Daly *Herit Sci (2016) 4:19*
DOI 10.1186/s40494-016-0088-z

Heritage Science

RESEARCH ARTICLE

Open Access

The design of a legacy indicator tool for measuring climate change related impacts on built heritage

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Abstract

Background: We are experiencing a period of climate change the extent and impact of which is uncertain. In the cultural heritage sector the need for monitoring to inform our understanding is widely agreed, yet there is a lack of consensus over what constitutes 'monitoring for climate change'. This is due, at least in part, to the extended timescales involved. In this paper the design and implementation of one solution is described; a sustainable legacy indicator tool (LegIT) for the long term tracking of surface weathering effects on built heritage.

Results: The assessment of climate change impacts requires 30–100 years of data collection, equal to the period referred to as the 'climate norm' by meteorologists. The LegIT is a sacrificial stone object that registers changes in the severity and/or magnitude of weathering patterns on built surfaces, providing a legacy data source for future decision makers. To ensure its sustainability, careful thought was given to the choice of materials, data retrieval and archiving. The tool aims to track surface changes caused by recession, salt crystallisation and microbiological growth.

Conclusion: The development and installation of the LegIT is the first long-term exposure trial to be initiated at heritage sites in Ireland and is intended as a legacy for future researchers.

Keywords: Cultural heritage, Management, Climate change, Stone, Weathering, Monitoring, Sustainability, Indicator

Background

Although the scientific consensus is that our global climate is changing, there is no certainty about either the scale of that change or its impacts [1]. Undoubtedly, as the climate alters, so too will the nature of its effects on cultural heritage buildings, sites and monuments. To manage this process an evidence base of observations from built heritage will be necessary. This task is complicated however, by the fact that distinguishing climate change impacts from those attributable to normal climate variability requires measurements spanning over at least 30 years (the 'climate norm'). The sustainability of monitoring procedures for extended periods (*vis à vis* staffing, equipment and funding for heritage) is therefore crucial in the selection of suitable monitoring solutions [2].

Some of the monitoring methods currently in use[1], both for indoor/outdoor climate and the deterioration of materials requires a level of funding and technical capability that may be difficult for under-resourced heritage sites to maintain [3, 4]. Computerised environmental monitoring systems and digital data are also at risk from equipment and/or software obsolescence over the long-term. Responses to interviews with experts in the field indicate that while monitoring is considered highly important, there is a lack of suitable tools available for this task [5].

The use of indicators in cultural heritage as a sustainable complement to direct monitoring has been proposed by the author previously [6]. Indicators are defined as quantifiable variables that, because of an established functional relationship, can be used as proxies for

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[1] Identified through literature review and interviews with heritage professionals [5].

processes not directly observable or involving interactions over a long period (as in the case of climate change) [7]. Indicators should *both quantify and simplify information about complex phenomenon* [8]. A legacy indicator tool (LegIT) has been developed as one possible solution, focussed on measuring the weathering of stone surfaces into the far future. The design of the LegIT, for a pilot study at five case study National Monuments in Ireland, is presented in this paper.

Stone exposure

The exposure of fresh stone allows the study of decay under real-world environmental conditions, without compromising the integrity of historic monuments. Short-term exposure trials using stone samples have been used in many scientific studies for understanding decay patterns and thus predicting future behaviour [9–11]. Most trials have been conducted to investigate pollution effects and have often focused on calcareous stone [12–14].

One of the most extensive exposure trials is that carried out by the International Co-operative Programme (ICP) [15, 16]. The ICP exposed standardised materials, including Mansfield sandstone and Portland limestone, at a network of test sites across Europe between 1987 and the present [17]. The British National Materials Exposure Programme (NMEP) ran from 1987–1995 and fed into the ICP programme [18]. The STEP project also placed samples at locations across Europe [14] and again the focus was on Portland limestone. More recent studies at Queen's University in Northern Ireland have used sandstone [9]. Unfortunately it can be difficult to compare results between studies given the variety of methodologies employed [19]. The vast majority are also short-term projects, and even in the lengthy ones, the most an individual sample was exposed for was 8 years [18, 20].

