



# **The Effects of Open Shelters on the Preservation of Limestone Remains at Archaeological Sites**

**Cristina Cabello Briones**

Harris Manchester College

Thesis submitted for the degree of

Doctor of Philosophy

at the University of Oxford

Trinity term

2015

## **ABSTRACT**

Shelters, as preventive conservation methods, have traditionally been considered a better option than leaving the site exposed. However, there has been limited research on their effect on the preservation of heritage materials and, as a result, there is no clear scientific evidence to support sheltering. This study aims to provide the first rigorous scientific assessment of the effect of lightweight, open shelters on limestone deterioration at archaeological sites. A method based on the use of low-cost environmental monitoring equipment and limestone blocks and tablets (as indicators of decay) has been developed to determine the degree of protection provided by the shelters at the Bishop' Palace (Witney, England) and Hagar Qim (Malta). Preliminary visual assessments of the field sites were followed by 12-18 month exposure trials. Temperature extremes and fluctuations, frost events, relative humidity extremes and fluctuations, NaCl crystallisation events, solar radiation, wetting events, salt content, atmospheric pollutants and dust deposition were monitored. In addition, stone decay was studied by analysing changes in weight, elasticity, surface hardness, ultrasonic pulse velocity, surface colour, moisture content and general appearance (microscopic and macroscopic pictures) in stone samples. An exhaustive assessment of the shelter at the Bishop's Palace was carried out using Chalk, Cotswold and Portland limestone blocks as well as Portland limestone tablets (specifically for studying dissolution, soiling and biological growth). Additionally, a comparative assessment of the effects of the two shelters in contrasting climatic environments, the Bishop's Palace (temperate maritime) and Hagar Qim (Mediterranean), was undertaken by monitoring Globigerina and Coralline limestone blocks simultaneously at both sites. The research has shown

that lightweight, open shelters do not exclude decay completely but minimise it. However, there are some areas at higher risk of decay, i.e. top parts of the walls and the periphery. In addition, problems with the shelter design can enhance some decay mechanisms, such as biocolonisation on the periphery at the Bishop's Palace and dust deposition under the shelter at Hagar Qim. Therefore, the effectiveness of shelters should not be assumed.

## **ACKNOWLEDGEMENTS**

First and foremost, I would like to thank my supervisor, Professor Heather Viles, to whom I am extremely grateful for her invaluable advice and constant support. Special thanks are also due to Dr Daniel Lunn for sharing his knowledge on statistical analysis, and Dr Julie Eklund for her guidance during my first year of research. I would like to thank Dr Katya Stroud, Christiane Jeuckens and Chris Welch for giving me permission to study Hagar Qim and the Bishop's Palace archaeological sites, and Mario Galea and Dr John Stewart for their words of wisdom. I would also like to extend acknowledgement to their institutions: Heritage Malta, Oxfordshire County Council and English Heritage. I wish to express my sincere thanks to Professor Daniel Bosence and Dr May Cassar for sharing their expertise. I must also thank Dr Mona Edwards and Hong Zhang for their advice and support with laboratory analysis.

I acknowledge the financial support of the Engineering and Physical Science Research Council (EPSRC), Fundacion Obra Social La Caixa and Harris Manchester College.

I must take this opportunity to thank Dr Javier Muñoz de Luna, Dr Andres Payo, David Sharpe and my colleagues at the Oxford Rock Breakdown Laboratory, especially Dr Martin Coombes. I am extremely thankful for their guidance and encouragement. Lastly, I would like to thank all my friends for being sympathetic during the worst moments, and my father, mother and sister for their love.

# TABLE OF CONTENTS

ABSTRACT .....	i
ACKNOWLEDGEMENTS.....	iii
1. RESEARCH CONTEXT	
1.1. Introduction.....	1
1.1.1. Preventive Conservation .....	1
1.1.2. The ethics of conservation .....	2
1.1.3. Types of shelters.....	3
1.1.4. History of protective structures .....	4
1.2. Stone deterioration in built cultural heritage.....	6
1.2.1. What is stone deterioration? .....	6
1.2.2. Causes of stone deterioration .....	7
1.2.3. Monitoring stone deterioration.....	13
1.3. Past and present research on shelters .....	18
1.3.1. Effects of shelters on archaeological sites .....	20
1.3.2. Shelter performance assessment .....	26
1.3.3. Recommendations in the literature for future research .....	31
1.4. Aim and objectives .....	33
1.5. Chapter summaries .....	34

2.	RESEARCH DESIGN	
2.1.	Overall approach of the research .....	41
2.2.	Sampling strategy and data collection rationale.....	45
2.2.1.	Summary of monitoring locations .....	45
2.2.2.	Monitoring of microclimatic conditions .....	48
2.2.3.	Monitoring deterioration with stone blocks .....	52
2.2.4.	Monitoring dissolution, soiling and microbial growth using stone tablets ..	56
2.3.	Summary of the research design .....	58
3.	MATERIALS AND METHODS	
3.1.	Conservation state of field sites.....	60
3.2.	Monitoring microclimatic conditions .....	62
3.2.1.	Data collection .....	63
3.2.2.	Data handling and aggregation.....	66
3.2.3.	Statistical analysis.....	69
3.3.	Monitoring deterioration with stone blocks .....	70
3.3.1.	Selection of stone types .....	71
3.3.2.	Data collection .....	75
3.3.3.	Data handling and aggregation.....	80
3.3.4.	Statistical analysis.....	81
3.3.5.	Validation of the dataset .....	82

3.4.	Monitoring dissolution, soiling and microbial growth with stone tablets .....	85
3.4.1.	Data collection, handling and aggregation.....	86
3.4.2.	Statistical analysis.....	88
3.4.3.	Validation of the dataset .....	88
4.	CONSERVATION STATE OF THE FIELD SITES	
4.1.	Introduction to the Bishop’s Palace, Witney .....	91
4.2.	Introduction to Hagar Qim, Malta .....	94
4.3.	Condition state of the remains .....	97
4.3.1.	Definitions .....	97
4.3.2.	Condition survey of the Bishop’s Palace, Witney .....	99
4.3.3.	Condition survey of Hagar Qim, Malta .....	103
4.4.	Condition state of the shelters.....	105
4.4.1.	The shelter at the Bishop’s Palace, Witney .....	105
4.4.2.	The shelter at Hagar Qim, Malta .....	108
4.5.	Discussion .....	110
5.	EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP’S PALACE (WITNEY) ON THE MICROCLIMATIC CONDITIONS	
5.1.	Introduction and aims .....	115
5.2.	Materials and methods .....	116
5.3.	Results.....	120

5.3.1.	Temperature .....	120
5.3.2.	Solar radiation .....	131
5.3.3.	Freeze-thaw events.....	133
5.3.4.	Relative Humidity .....	135
5.3.5.	Surface wetting events .....	143
5.4.	Discussion and conclusions.....	148
6.	EVALUATING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON LIMESTONE DECAY WITH CHALK, COTSWOLD LIMESTONE AND PORTLAND STONE BLOCKS	
6.1.	Introduction and aims .....	154
6.2.	Materials and methods .....	155
6.3.	Results.....	159
6.3.1.	Dry weight change.....	159
6.3.2.	Elasticity changes .....	163
6.3.3.	Surface hardness changes .....	165
6.3.4.	Changes in ultrasonic pulse velocity (UPV) .....	168
6.3.5.	Surface colour changes.....	170
6.3.6.	Macroscopic and microscopic surface changes.....	176
6.3.7.	Moisture content changes .....	181
6.3.8.	Surface temperature.....	185

