impact of individual techniques (e.g. Clarke and Ashurst 1972; Odgers 2013). In highly exposed or fluctuating environments no treatment appears able to provide long-lasting protection. The evidence presented here indicates that wax treatment can accelerate decay in unsuitable environments. Although HCT and lime treatment appear more benign, mineralogical factors should be considered. Whilst calcite content is likely to improve compatibility, harder, calcareous stones are likely to be less at risk of rapid decay. Lime-watering and water-borne HCT may present a risk to more vulnerable, clay-bearing stones. This could explain the different response of stones treated in 2001 and 2015; treatment has only improved resistance in paler, probably calcareous stones. In situ identification of Reigate stone typologies can facilitate more effective treatment. On-going use of limewash would benefit greatly from controlled field experiments.

Conclusion

The objective of this study was to assess historic Reigate stone conservation, with the purpose of informing on-going conservation strategies. Stones believed to have been treated with wax in the 1880s, known to have been treated with the lime method in the 1980s and 1990s and treated with HCT in a controlled field-experiment in 2001 were investigated. No technique provides long-term protection of every treated stone; however, whilst impermeable wax coatings can trap moisture and cause a sudden acceleration in decay rate, limewash is benign and detaches quickly. HCT was only effective on certain stones. This is likely to be related to variable calcite content. The findings imply that inherent stone mineralogy, past decay pathways and/or present environmental factors are a greater control on on-going decay than past treatment. These findings support previous research, which suggests long-term consolidation is frequently ineffective without regular maintenance. On-going conservation must be tailored to specific circumstances; different mineral typologies are likely to necessitate precise techniques; certain environments or histories may preclude any effective conservation.

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