Damage correlation

Estimation of future deterioration can be carried out using damage functions[2] that have been established for some specific decay mechanisms. For example, the Lipfert function calculates dissolution rates of calcareous stone. This formula uses variables, namely rainfall volume and temperature, which can be related to climate change projections. Unfortunately the accuracy of damage functions over long time periods is unreliable [21]. Dose–response functions[3] offer an alternative approach by looking at whether a process is increasing or decreasing, as illustrated by a dosimeter. Dosimeters are devices that demonstrate exposure through physical change, and are frequently utilised in objects conservation. The Oddy test for corrosion using metal coupons [22] and the blue wool fading standards [23] are two such examples. Designed to provide an early warning signal, they are often composed of materials similar to those of the artefact being studied, but which are more sensitive and will react faster [24]. The European Commission have funded a number of projects that developed dosimeters for indoor environmental monitoring including MIMIC, ERA, PROPAINT and SENSORGAN [24]. In general all of these studies take a common approach, comparing samples aged in the laboratory under known conditions with site-exposed samples. Although this process was not replicated with the LegIT, the dosimeter concept of using a sacrificial object to indicate the effects of environmental conditions was central to the tool's design. Thus the LegIT will illustrate actual weathering as it occurs on heritage sites. Relating this data to long term climate records will enable an understanding of the influence of climate change on deterioration processes.

Methods

Experimental design

Brimblecombe suggests that an embedded tool, capable of gathering and storing data without maintenance or management requirements would be ideal for monitoring climate change impacts on individual heritage sites [25]. The LegIT is an attempt to create one such tool, in this case for the capture of surface and near surface effects. Salt crystallisation cycles, physical and chemical surface recession and microbiological activity are the impacts it aims to capture. These are the issues noted by Noah's Ark [26] and researchers in Northern Ireland [27, 28] as being of primary concern for heritage in Western Europe under future climate projections.

The exposure of fresh stone allows the study of stone decay patterns under real-world environmental conditions, however, there are a number of issues that must be considered. Initial rapid weathering of newly exposed surfaces is generally followed by slower on-going deterioration. Therefore exposure trials using fresh samples cannot replicate the current weathering of historic stone [12]. Turkington [9] argues that while long-term decay rates cannot be reliably extrapolated, short-term exposure trials can be useful for explaining decay patterns, and thus for predicting future behaviour. The LegIT will act as a *proxy dosimeter* for the impacts of climate change on cultural heritage [29], registering weathering processes for future research. Cubes of seven different stones, plus one brick and one concrete, were included in the study (Table 1).

[2] Damage functions are mathematical equations used to represent the relationship between damage and the contributing factors.

[3] Dose response functions explain the link between change in a dosimeter and exposure to specific hazard.

Table 1 Composition of LegIT pilot trial at case study sites

Case study	Site specific stone	Reference cubes	Plate no	Installed
1. Brú na Bóinne, World Heritage (Co. Meath)	Gallstown Greywhacke	Historic brick Concrete Peakmoor sandstone Portland limestone	BnaB1-3	2012
2. Dublin Castle (Dublin city)	Wicklow granite	As above	DC1-3	2014
3. Clonmacnoise (Co. Offaly)	Sandstone	As above	CL1-3	2013
4. Rock of Cashel (Co. Tipperary)	Sandstone	As above	RC1-3	2013
5. Skellig Michael, World Heritage (Co. Kerry)	Old red sandstone	As above	SKM1-3	2011 SKM3 2012 SKM1-2

Once a period of 30 years has elapsed, observed changes in the cubes can be interpreted in relation to climate measurements for the same period. An example of how one such process evolved is the 30 year project at St Paul's Cathedral on surface erosion and surface change (including accretion) [30–32]. This study uses microerosion meters[4] to measure changes in the surface elevation of a limestone balustrade, concentrating on near-horizontal surfaces [30]. The results showed a general decrease in erosion rates attributable to an improvement in air quality in London. Measurements taken in 2010 demonstrated a slight rise however, attributable to microbiological growth. A pattern was also reported relating to variations in rainfall, although the association between volume and surface loss noted was not a simple linear one [31]. Similarly, it is unlikely that linear relationships between climate variables and weathering processes will be established with the LegIT. The hope and expectation is that long-term data will allow trends and correlations to be determined.

Caution will be required in the interpretation of the results as surface decay and soiling do not tend to a linear progression [18: 228], and a lack of visible degradation can be followed by sudden loss [9, 20]. Surface analysis methodologies for describing changes in the stone, such as surface roughness, overlook internal chemical changes that may in fact be driving decay. To fully understand these, sampling and analysis of the stone would need to be taken at depth. The restricted size (50 mm) of the cubes used on the LegIT means they cannot reflect internal processes present in masonry stone and are more comparable to sculptural stone i.e. artefacts or architectural details. The advantage of this is that the cubes are likely to be more responsive to fluctuating temperature and moisture cycles than large blocks. This sensitivity to climatic influences should make the LegIT a good early indicator of surface weathering patterns.