6.4.	Discussion and Conclusions .....	190
7.	EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON DISSOLUTION, SOILING AND MICROBIAL GROWTH ON PORTLAND LIMESTONE TABLETS	
7.1.	Introduction and aims .....	196
7.2.	Materials and methods .....	199
7.3.	Results .....	202
7.3.1.	Colour change .....	202
7.3.2.	Microscopy .....	205
7.3.3.	Salt content .....	206
7.3.4.	Weight change .....	209
7.3.5.	Rates of decay .....	211
7.4.	Discussion and Conclusions .....	214
8.	COMPARATIVE STUDY ON THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP'S PALACE (WITNEY) ON MICROCLIMATIC CONDITIONS	
8.1.	Introduction and aims .....	218
8.2.	Materials and methods .....	219
8.3.	Results .....	222
8.3.1.	Temperature .....	222
8.3.2.	Freeze-thaw events .....	233

8.3.3.	Relative Humidity .....	235
8.3.4.	Dust deposition.....	241
8.4.	Discussion and conclusions.....	244
9.	EVALUATING THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP’S PALACE (WITNEY) ON LIMESTONE DECAY WITH GLOBIGERINA AND CORALLINE LIMESTONE BLOCKS	
9.1.	Introduction and aims .....	250
9.2.	Materials and methods .....	251
9.3.	Results .....	256
9.3.1.	Dry weight change.....	256
9.3.2.	Elasticity changes .....	259
9.3.3.	Surface hardness changes .....	262
9.3.4.	Changes in ultrasonic pulse velocity (UPV) .....	265
9.3.5.	Surface colour changes.....	267
9.3.6.	Macroscopic and microscopic surface changes.....	274
9.3.7.	Moisture content and wetting events on stone blocks .....	279
9.3.8.	Surface temperature.....	286
9.4.	Discussion and Conclusions .....	290

10.	DISCUSSION AND CONCLUSIONS	
10.1.	Addressing objective number 1 .....	297
10.2.	Addressing objective number 2 .....	301
10.3.	Addressing objective number 3 .....	305
10.4.	Suggestions for future research.....	309
10.5.	Conclusions.....	310
APPENDIX A: CONDITION SURVEYS		
	Results of the condition survey at the Bishop’s Palace.....	312
	Results of the condition survey at Hagar Qim.....	313
	BIBLIOGRAPHY .....	316

# **1. RESEARCH CONTEXT**

## **1.1. Introduction**

Archaeological excavations often involve exposing remains from a buried environment. After exposure, different environmental factors such as temperature, moisture, pollution and/or biological communities may interact with the archaeological remains, damaging or altering them. Archaeological sites are often left exposed without protection after excavation (Woolfitt, 2007). However, in most cases an excavated site requires continuous maintenance to keep it stable (Ranellucci, 1996). According to article 6 of the Lausanne Charter, “archaeological heritage should not be [...] left exposed after excavation if provision for its proper maintenance and management [...] cannot be guaranteed” (International Committee for the Management of Archaeological Heritage, 1990). Additionally, phenomena associated with predicted climate change may make excavated archaeological heritage more vulnerable in the future in some areas. For instance, changes in annual precipitation as well as in wind-driven rain will affect stone decay in Britain by inducing changes in salt crystallisation frequency (Sabbioni et al., 2010). Therefore, research on preventive conservation strategies is essential to ensure the preservation of archaeological remains nowadays and in the future.

### **1.1.1. Preventive Conservation**

The main aim of “preventive conservation” is to maintain cultural heritage in a stable condition without direct physical intervention with the material. The Canadian Association for Conservation of Cultural Property (2000) defines it as “all actions taken

to mitigate deterioration and damage to cultural property. This is achieved through the formulation and implementation of policies and procedures in areas such as lighting, environmental conditions, air quality, integrated pest management; handling, packing and transport, exhibition, storage, maintenance; [...] and emergency preparedness” (p. 17). As opposed to interventive conservation, preventive conservation measures do not interfere with the original materials. Although traditionally used in museums, archaeological sites can also benefit from preventive conservation strategies such as the control of environmental conditions and the implementation of maintenance procedures. Shelters and reburial are commonly considered two of the most effective methods of preventive conservation for excavated archaeological sites (Roby, 2006). They attempt to provide optimum conditions for the preservation of archaeological remains. They are also considered to be less intrusive than interventive methods such as consolidation or reconstruction.

### **1.1.2. The ethics of conservation**

According to article 9 of the Code of Ethics for Conservators (European Confederation of Conservator-Restorers’ Organisations, 2003), conservation professionals should “strive to use only products, materials and procedures which, according to the current knowledge, will not harm the cultural heritage, the environment or people. The action itself and the materials used should not interfere, if at all possible, with any future examination, treatment or analysis”. In practical terms, this means that any conservation intervention should not damage archaeological materials or impede their re-treatability. Therefore, shelters should avoid destroying any archaeological evidence during and after construction and only non-destructive techniques or visual surveys

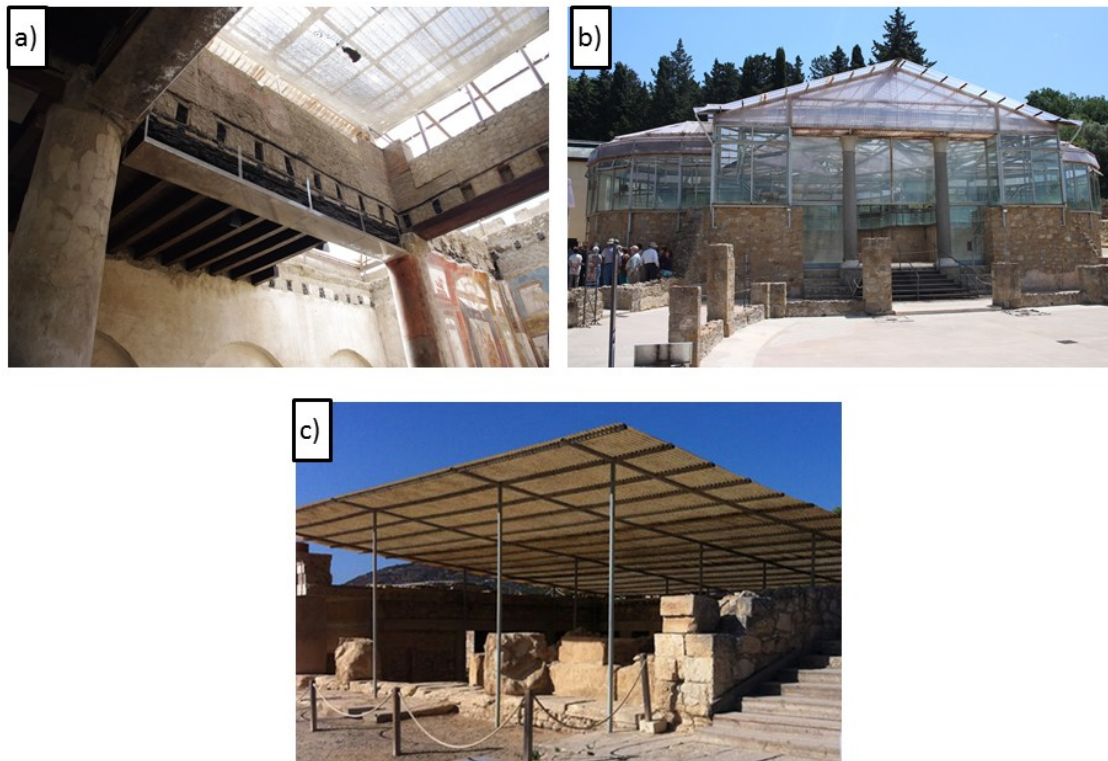
should be used for examination. Authenticity is another important consideration related to the values expressed in cultural heritage. Any addition to the site should be identifiable as new in order to preserve the site's authentic characteristics (International Committee for the Management of Archaeological Heritage, 1990). Thus, shelters should be recognisable as new additions, but on the other hand, they should not be visually too intrusive, which could cause a loss of context. However, conserving authenticity must be balanced with the necessity of physical protection for the archaeological materials when a shelter is designed (Cassar et al., 2001).

### **1.1.3. Types of shelters**

Shelters are structures that cover archaeological sites. They act as a preventive conservation method in order to protect the sites from anthropogenic or environmental damaging factors. Shelters can be classified according to different criteria, for example, materials (Laurenti, 2003) or shape (Ferroni and Laurenti, 2006). However, the distinction between roofs (Figure 1.1, a), enclosures (Figure 1.1, b) and open shelters (Figure 1.1, c) is the most commonly used. New roofs are used for those archaeological sites which still have standing walls; enclosures are effectively buildings over a site, and open shelters provide partial cover to the site without lateral cladding (Woolfitt, 2007).

Shelters can also be classified as temporary or permanent structures (Franceschetti et al., 2000, Laurenti, 2003). In contrast to permanent shelters, which typically are designed to fulfil an on-going preservation role at decadal timescales, temporary or seasonal shelters are usually built over archaeological sites that are under excavation or between excavation campaigns. In general, they are made of cheap and locally

available materials and they are also quite easy to assemble. Many temporary shelters are left for much longer than originally expected. However, temporary shelters tend to deteriorate more quickly and this could affect the archaeological remains (Teutonico, 2001, Laurenti, 2003).



**Figure 1.1:** a) New roof for a Roman house in Herculaneum, Italy; b) enclosed shelter at Villa del Casale, Italy; c) open shelter at Knossos, Crete. Images: C. Cabello-Briones

#### **1.1.4. History of protective structures**

The use of shelters to preserve archaeological remains started in the 18<sup>th</sup> century when systematic excavation campaigns were undertaken. At that time, it was a common practice to remove wall paintings from their original support and transfer them to museums. Only those decorative pavements considered less artistically important were left *in situ*. At the end of that century, these elements began to be appreciated because of their didactic value and shelters became more popular. In this

context, J.L. Desprez illustrated the wooden shelter built over the temple of Isis in Pompeii in 1777 (Soprintendenza Archeologica per le Province di Napoli e Caserta, 1992). The temporary shelter protected the decorative features *in situ* from the weather according to Pompeii excavation diaries (D'Alconzo, 2002). However, the structure deteriorated perhaps due to lack of maintenance and was dismantled in 1794. Northern European sites were usually covered with enclosed structures to protect the remains from the more adverse climatic conditions (Ferroni and Laurenti, 2006). Famous examples are the shelters at Bignor Roman Villa, West Sussex, dating from 1812, and at Hüfingen Roman Baths, Germany, built in 1821.

However, shelters were not considered as specific preventive conservation strategies until the second part of the 20<sup>th</sup> century. This new approach resulted from developments in excavation techniques (ICCROM and Centro di Conservazione Archeologica, 1986) and the increasing importance of *in situ* preservation of archaeological materials (Ferroni and Laurenti, 2006). New materials and techniques used in modern architecture, such as reinforced cement or glass, began to be employed for the new shelters. Franco Minissi built the shelter at Villa del Casale in Piazza Armerina, Italy, in 1957. He introduced the idea of shelters as transparent showcases to provide both protection and visibility of the remains (see Figure 1.1, b). However, research has found that glass and transparent synthetic materials can produce adverse environments for the conservation of the remains (Stanley-Price and Jokilehto, 2001).

Open shelters made of lightweight membranes have increasingly been proposed as medium-term preventive conservation methods due to their minimal impact on the

archaeological substrates (Salvatore, 2004, Zanelli, 2015). They are usually more easily reversible and less physically invasive than other types of shelters such as enclosures, thus making them a suitable preventive solution according to the principles of conservation. In addition, these structures are relatively low cost and might be prefabricated and dry assembled, which allows a wider applicability, for instance when the site is still under excavation (Agnew et al., 1996, Hebbelinck et al., 2001, Rosina et al., 2011).

## **1.2. Stone deterioration in built cultural heritage**

### **1.2.1. What is stone deterioration?**

Deterioration has been commonly used to describe the interconnected mechanisms of stone breakdown (Viles et al., 1997). Deterioration, degradation, alteration and decay are often used as interchangeable words (Steiger et al., 2011). However, there are some slight differences in meaning. According to the ICOMOS-ISCS Illustrated Glossary on Stone Deterioration Patterns (2008), there are several terms for describing change:

- Alteration: modification of the material that does not necessarily imply worsening of its characteristics from the point of view of conservation.
- Damage: human perception of the loss of value due to decay.
- Decay: any chemical or physical modification of the intrinsic stone properties leading to a loss of value or to the impairment of use.
- Degradation: decline in condition, quality, or functional capacity.
- Deterioration: process of making or becoming worse or lower in quality, value or character.

- Weathering: any chemical or mechanical process by which stones exposed to the weather undergo changes in character and deteriorate.

In this study, damage, deterioration, degradation and decay will be used as generic terms to describe modification of the material by external or internal factors leading to a worsening of the preservation state; weathering as environmentally induced processes of degradation; and alteration as change in material properties without any influence on the conservation state. In this context, patinas are considered alterations (see section 4.3.1 in Chapter 4).

### **1.2.2. Causes of stone deterioration**

Stone deterioration involves a complex set of processes resulting from interconnected physical, chemical and/or biological causes (Schaffer, 1932, Watt and Swallow, 1996, Camuffo, 2013). During deterioration, stone properties such as porosity, colour or mechanical characteristics may be altered (Rovaníková, 2007). The result will not only depend on external variables but also the internal factors such as the mineralogical and chemical composition of the stone, its physical fabric and the presence of inhomogeneities (Přikryl, 2013). In addition, stone weaknesses caused by past stress episodes or previous conditions which affected the stone composition and structure can influence deterioration through the “memory effect” (Smith et al., 2008).

Physical deterioration results from application of stresses higher than the stone’s mechanical resistance (Steiger et al., 2011). Solar heating and night cooling events result in compressive and tensile stresses, which eventually provoke de-cohesion of minerals in susceptible materials (Yavuz et al., 2010). Weathering due to changes in temperature is caused by the different thermal expansion coefficients of the stone-

forming components (Weiss et al., 2004) and the differential expansion and tensile strength between surface and subsurface layers (Halsey et al., 1998). Shorter fluctuations, provoked by wind and cloud cover, affect especially the surface (Camuffo, 2013). Stress due to freezing-thawing cycles results from a slightly different process. When water freezes in stone pores it exerts a pressure, which can induce microcrack development and an increase in void space (Honeyborne, 1998). A high degree of saturation and repeated freezing will increase the amount of damage (Ingham, 2005).