Materials characterisation

The relationship between geomorphological properties and weathering processes is highly complex [33]. Nonetheless, quantification of certain key characteristics is useful in understanding the susceptibility of different materials to weathering. The 'reference' cubes (Portland, Peakmoor, brick and concrete) were tested by the Building Research Establishment (BRE) for porosity, saturation coefficient, water absorption and density (results presented in Table 2).

Salt crystallisation cycles

Salt weathering is dependent on fluctuations in temperature and relative humidity (RH). The physical effect of salt crystallisation cycles will depend on the type of salt (crystallisation pressure), the pore size and distribution within the substrate, and the depth at which crystallisation occurs [34]. Very small pores do not absorb water, therefore water absorption characteristics, when combined with porosity and saturation coefficient, can be used to build a picture not only of the quantity of pores but also the pore size [35]. The resistance of stone to salt damage decreases as the proportion of fine pores increases [36]. When considering the characteristics of the tested samples, it would appear that concrete is the material most at risk from salt damage, as it has the highest saturation coefficient and a relatively low absorption. Concrete is an aggregate material however which makes this interpretation less reliable than it would be for natural stone. Of the materials tested (Table 2) brick is by far the most porous yet has a saturation coefficient similar to the other materials, suggesting that many of its pore spaces are large and not likely to be affected by salt crystallisation pressure.

Noah's Ark used the phase change of sodium chloride (NaCl) that takes place at 75.5 % RH as a means of assessing probable crystallisation cycles in the future

[4] This method uses a dial gauge to record changes in surface elevation relative to control points (metallic markers) located on the object. Accurate to 10 µm.

Table 2 Results of materials testing (BR141 1989) conducted by BRE on samples of the reference cube materials (Test Report Number 283806, 2013. Unpublished)

BRE material tests results (BR141 1989)	Porosity % by volume	Saturation coefficient	Water absorption % by mass	Apparent density Kgm^{-3}
Portland limestone *(Jordan's Basebed)*	18.35	0.73	6.07	2208
Peakmoor sandstone	12.79	0.66	3.66	2309
Brick	39.19	0.75	17.47	1675
Concrete (CEMEX 20116841 8.00 M3 c25/30 10 CEM IIB S2 WRA-07)	14.86	0.76	4.97	2263

[37]. Using A2 scenario data from the Hadley Regional Climate Model HADCM3 (50 km resolution) Noah's Ark projected an increase in the frequency of crystallisation events in Western Europe due to drier summers. They also predicted an increase in hydration cycles and damage due to transitions of sodium and magnesium sulphates, which exert a high hydration pressure (Table 3). Sodium sulphate is one of the salts that is commonly implicated in salt weathering of concrete [38]. The British Stone List gives results for resistance to salts using a sodium sulphate test (BS EN 12370) and Portland demonstrates an extremely low resistance to this form of weathering [39].

Physical and chemical recession

The recession of carbonate stones in rainwater is due to both dissolution (chemical erosion) and mechanical removal of grains (physical erosion) [12]. When pollution reduces the pH of rainwater, this increases the quantity of material lost by dissolution. Higher concentrations of CO_2 will also have this effect. Higher temperatures also slightly favours chemical weathering [18, 40].

Given projections for the shift towards shorter periods of heavy precipitation at the case study sites (see example in Table 4), it is expected that the recession rate caused by the physical action of rain will increase (Table 5). Aspect will be crucial to this as wind driven rain is likely to play a significant role. It is also likely that the effect will be evidenced initially on the softer and less dense materials such as Portland, brick and Peakmoor. Harder stones such as Greywhacke[5], concrete (compression strength 25–30 MPa) and Old Red Sandstone will be more resistant.

Microbiological activity

Once microbiological growth (e.g. fungi, algae, lichens) occurs on a stone surface, it tends to encourage the retention of moisture and therefore further growth, establishing a positive feedback loop [41] (Table 6). Sandstone is known to be particularly susceptible to biological colonization as *its mineral and pore characteristics are especially bioreceptive* [42: 167]. Biological activity can be physically and chemically destructive [14], yet there is also evidence of a bioprotective role of some surface growth [28]. Unlike previous short term exposure trials the LegIT will provide an opportunity to study the long-term effects of biological growth, addressing a gap identified by researchers [20: 479]. Test exposures of sandstone have found that aspect plays an important role in algal growth, with rates being highest on north facing surfaces due to moisture retention and solar radiation [10, 43].

Noah's Ark calculated the relationship between climate and annual growth of biomass on stone using the following exponential model [44]:

$$B = e(-0.964 + (0.003P) - (0.01T))$$

B = biomass per area in mg/cm^2, P = yearly mean of precipitation in mm, T = yearly mean of temperature in °C.

This equation derives from research in Spain where high temperatures correspond with high evaporation rates and therefore restricted biological growth (Brimblecombe, pers. comm.). Thus the formula implies that lower temperatures result in greater growth, which is not necessarily the case for northern climates where temperatures in winter can be low enough to retard growth [45]. Research on algal greening in Belfast did note a negative correlation with the stone surface temperature, but also found that it only explained 14 % of the variance [28]. Moisture levels are likely to be integral to the distribution of algal films but again, the relationship between moisture and growth is not straightforward [28]. Growing-season temperature, numbers of warm days or annual time of wetness, are other possible indicators for microbiological growth in Ireland's climate.

Preliminary results from the LegIT at the case study site of Brú na Bóinne are that the material initially most affected by microbiological growth is Peakmoor

[5] EN1341 tests the abrasion resistance of stone for construction applications. Values <23.0 are considered suitable for use in heavily trafficked areas i.e. are resistant to abrasion. The abrasion resistance of Peakmoor has been measured at 26.8 and of Portland Base Bed at approximately 25, Gallstown Greywhacke has an abrasion resistance of 11.7.

Table 3 Summary of expected outcomes for surface recession/loss from the LegIT caused by salt crystallization pressure

Period
Near future (to 2020)
Salts present in fresh stone together with pore size and distribution will determine the initial occurrence of salt weathering. Most susceptible are likely to be Portland and brick
Medium term (to 2050)
Surface porosity of stones is likely to alter due to weathering; salt loading from the atmosphere will also change the availability of soluble salt. Salt action is likely to increase in this period
Far future (to 2101)
The REMO modeling by climate for culture (C4C) provided to the author for the case study sites [5] suggests a slight reduction in NaCl crystallization while projections by Noah's Ark and research into deep wetting at Queens suggest salt damage will increase. The outcome remains uncertain

Table 4 Precipitation change at two case study sites between reference period (1960–1991) and far future (2070–2101); REMO model projections provided by Max Plank Institute and C4C

Case study	Precipitation volume	Intense precipitation (No. of days ppt. >5 mm/hr)
Brú na Bóinne	1.6 % increase projected for far future	90 % increase projected for far future (from 84 to 159 days)
Skellig Michael	0.26 % increase projected for far future	38 % increase projected for far future (from 344 to 474 days)

Table 5 Summary of expected outcomes for surface recession from mechanical and chemical action of rainfall for period 2012–2101

Period
Near future (to 2020)
Fresh cut stone erodes quickly when first exposed, and then comes towards equilibrium
Medium term (to 2050)
Rate of loss likely to stabilise after initial exposure. Weathering tests by Albion Stone under current climatic conditions give a recession rate for Portland (Jordan's basebed) limestone of 3–4 mm every century (http://www.albionstone.com/portland-stone/beds/jordans-basebed/. Accessed 25 Sep 2012)
Far future (to 2101)
Projected increase in the intensity of precipitation likely to be reflected in an increased rate of recession due to the mechanical action of rain, especially where exposed to predominant winds. The projected increase in rain volume is negligible for most of Ireland thus the Karst effect (clean rain dissolution) is unlikely to increase

Table 6 Summary of expected outcomes for microbiological activity for period 2012–2101

Period
Near future (to 2020)
Colour change was found on a sample of cubes measured after 1 year exposure, indicating algal growth. Sandstone exhibited highest colonization as did north facing surfaces. In N. Ireland lichens on rural samples were noted by end of second year [43]
Medium term (to 2050)
Weathering will make less porous rocks vulnerable to colonization. North facing surfaces should continue to experience most rapid growth. With increased temperature and precipitation, the rate of microbiological growth is likely to increase during winter/autumn
Far future (to 2101)
Growth may continue with higher level species, and/or a change in the colour of microbiological growth may occur, indicating an altering profile of species. Future levels of atmospheric NO_x will contribute to this effect—comparison between case studies will help to account for this

sandstone. After 1 year of exposure these cubes exhibited both a large degree of darkening (reduced L* value) and a significant movement towards green on the spectrum (approx 50 % drop in a* value).