Temperature variations cause changes in the degree of saturation of water vapour in the air and moisture content in the material. The changes in relative humidity and stone moisture content lead to deterioration mechanisms such as wetting-drying cycles, which enhance hygric expansion of materials (such as clays) and differential stresses between layers, and facilitate salt migration, precipitation and growth (Robinson and Moses, 2011). Slow evaporation of water from the stone leads to salt migration to the surface. Surface efflorescences have mainly an aesthetic effect but salt crystallisation and hydration pressures exerted from subflorescences inside the stone might also result in the breaking of the material (Watt and Swallow, 1996, Halsey et al., 1998). High temperatures, high wind speeds and low relative humidity encourage the process (Torraca, 2009).

Chemical deterioration of stone involves chemical reactions and leads to a change in mineral structure. Chemical weathering related to pollutants can be caused by acid rain or dry deposition of gaseous and particulate pollutants, which become chemically reactive when the surface is wet due to rain or dew (Feilden, 2003). The rate of dissolution depends of the amount and contact time of liquid water, the solubility of

the stone minerals and the pH of the aqueous solution (Steiger et al., 2011). Limestone is particularly susceptible to dissolution. Even unpolluted rain has a slightly acidic pH, due to the presence of carbon dioxide. This natural dissolution process, known as the karst effect, can be enhanced by reactions with other atmospheric pollutants such as sulphur and nitrogen oxides, derived from the combustion of fossil fuels (Livingstone, 1992). One of the most damaging processes is sulphation. It involves dry aerosols from hydrogen sulphide and sulphur dioxide gases or sulphurous rain, which can react with calcium carbonate to form calcium sulphite, and eventually calcium sulphate (Odgers et al., 2012). Although intensive showers can remove pollutants from the surface (Camuffo, 1997), the reaction products remain on sheltered stones and often result in ongoing damage (Doehne and Price, 2010). Calcium sulphate (gypsum) has a higher molecular volume than calcium carbonate, which induces mechanical stresses (Brimblecombe, 2011). Salts with low mobility, such as gypsum, tend to accumulate at the evaporation zones blocking the stone pores, reducing the drying rate and increasing other deterioration processes such as salt migration or biological growth (Charola et al., 2007). Additionally, crusts of sulphates (gypsum) and other reaction compounds are more soluble than carbonates so they can be removed via dissolution leading to a loss of cohesion (Steiger et al., 2011).

The effects of chemical weathering on buildings and monuments in Europe and USA were particularly studied between the 1970s and 1990s due to an increased concern about pollution in urban areas. In this context, there were numerous projects focused on determining the rate of surface recession caused by sulphation. The use of damage functions based on pollution levels, rainfall acidity, and amount of rainfall has been the

most common approach (Lipfert, 1989, Webb et al., 1992, Butlin et al., 1992, Livingstone, 1992).

Biodeterioration associated with microorganisms, such as algae, fungi and lichens, can involve chemical and/or physical processes (Pinna and Salvadori, 2008). Biofilms are complex mixes of cells embedded in extracellular polymeric substances on the stone surface, which can trap airborne particulates (Camuffo, 2013). In addition, enzymes or metabolic products excreted by microorganisms can interact with the stone minerals leading to dissolution and/or crust formation (Robinson and Moses, 2011). On the other hand, biofilms may expand and contract as a result of wetting-drying cycles causing physical breakdown (Inkpen and May, 2006), especially endolithic microorganisms which grow in cracks and pores. Biofilms can modify surface properties such as porosity or thermal conductivity, which could lead to physical weathering or protection of the stone (Viles, 2012, Pinna, 2014). For example, epilithic lichens can have a protective role by decreasing moisture and temperature fluctuations on the stone surface (Carter and Viles, 2003).

The most decisive factor for microbial growth is the presence of water, although fungi and lichens are generally able to tolerate certain amount of dryness (Steiger et al., 2011). Additionally, biological colonisation may be induced by nitrogen-containing pollutants already deposited on the surface, which act as sources of nutrition (Koestler et al., 1997). In addition to external factors such as microenvironmental conditions, the biocolonisation potential or bioreceptivity is determined by the nature of the underlying substrate. For example, porous stones with rough surfaces are particularly susceptible to microbial colonisation (Miller A.Z. et al., 2012).

Stone remains at archaeological sites are likely to be affected by a combination of the physical, chemical and/or biological mechanisms of decay described above resulting in deterioration patterns such as delaminations, cracks or salt crusts among others. Table 1.1 summarises the main stone decay mechanisms affecting archaeological sites in relation to the controlling factors and the resulting decay phenomena.

The main external causes of stone decay are temperature, water availability and air quality. These factors are particularly relevant for the decay mechanisms observed at archaeological sites (see Table 1.1). In addition, these decay mechanisms usually lead to specific decay phenomena as described in the glossary published by the ICOMOS International Scientific Committee for Stone (2008). Some of the decay patterns mentioned in Table 1.1 have been reported in studies about unsheltered archaeological sites and sites before they were sheltered. However, active deterioration has also been documented in some sheltered sites. This indicates that shelters are not totally effective in their protective role or that they can even have a more direct influence in the preservation state of the sites by inducing decay. Table 1.1 also shows some possible connections of the main decay mechanisms with faults in the shelter design, based on observations of M. Demas (Stewart, 2008). These remarks were made after undertaken visual rapid assessments of 70 shelters over mosaics in England and Israel (Getty Conservation Institute, 2009).

**Table 1.1:** Main stone decay mechanisms at archaeological sites and their possible connections with shelter design

	<b>Thermal expansion/ contraction</b>	<b>Frost weathering</b>	<b>Salt weathering</b>	<b>Weathering related to pollutants</b>	<b>Bio-deterioration</b>
<b>Description</b>	Stone expands when heated and contracts upon cooling	Increase of water volume exerting pressure on pore walls	Salt crystallises within pores exerting pressure on pore walls	Dry and wet deposition of pollutants	Colonisation of microorganisms
<b>Type</b>	Physical (heating/ cooling events)	Physical (freeze-thaw cycles)	Physical (wetting-drying cycles)	Chemical (eg. hydrolysis and oxidation)	Physical (change in properties, stresses) and chemical (acidic, red-ox reactions)
<b>Controlling factors</b>	Temperature, material characteristics	Temperature, material properties, moisture content	Temperature, evaporation (insolation, wind), material properties, presence of salts, RH, moisture content	Presence of pollutants, material composition, rainfall (pH, amount, frequency), surface wetness	RH, moisture content, light, nutritive elements (dust, pollution, first colonisation)
<b>Decay phenomena</b>	Dimensional change, delamination, blistering, cracking	Disintegration, blistering, cracking, delamination	Disintegration, cracking, delamination, blistering, scaling	Soiling, crusts, salt formation, dissolution	Pitting, exfoliation, disintegration
<b>Possible connection with shelter design</b>	Lack of insulation, limited shelter coverage, concentrated direct thermal gain	Poor insulation, inadequate lateral protection, inadequate drainage, water infiltration, limited shelter coverage	Lack of insulation, inadequate lateral protection/ drainage, passive ventilation, water infiltration, limited shelter coverage, unstable climatic conditions	Inadequate lateral protection, water infiltration, lack of insulation/ condensation	Insufficient ventilation, too little/much light, inadequate lateral protection or drainage, water infiltration, limited shelter coverage
<b>Examples- unsheltered sites</b>	Ein Gedi Synagogue, Israel (Neguer and Alef, 2008)	Sculptures, Schlossbrück Berlin, Germany (Siegesmund et al., 2012)	Mnadra and Hagar Qim, Malta (Cassar et al., 2011)	Citadella, Budapest (Török, 2002b)	Archaeological site in Uxmal, Mexico (Ortega-Morales et al., 2000)
<b>Examples- sheltered sites</b>	Fishbourne Roman Villa (Stewart et al., 2006)	Chedworth Roman Villa, UK (Stewart et al., 2004)	Bethlehem, Czech Republic (Kotlík and Heidingsfeld, 2002)	Experimental shelter in Caesarea (Neguer and Alef, 2008)	Copán, Honduras (Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006)