Practical design

The LegIT consists of five 50 mm^3 cubes attached to a stainless steel plate (Fig. 1), it is visually unobtrusive and easy to handle. There are five cubes on each plate, four

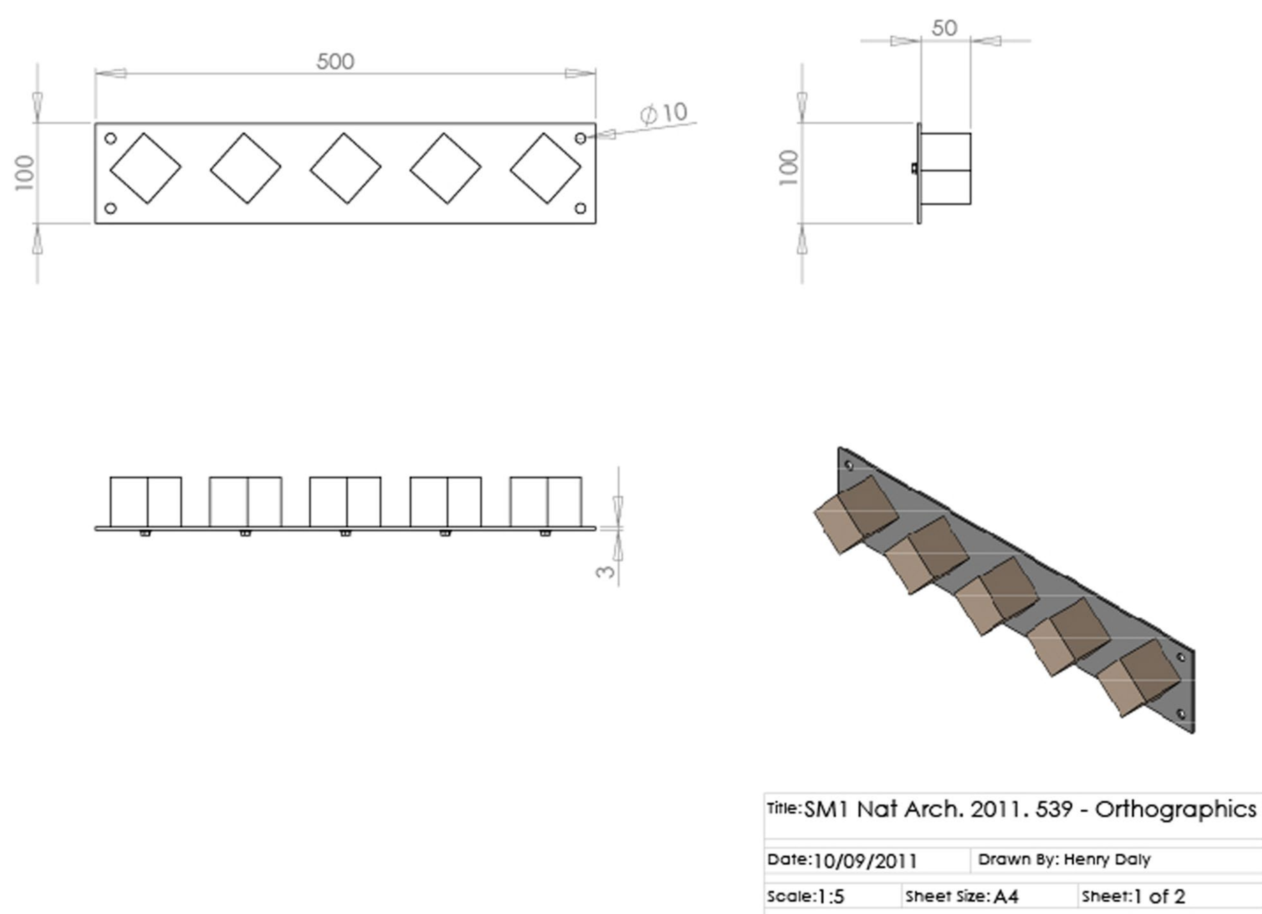

Fig. 1 Design of the LegIT (drawing by H. Daly 2011)

reference cubes common to all sites and one site-specific cube. An inert mounting system was required for the cubes which would not interfere in any way with weathering mechanisms and which would remain stable over 100 years. A high strength corrosion resistant stainless steel, grade 316, was chosen for both support and fixings. The cubes were attached to the base plate using a 316 nut and bolt (Fig. 2). The nut was held with adhesive in a hole drilled into the base of the stone and the block could then be bolted to the plate. Using this system the cubes are completely demountable and there is no internal pressure from the fixing.

Araldite 2014 epoxy resin was recommended to provide the bond between the stone and metal nut (Chouvet[6], pers. comm.), it has a lap shear strength of >20 Mpa on stainless steel joints and a high glass transition temperature (Tg) of 85 °C. Unlike most epoxies it also exhibits a good resistance to water, crucial in a temperate climate (Huntsman Advanced Materials, 2009). As commercial resins are only tested for industrial purposes, there is no data available on aging properties. While only guaranteed for 20–30 years the resins are likely to function well much beyond that however, especially when not placed under severe stress (Baines[7], pers. comm.).

To ensure longevity for the supporting data, and maintenance of its link with the object into the future, the associated documentation was lodged with the National Archives of Ireland. The National Archives accession number, together with a unique site and plate number, was then engraved onto each steel plate (Fig. 3).