One of the stone types commonly used in European archaeological sites is bioclastic limestone, including oolitic, coccolitic and foraminiferal. Limestones of this category are composed of shell fragments and/or skeletal remains between a matrix of carbonate cement, often in the form of calcite. Bioclastic limestones are especially susceptible to chemical attack and physical weathering. As explained before, natural dissolution by rainfall is a gradual process but it can be enhanced in polluted environments. Acid rain and dry deposition of pollutants can also lead to formation of surface crusts, such as gypsum, with a subsequent change in the stone's physical properties (Török, 2002b). In addition, salt-induced decay and severe and/or prolonged freezing can lead to granular disaggregation (Smith et al., 2003, Smith et al., 2010a). Bioclastic limestones, as the majority of building stones, tend to be less crystalline and dense than many geologically older limestones (Leary, 1983, Smith et al., 2010a). However, specific physical characteristics such as porosity determine their durability (Palmer, 2008). Coarse shell fragments can increase the durability whereas fine pores can result in a much less durable stone (Leary, 1983). Examples of fine-grained bioclastic limestones are Chalk and Globigerina whereas Portland, Cotswold or Coralline might be considered coarse-grained bioclastic limestones.

### **1.2.3. Monitoring stone deterioration**

There are three main approaches to studying stone deterioration: monitoring of *in situ* materials, laboratory tests and on site exposure trials.

The first approach, *in situ* assessments, is based on direct measurements and analyses on materials from the built heritage site. The studies of the Paphos mosaic in Cyprus (Doehne, 1991) and the marble surfaces of the Sanctuary of Demeter in Eleusis, Greece

(Moropoulou and Bisbikou, 1995) are examples of analyses of decay products, such as crusts, extracted from the original surfaces to evaluate the conservation state of the ruins. In both cases, destructive techniques, such as x-ray diffraction, were used to analyse the samples and determine their mineral chemistry. Another case of *in situ* assessment is the study of erosion rates at St Paul's Cathedral in London. Trudgill *et al.* (2001) used micro-erosion measurements to monitor changes on the monument surface over a twenty-five year period. Some authors, such as Siedel (2011), believe that *in situ* investigations may provide more reliable information about weathering than exposure trials or laboratory tests. However, original materials are usually altered by past interventions (such as water repellent coatings) or past deterioration patterns (such as crusts), which can change the response to current weathering conditions (Viles, 2013). This makes observed weathering phenomena difficult to extrapolate to other cases or even to other parts of the same site. In addition, the use of destructive or invasive techniques has been largely criticised in the field of conservation, as they cause material loss of the original surface (Cassar *et al.*, 2001).

Comparative field surveys of weathering patterns might be also considered as examples of *in situ* assessments (Přikryl, 2013). Surveys, when undertaken periodically, can be used to monitor stone deterioration and estimate decay rates. For example, a detailed survey based on 1420 images of the Stairway of Copan in Honduras was undertaken to create a 3-D visual record which could be used for future comparisons (Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006). However, decay in terms of changes in surface appearance can be detected by visual examinations after a much longer time of exposure than by the other two approaches (exposure trials and laboratory investigations). For example, the amount of

reliefs lost at Angkor Wat in Cambodia were revealed after comparing photographs taken in 1995 with a photographic archive from 1963 (Leisen, 2002). In addition, observation techniques may only reveal superficial damage, which may lead to the wrong conclusions if they are not combined with in-depth examinations (Mirwald and Brüggerhoff, 1997). Digital photography and image processing methods have been increasingly used for research on soiling and superficial decay. However, these techniques may be more useful if applied to exposure samples because of the variability in appearance found in monuments' surfaces. An example of this approach is the study of colour changes on limestone samples undertaken by Thornbush and Viles (2004). Mean values of L\*a\*b were derived from digital images using an image processing software.

Laboratory tests simulate the impact of certain degradation factors, such as wetting-drying cycles, on specially prepared specimens under controlled conditions. Accelerated laboratory tests take place when samples are subjected to conditions in excess by amount or frequency of what would be expected in real-life situations. For this purpose, it is frequent the use of environmental cabinets. Laycock *et al.* (2008) used accelerated laboratory tests to select a replacement stone for Truro Cathedral, England. To test their suitability, several stone types were subjected to sodium sulphate crystallization and freeze-thaw tests, following national standards. Changes in physical parameters have often been used to examine samples after the tests. For example, Allison and Bristow (1999) used changes in the modulus of elasticity to determine the effects of fire on stone weathering.

Laboratory tests are designed to measure decay in a replicable way so results benefit from comparison with other studies. Standard tests can be particularly useful for determining stone quality, but they have been criticised for their lack of representativeness of historic buildings (Viles, 2013). Although results can be obtained in months, these tests do not reproduce natural conditions and it may be unrealistic to transfer the results to real monuments, where diverse combinations of factors might be taking place (Trudgill and Viles, 1998).

In laboratory tests, samples are usually cut into regular shapes, such as cubes or cylinders (Trudgill and Viles, 1998). The choice mainly depends on the standard tests followed by the experiment. For example, cubes of 50 x 50 x 50 mm are recommended for tests on water absorption coefficient (BS EN1925:1999) or resistance to salt crystallisation (BS EN12370:1999). This makes them particularly used in salt weathering studies (Cooke, 1979, Rothert et al., 2007, Gomez-Heras and Fort, 2007).

Exposure trials consist of placing stone samples in real-life conditions. Their behaviour may be employed as an indicative sensor of decay under complex environmental conditions. The specimens can be brought into the laboratory at intervals for evaluation, which can provide a link between laboratory simulations and field observations (Trudgill and Viles, 1998).

Percentage weight loss has often been used to quantify deterioration in exposure trials. However, many studies have also used it in combination with other methods (mainly colour, elastic properties and strength) to obtain more information about internal breakdown or decay phenomena occurring at a microscale (Nicholson, 2002). Exposure trials last from a few months to determine early stages of decay, for example

the research undertaken over 2 months by Viles (1990), to several decades to establish dose-response functions, such as the ICP Materials project on wet and dry acid deposition, which started in 1985 (Tidblad et al., 2001). However, the most common approach is for exposure trials to last between 1 and 3 years, during which time relevant results have been obtained (Moses, 1996, Yates, 2007, Viles and Goudie, 2007).