Each of the five cubes is of a different material, four 'reference' materials are common to all plates; the fifth is unique to each site. The reference cubes will act as a control for the site-specific stone and also allow comparisons between different locations. The site specific cubes

[6] By Email; Laurent Chouvet, field promotion and technical support, adhesives, composites and tooling, Huntsman advanced materials, Basel, Switzerland (31.8.2011).

[7] By phone; Paul Baines, specialist sales engineer, Huntsman advanced materials, UK (29.8.2011).

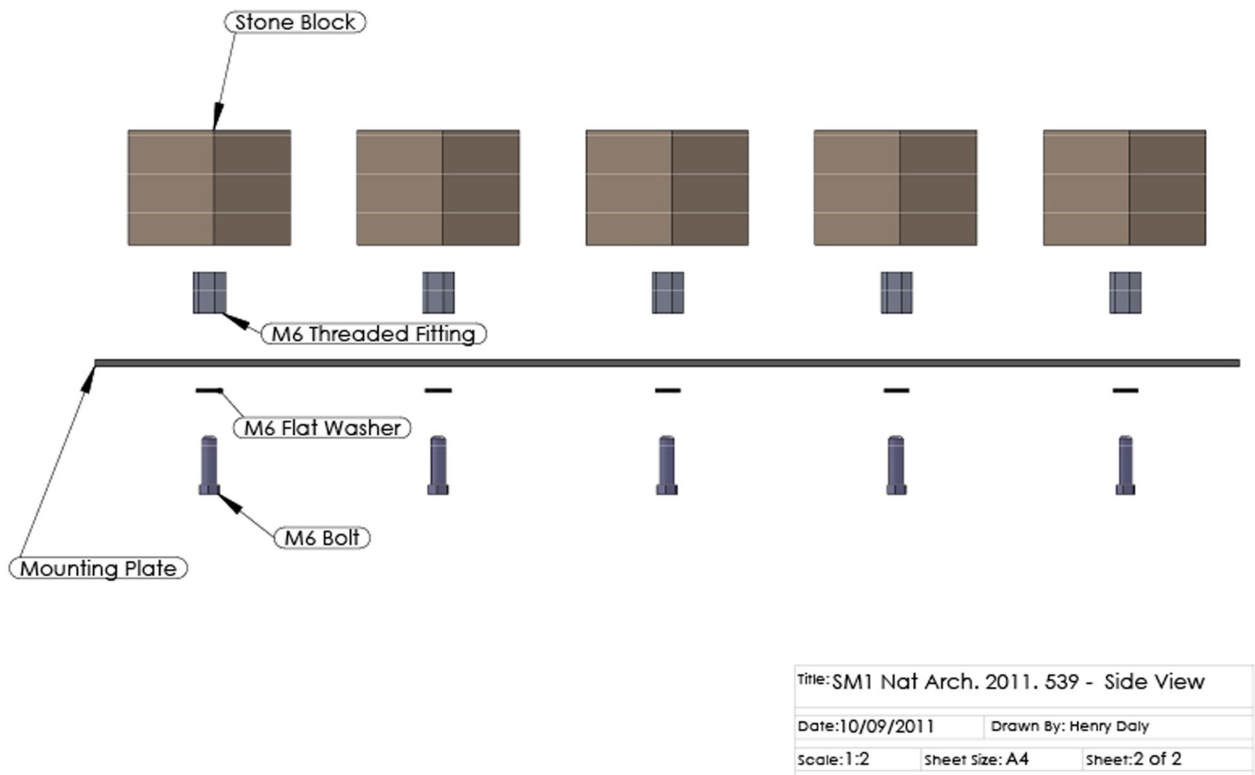

Fig. 2 Exploded *side view* of LegIT fixing system (drawing by H. Daly 2011)

Fig. 3 Engraved label on Brú na Bóinne stainless steel plate: abbreviated site name (BnB), plate number (3) and National Archives reference number (2011/62)

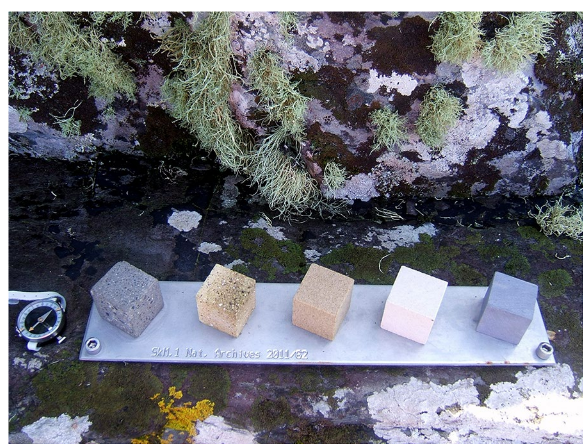

Fig. 4 Skellig Michael LegIT plate No. 1 in situ, from *left* to *right*: concrete, brick, Peakmoor, Portland, Old Red Sandstone (August 2012)

were made from stone the same or similar to that used by the original builders (Table 1). At each of the monuments three plates were fixed onto a horizontal surface, for consistency an East West alignment was used (Fig. 4).