Exposure trials often use discs, blocks or tablets. For example, disc-shaped specimens have been selected to research deposition of pollutants with scanning electron microscopy (Moses, 1996) or spectrophotometry (Thornbush and Viles, 2004). Stone blocks have been used on a greater variety of projects, from salt weathering in a coastal desert (Viles and Goudie, 2007) to implications of time-of-wetness for soiling and decay (Smith et al., 2004). Tablets have been used, for instance, to measure erosion rates (Trudgill, 1977), study stone weathering in polluted environments in terms of weight loss, surface roughness and salt content (Jaynes and Cooke, 1987, Butlin et al., 1992, Butlin et al., 1995), and monitor the distribution and nature of deposited particulate matter (Viles et al., 2002). While discs and blocks are usually located in frames or racks, to leave one face completely exposed, tablets are often placed vertically on freely rotated carousels, which allow more equal exposure for all faces, in addition to prevent samples from standing in water when it rains (Moses, 2000). As for laboratory experiments, requirements of the methods used to assess deterioration were in general key reasons in the selection.

Larger stone blocks can potentially offer more realistic representations of the deterioration of real buildings, as they are similar in scale (Moses, 1996). However,

direct comparisons with ruins may still be difficult. Remains at archaeological sites are part of a more complex system where surrounding materials, such as mortars, can influence the decay rates (Přikryl, 2013). Stone test walls and replicas may offer an alternative. They can be used to monitor changes at depth within the wall and may represent the weathering mechanisms better. Nevertheless, these kinds of structures when built near the site can interfere with the site's authenticity and significance (see section 1.1.2). They are also time-consuming and expensive to construct. On the other hand, small blocks and tablets are easily portable and they can be distributed around a site (Moses, 2000). This allows the use of replicates and stronger statistical analysis.

Most studies for exposure trials and laboratory investigations have used freshly quarried stones because the starting conditions are equal for all samples, which remove some of the variability found in studies of monuments. Some studies pre-weathered samples before testing them in the laboratory or exposing them in the field to accelerate the rate of decay or to study the effects of stress histories (Warke, 2007). This method can also be used to simulate the original weathered stone surfaces, as it was the case of the study on consolidants carried out by Natali *et al.* (2015). Nevertheless, the complexity of weathering phenomena observed in exposure trials or laboratory experiments may be difficult to interpret and damage processes may not be significantly developed in short to medium term exposures (Mirwald and Brüggerhoff, 1997).

### **1.3. Past and present research on shelters**

Previous studies have used value and accessibility criteria to assess shelters at archaeological sites (Aslan, 2003, Aslan, 2007, Rivero Weber, 2011). In this respect,

publications about aesthetics (Schmid, 1998), criteria for construction and planning process (Fiero, 2001, Thompson and Taylor, 2001, Parandowska, 2003, Fanood, 2012), design and materials (Agnew and Coffman, 1991, Cannarozzi et al., 2000, Salvatore, 2004, Pesaresi and Rizzi, 2007, Rizzi, 2008), cost (Carroll, 1998, Sgarbi, 2007), long-term maintenance (Roby, 2006), public access (Stanley-Price and Ponti, 2003) and technical expertise (Palumbo, 2001) are frequent. It is generally agreed that the main criteria for shelter design are cost efficiency, availability of material and personnel, public access, non-intrusion into archaeological deposits and economic impact on the local community. The visual interaction of the shelter with the landscape and the archaeological site (Jerome, 1995, Michaelides and Savvides, 2008) and the role of shelters as educational tools, for example, due to their interpretation of the original building shapes (Bertaux et al., 1998, Österreichisches archäologisches Institut, 2002) are also emphasised.

Although factors related to visitors' experience are very important (Cannarozzi et al., 2000, Santoro and Santopuoli, 2000), the influence of shelters on environmental conditions is considered essential for shelter design (Aslan, 1997, Laurenti, 2000). Some authors such as Z. Aslan (2001) state that enclosures are the best form of protection in regard to environmental control. Although this could make enclosures more appropriate for harsh climates, such as continental or temperate maritime, numerous limitations related to the design of these structures have been documented. The enclosed shelters at the Chedworth Roman Villa (England), from the mid 19<sup>th</sup> to mid 20<sup>th</sup> centuries, suffer from insulation deficiencies and possible solutions could increase energy costs (Aslan, 2007). Moreover, the construction of an enclosure does not guarantee a solution to high groundwater levels, as was corroborated in the study

of the shelter at Fishbourne Roman Villa (England) built in 1960 (Woolfitt, 2007). Additionally, these types of structures, when made of transparent materials, can lead to decay of the remains, mainly in the Mediterranean region, due to condensation and overheating (Yaka Çetin and İpekoğlu B., 2013).

On the other hand, some authors explain that open shelters might provide the same level of protection against environmental factors such as solar irradiation as enclosed ones but with fewer costs and risks of for the archaeological substrate (Mollaert et al., 2011, Zanelli, 2015). Open shelters, and more specifically those built with lightweight membranes, are becoming increasingly popular (Demas, 2013). They not only offer an alternative to more invasive solutions but they can also be produced, installed and dismantled rapidly and more economically (Zanelli et al., 2013). All these factors are in line with the required criteria for shelter design suggested in previous studies regarding the construction process, aesthetics and costs (Teutonico, 2001, Aslan, 2007, Woolfitt, 2007). Such open shelters could be a highly recommended solution for shelter construction if more specific research on them is undertaken on their impacts.

### **1.3.1. Effects of shelters on archaeological sites**

The purpose of shelters is to retard deterioration on the archaeological remains. As they can provide a physical barrier to rain and direct sunlight, appraisals of shelters in the literature have generally been based on the idea that covering a site will always be better than leaving it exposed to the environment. However, shelters can also have an indirect effect on the microenvironment, for example modifying temperature and relative humidity conditions in comparison to outside.

Shelters will only be effective if they are able to reduce environmental damaging factors and keep the microclimate stable (Tringham and Stewart, 2008). This aim, however, is not fully accomplished in most cases (Demas, 2013). For example, the open shelters made of metal panels over adobe remains in Joya de Cerén, El Salvador, (Maekawa, 2006) were found to be affected by excessive air infiltration and strong winds from outside. The glass enclosure over the mosaics at Villa del Casale, Italy, is another case (Ministero per i Beni e le Attività Culturali and Istituto Centrale per il Restauro, 2006, Centro Regionale per la Progettazione e il Restauro e per le Scienze Naturali ed Applicate ai Beni Culturali, 2007). High solar gain in the transparent enclosure led to frequent temperature and relative humidity fluctuations and extreme values; in addition to condensation and glazing problems. These effects were also observed at other transparent enclosed shelters such as the Fishbourne Roman Palace (Stewart et al., 2006) and Hamar Cathedral (Ibenholt, 2003). Furthermore, shelters may have a negative impact on archaeological features (see Table 1.1). In a survey conducted by the Israel Antiquities Authority, it was found that half of the 106 mosaics covered with shelters were still deteriorating and in some cases, the shelters contributed to exacerbating the damage due to insufficient roofing and lack of drainage or maintenance (Neguer, 2004, Neguer and Alef, 2008).

The literature is dominated by a large number of publications on shelters that are mainly descriptive (Demas, 2001, Demas, 2003, Demas, 2013). Only a limited number of projects followed a scientific approach, where laboratory analyses of materials, monitoring of field conditions and/or surveys were taken into account.

Table 1.2 and Table 1.3 show the main research initiatives on shelter assessment carried out to date and include a brief summary of the types of studies undertaken by each of these projects. Although some research has been carried out on stone, adobe and mixed materials, the majority of the projects have focused on shelters over mosaics. Additionally, only a few of the projects covered more than one aspect of each category (laboratory analyses, monitoring of field conditions and surveys). In general, relevant comments on the performance of the shelters which could be applied more extensively to other sites are scarce.

**Table 1.2:** Main projects to date regarding assessment of shelters over mixed collections and adobe remains

	Site		Analysis				Monitoring				Survey					
	Name and location	Reference	Material characterisation	Physical/chemical properties	Salts	Biofilms	Site condition	Internal environment	External environment	Soil properties	Heritage moisture/Temp	Air quality	Condition of remains	Shelter	Hydrology/Geology	Site drainage
Mixed materials	Ercolano, Italy	(Pesaresi and Rizzi, 2007)	✓	✓			✓						✓	✓	✓	✓
	House 2, Ephesus, Turkey	(Österreichisches archäologisches Institut, 2002)	✓					✓	✓	✓	✓		✓	✓	✓	✓
	Villa Arianna, Italy	Ministero per i Beni e le Attività Culturali et al. (2006)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Adobe	Joya de Ceren, Salvador	(Maekawa, 2006)	✓	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓
	Fort Selden, USA	(Agnew et al., 1996)						✓	✓		✓		✓	✓		

**Table 1.3:** Main projects to date regarding assessment of shelters over mosaics and stone remains

	Site		Analysis				Monitoring				Survey						
	Name and location	Reference	Material characterisation	Physical/chemical properties	Salts	Biofilms	Site condition	Internal environment	External environment	Soil properties	Heritage moisture/Temp	Air quality	Site condition	Shelter	Hydrology/Geology	Site drainage	
Mosaics	Chedworth, UK	(Stewart et al., 2003, Stewart et al., 2004)			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	
	Brading, UK	(Edwards et al., 2003)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
	Orbe, Switzerland	(Weidmann et al., 2003, Weidmann, 2008)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Paphos, Cyprus	(Doehne, 1991, Agnew and Coffman, 1991)	✓	✓	✓		✓	✓	✓				✓	✓	✓		
	Villa del Casale, Italy	Centro Regionale per la Progettazione e il Restauro (2007)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Israel (106 mosaics)	Israel Antiquities Authority (Neguer and Alef, 2008)											✓	✓	✓	✓	
	England (14 sites)	English Heritage (Stewart, 2008)											✓	✓	✓	✓	
Stone	Apollo Epikourios, Greece	(Theoulakis, 1993)	✓	✓				✓	✓		✓	✓					
	Nový les sandstone sculptures, Czech Republic	(Kotlík and Heidingsfeld, 2002)	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	
	Stairway Copán, Honduras	Getty Conservation Institute et al. (2006)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
	Megalithic temples, Malta	(Cassar et al., 2011) – study before sheltering	✓	✓	✓	✓	✓		✓		✓	✓	✓		✓	✓	
	Hamar cathedral, Norway	(Ibenholt, 2003)						✓			✓		✓	✓			
	Schlossbrucke marble sculptures, Germany	(Siegesmund et al., 2012) – study before sheltering	✓	✓					✓		✓		✓				

Studies on shelters are usually part of more general projects related to restoration proposals for individual heritage sites. For example, the studies on the limestone temple at Bassai, Greece, (Theoulakis, 1993) and the sandstones sculptures in Bethlehem, Czech Republic (Kotlík and Heidingsfeld, 2002). Some other investigations are carried out before sheltering the site to determine the criteria for shelter design. For example, the marble sculptures at the Schlossbrucke in Germany. However, followed-up studies are rarely undertaken. An exception is the study of Hagar Qim presented here (Chapters 8 and 9), which intends to expand the knowledge gained from a previous publication (Cassar et al., 2011).

The study on the lightweight, open shelter over the Stairway in Copan, made of volcanic tuff, is particularly interesting (Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006). This is a very complete study which includes laboratory analyses on the stone and decay products, photographic records, mapping survey of weathering patterns and monitoring of microclimatic conditions inside and outside the shelter. The shelter was found to keep the stone surface dry, limiting biological growth, and reduce wetting-drying cycles and thermal fluctuations. Nevertheless, active deterioration of some surfaces by disaggregation and flaking was still happening despite the shelter, perhaps due to previous interventions or human access to the site. This three-year study relied on a great amount of human and material resources. For example, only the survey took the equivalent to 86 one-person workdays. Nevertheless, the study focused on the conservation of just one architectural element of the site of Copán.

An attempt to a more general approach is the project conducted by the Istituto Centrale per il Restauro and ENEA, Italy. The aim was to create a methodology to guide on the shelter design process (Ministero per i Beni e le Attività Culturali and Istituto Centrale per il Restauro, 2006). For this purpose, a study of 10 open shelters made of different materials (but primarily plastic and metal panels) at Villa Arianna in Castellammare di Stabia was undertaken. As a result, a new shelter with polycarbonate sheets and a more integrating structure was designed and constructed to reduce the access of dust while increasing ventilation. In addition, as part of the same project, exposure trials were undertaken at four partially-sheltered sites in Italy, including Villa Arianna. The results were presented individually; therefore, some conclusions about how to improve the shelter design process are difficult to reach. In addition, there are no clear trends on the effects of shelters on the ruins as sites and shelters are too diverse.

Additionally, only the project on shelters over mosaics in England and Israel carried out by the Getty Conservation Institute (GCI), English Heritage (EH) and the Israel Antiquities Authority (IAA) was undertaken at sites under different climatic conditions (Getty Conservation Institute, 2009). However, results were just based on visual assessments and estimations of damage (see section 1.3.2 for more information).

Shelters are usually built over sites with valuable or vulnerable remains such as mosaics or wall paintings. However, these decorative elements are usually only part of a site that also contains stone remains. Although the conservation principles emphasise that authenticity and cultural values of a site depend on its integrity as a combination of built and decorative elements (International Committee for the

Management of Archaeological Heritage, 1990, Roby, 2006), stone has been traditionally excluded from the investigations. Shelter assessment projects have not often taken a holistic point of view and little consideration has been given to the preservation state of the built materials on site compared to the decorative elements (Laurenti, 2001). In addition, there has been limited research on the relationship between microclimatic conditions inside and outside the shelters and materials decay and a more critical review of the effectiveness of the shelters is required (Zanelli, 2015).

### **1.3.2. Shelter performance assessment**

Environmental monitoring of the conditions outside and/or inside the shelter with data loggers and meteorological stations has been the most common method to assess the effectiveness of shelters. Such programmes have lasted between 9 months (Agnew et al., 1996) and 8 years (Stewart et al., 2003, Stewart, 2008). The average was 3 years with measurement intervals from 60 (Kotlík and Heidingsfeld, 2002) to 1 minute (Agnew et al., 1996, Maekawa, 2006), although the most common approach was to collect data every 15 minutes (Theoulakis, 1993, Maekawa, 2006, Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006, Cassar et al., 2011).