The stone reference cubes chosen were Portland limestone and Peakmoor sandstone, both of which have previously been used in weathering research [9, 18, 19]. The manufactured reference cubes selected were a poured concrete and a machine-made historic brick from the Dolphin's Barn Brick and Tile Co. Dublin. These two man-made materials will offer an interesting contrast with the natural stone as they have different sensitivities to weathering [46]. Concrete also provides a standardisable sample and, unlike natural stone, the degradation of cement tends to a linear path [47].

Case studies

The LegIT was installed on five National Monuments across Ireland (Table 1). Selected in conjunction with the Office of Public Works they represent built heritage sites of high importance (including Ireland's two World Heritage properties) and range in date from the Megalithic to Post-Medieval. In addition they provide a diversity of environments including rural (Brú na Bóinne and Clonmacnoise), semi-urban (Rock of Cashel), urban (Dublin Castle) and coastal (Skellig Michael) (Fig. 5).

Fig. 5 Location of case study sites around Ireland. (http://www.scribblemaps.com); *1.* Brú na Bóinne, *2.* Dublin Castle, *3.* Clonmacnoise, *4.* Rock of Cashel, *5.* Skellig Michael

Periodic measurements

The cubes were measured prior to exposure of the LegIT on the case study sites and will be demounted every 3–5 years to monitor surface change. This period was selected on the basis that higher frequency measurements would be of limited value over the long-term (and hard to maintain), while gaps of greater than 5 years risked losing detail in the progression of weathering. If this regime is interrupted or abandoned however, assessment can begin again at a far-future date utilising the archived data for comparative purposes.

Comparison between measured change in the cubes and atmospheric climate for the same period will give an indication of climatic impacts, both on and between sites. Ideally, as in the case of Clonmacnoise, site based climate recording will be carried out. Where this is not possible data from local weather stations can be used. The Irish Meteorological Service (Met Eireann) collects and archives climate data from the national network of stations securing the data for researchers in years to come.

In a further attempt to future-proof the tool a combination of low and high tech measurement methods were employed (Table 7). These methods provide a series of complementary, non-destructive measurements of surface properties. With the exception of the 3D profiling all the techniques are also achievable on a low budget and require little operator expertise or high-tech equipment.

Results

The LegIT was installed on the case study sites between 2011 and 2013 and the first full set of measurements is due in 2016. Issues experienced during this initial exposure period have highlighted areas in design and implementation that could be improved. One concrete cube disintegrated in position, possibly the result of a weakness in the poured block due to its small size. Either the use of concrete or the aggregate dimensions may need to be revisited. More seriously, after 1 year of weathering several stone cubes exhibited cracks, thought to be stress fractures, radiating from the drilled hole. The cracks were consolidated by localised injection of a low viscosity epoxy resin but an alternative low-vibration drill or redesign of the fixing system is now a priority. Lastly, although clearly of no inherent value a cube was stolen from a LegIT at Brú na Bóinne in 2012. A replacement was put in its place, but resulted in a loss of continuity in the data sequence. Security of situation is therefore another priority for future development.

Discussion

In the interpretation of measured and observed changes in the cubes disentangling causality will be a challenge and there is a need to account for the contribution of factors other than those of direct interest [48]. The cross comparison of results between case studies is one way this can be approached. For example, comparisons between rural and urban locations should help in interpreting the contribution of pollution, including NO_x levels, to changes in microbiological growth. Extrapolating from a dosimeter to a heritage object is a challenge faced by all studies where, for ethical reasons, the original fabric is not used. Each material reacts differently and within stone types, even within single blocks, structural and mineralogical variations can be significant [49, 50]. Averaging of results and the collection of long-term data sets will smooth out some of the variables but it remains a challenge for the study. Despite these shortcomings it is anticipated that over time useful results will be gained. It is also intended that feedback from experts and end-users should go towards improving the design of the tool.

Conclusions

The short-term exposure of fresh stone is a common method for determining initial rates of weathering, when processes are at their most rapid;

Exposure trials provide an important link between knowledge of decay processes derived from laboratory-based experimentation and observed decay of stone buildings and monuments [9: 1205].

Alternatively, long-term studies of weathering rates tend to be based on dateable historic samples such as gravestones. The newly created LegIT attempts to combine these two traditions by creating a fresh baseline for long-term measurements.

To ensure sustainability, careful thought was given to the choice of materials, design of the tool and the manner of data retrieval and archiving. Surface recession, salt crystallisation and microbiological growth are the deterioration mechanisms the tool aims to track. Although based on the existing scientific tradition of using exposed samples, the LegIT is original in that it has been designed for the measurement of long-term exposure. It is also original in its use of multiple materials (including man-made) and in being embedded in at heritage sites. The main threat to the sustainability of the LegIT, as experienced during the first year of exposure, is human interference. A second design issue, relating to stress fractures caused by the drilling of certain stone types, can be addressed in future by altering the manufacturing method.

By the end of 2016 one full set of exposure measurements will be completed and it will be possible to make some early assessments on the success of this pilot study. The hope is that the LegIT will indeed be a legacy; a

Table 7 Measurements carried out on cubes before and during exposure trial

Method and requirements	Procedure	Comment
Photography		
	Digital colour photographs, of each exposed face	Low tech, low cost; comparison will be visual
Average surface roughness (Ra)		
Diavite DH-6 or similar. Industry standard settings used = Lt 4.80 mm trace (sample length) and Lc 0.8 cut off filter (does not measure wavelengths >0.8 mm)	The profile of the surface is measured using a stylus, magnified through software and quantified as roughness average (Ra) in μm, accurate to 0.01 mm Average from 10 profiles on each exposed face	Highlights any changes in surface characteristics, e.g. smoothing or roughening Standard deviation in the Ra measurements can be used to indicate homogeneity of the surface
Colour meter		
Ultra Scan Pro USP1577 Hunter Lab. Mode #3 RSEX or similar	Values for brightness (L*) redness (a+) and yellowness (b+) are taken. Average values are calculated from the five points by the Ultrascan	Colorimetry has successfully been used as a measure of biomass on stone [10, 43]. Visual examination must accompany this assessment
Callipers		
Vernier callipers	Digital Vernier callipers. Measurements taken in three dimensions (width, depth and height). Three measurements taken in each case	Measurements accurate to ± 0.1 mm; quantifiable but of low accuracy
Weight		
Digital laboratory scales (measure to 0.00 g)	Demounted stones (including internally fixed nut) weighed in grams. Stones must be dry before weighing	The requirement for bringing the stones to a standard RH (approx 50–60 %) can delay this method of assessment for several weeks after demounting
3D profile scanning		
Renishaw Cyclone Series 2 SP600M machine or similar. Used Tracecut programme	Profiling done in Z plane in increments of 5–10 mm (i.e. profiles taken at 45, 40, 35, 30, 20 and 10 mm from base). Profiles stored as DXF lines and arcs in CAD	The CAD software will compare profiles over time, quantify change and can produce visual overlays that show the progression of loss

CIE LAB system where L* can have a positive or negative value resource for conservators and heritage managers of the future wishing to understand in real terms how climate change is affecting the sites and monuments in their care.

Author's information

Cathy Daly is a Lecturer in Conservation in the School of History and Heritage at the University of Lincoln and has a research interest in conservation management. In 2010 Cathy was lead author on *Monitoring Impacts of Climate Change on Built Heritage*, a report commissioned from ICOMOS Ireland by the Department of Environment Heritage and Local Government. In 2013 she completed her Ph.D. with the Dublin Institute of Technology. In this research transferable methodologies for the site level assessment and measurement of climate change vulnerabilities were developed and applied in practice at Ireland's two World Heritage sites.

Acknowledgements

I owe my thanks to the many people that helped in the design, manufacture, installation and evaluation of the LegIT. Special thanks are due to: Conor Dore, Ger Reilly, Ray Ekins, Mark Barry and Derek McEvoy of DIT; Neil Kearney, Geology Department Trinity College; Peter Cox of Carrig Conservation; David Weldon; Prof Bernie Smith; Henry Daly; Susan Roundtree; Paul Allen, Teagasc Ashtown and Albion Stone. Also to the OPW staff for the sites of Brú na Bóinne, Clonmacnoise, Dublin Castle, Rock of Cashel and Skellig Michael. I would also like to acknowledge the financial support of the Department of Arts Heritage and the Gaeltacht (formerly Environment) under the Environment Fund 2011. Finally I would like to thank Dr. Lynda Skipper and the journal reviewers for comments and suggestions which greatly improved this paper.

Competing interests

The author declares that they have no competing interests.

Received: 1 February 2016 Accepted: 12 May 2016
Published online: 09 June 2016

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