There is a wide range of environmental factors pertinent to protective shelters such as temperature, solar radiation, relative humidity, moisture content and pollution (Neguer and Alef, 2008). However, the majority of the projects which provided information on the methods used only gathered data related to relative humidity and temperature (Agnew and Lin, 1991, Theoulakis, 1993, Edwards et al., 2003). Other

publications also took into account additional information such as rainfall averages (Thompson and Taylor, 2001, Agnew, 2001, Kotlík and Heidingsfeld, 2002, Stewart et al., 2003, Stewart, 2008), wind speed and direction (Maekawa, 2006, Citterio and Giani, 2006c) or solar radiation (Maekawa, 2006, Cassar et al., 2011). In a few cases, there were complete studies of the parameters mentioned above (Agnew et al., 1996, Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006). In addition, a few studies considered subsurface temperature (Theoulakis, 1993, Edwards et al., 2003, Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006, Citterio and Giani, 2006a), or illumination (Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006). In order to obtain a better understanding of the identified decay factors, some studies also measured dimensional change of artefacts through photogrammetric surveys (Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006, Stewart, 2008) or quantified hygroscopic salts to determine the critical range of relative humidity for mosaics (Flatt et al., 1997, Weidmann and Girardet, 2005). In some cases, information about current environment conditions was completed with the use of computer modelling techniques (Wunderer, 2002, Citterio and Giani, 2006b, Aslan, 2007)

Laboratory analyses of original materials have also been used but mainly to determine the current conservation state of the site. For example, energy dispersive x-ray analysis, petrographic observations, x-ray diffraction, and electron microprobe analysis were used to determine the composition, structure, and the presence of deterioration products in tesserae from the Paphos mosaics in Cyprus (Doehne, 1991). Laboratory tests have usually been carried out before restoration interventions and little

consideration has been given to connect these findings with problems with the shelter. Other methods, such as exposure trials, have been demonstrated to be of potential value in other fields (see section 1.2.3). This approach was implemented by the Istituto per il Restauro and ENEA to assess four partially-sheltered sites in Italy (Ministero per i Beni e le Attività Culturali and Istituto Centrale per il Restauro, 2006). Small marble, calcite and painted brick tablets (with and without different consolidation products) were placed at different locations at four sites with enclosures and open shelters. The samples were analysed after 4 and 12 months by determining colour change, amount of soluble salts, water uptake and particulate deposition under microscope. One of the main benefits of exposure trials is the possibility to compare the results more easily due to the use of the same materials for the samples. However, no comparative analyses amongst sites and shelters were published as the shelters are very different from each other in both typology and materials of construction.

Modern replicas placed beneath and outside shelters have been used to monitor changes on the material surfaces without causing damage to the sites. This is the case of the adobe walls at Fort Selden (Agnew, 2001) and brick sculptures at Wat Sri Chum (Nishiura and Aranyanark, 2002). For predicting the performance of proposed shelters, test structures, for example, the hexashelter built by the GCI in Cyprus and New Mexico (Agnew et al., 1996) and a temporary tent by English Heritage at Cleeve Abbey, England (Tringham and Stewart, 2008) have been used. The main drawback of these approaches is that they are, in general, time-consuming and very expensive, and might even need the help of specialists. In addition, the cultural values of the site can be affected as indicated in section 1.2.3.

There have been some attempts to establish a methodology for studying the effectiveness of shelter design for archaeological preservation in the last ten years. The first systematic approach to shelter assessment involved the modular structure built in 1991 by the GCI at Fort Selden, New Mexico (Agnew et al., 1996). The purpose of the study was to evaluate the effects of the shelter over mud brick remains through the collection of quantitative data. The analysis included a comparison between meteorological parameters inside and outside the shelter through protective indices used later by Maekawa (2006). These risk indices are mathematical expressions of the variation between the sheltered and exposed environmental parameters (Equation 1.1, a and b). However, the protective indices do not consider the quantitative response of the heritage materials to these varied conditions and, therefore, their applicability is limited.

**Equation 1.1:** Variance of environmental data ( $\delta$ ) summarised by daily means (between days) and daily means per seasons (within a day) to remove, respectively, the daily and seasonal effects from data

$$a) \text{ Protective Index (PI) between days} = 1 - \frac{\delta \text{ sheltered between days}}{\delta \text{ outside between days}}$$

$$b) \text{ Protective Index (PI) within a day} = 1 - \frac{\delta \text{ sheltered within a day}}{\delta \text{ outside within a day}}$$

Another attempt to quantify shelter effectiveness has been suggested by Cacace et al. (2006). Construction effectiveness and adequacy to the specific site are evaluated by a point factor system based on a qualitative assessment. More than 100 sheltered archaeological sites in Italy were evaluated with this system (Laurenti, 2001). Aspects such as the morphology of the archaeological area, materials used for shelter construction, state of building components, and functionality were studied. It was found that only 38.7% of the shelters were considered efficient. For example, the

transparent roofs of the House of Ariadne at Pompeii were classified with a score of 5.5 (intermediate protection). However, a study on the murals paintings in 2008 demonstrated that the shelters were enhancing excessive temperatures, particularly in summer and, as a result, a new shelter made of opaque sheet of cement was constructed in the following year (Merello et al., 2013). This second assessment was determined after undertaking a microclimatic monitoring instead of using scores based on qualitative criteria. This demonstrates that visual assessments rarely provide a complete understanding of the problems affecting a site when used in their own.

The same problem can be observed with the methodology proposed by the GCI, EH and the IAA to establish a relationship between the condition of a mosaic and the environment created by the shelter (Stewart et al., 2006, Getty Conservation Institute, 2009). The methodology was based on a rapid visual survey, used to record mosaic materials, deterioration phenomena, site environment and shelter construction at 50 sites in England and Israel (Neguer and Alef, 2008, Stewart, 2008). Deterioration phenomena were numerically graded by their extent (percentage of surface area) and an estimation of the degree of severity. A similar methodology was implemented by the GCI (2009) at Caesarea, Israel. Standardised forms and photographs were used to compare adjacent mosaics with similar conservation history but different levels of exposure (exposed, sheltered, under shallow covering and reburied). The aim was to elucidate the role of maintenance in the long-term preservation of the site through the evaluation of the amount and type of interventions and time required for each intervention (Piqué et al., 2003).

Assessments of shelter behaviour should be based on the identification of possible decay factors, but also analysis of environmental data and evaluation of the material decay and shelter condition (Tringham and Stewart, 2008). However, to date, research has been mainly based on environmental monitoring and visual inspections and very few studies have provided a scientific explanation of the decay processes affecting the site in relation to the microenvironment created by the shelter. Information about stone decay and shelter condition can be obtained by undertaking a survey but this method is not enough to achieve a complete picture of the effects of shelters. In addition, environmental data should be assessed in relation to materials decay. Exposure trials are an effective method to monitor stone weathering when comparisons are required and direct tests on original surfaces want to be avoided.

### **1.3.3. Recommendations in the literature for future research**

The increasing interest in studies on shelters was first highlighted in 2001 when participants at a monographic conference called for a critical review of existing shelters to improve the decision-making process and practice (Teutonico, 2001) and the need to establish detailed criteria before sheltering (Avrami et al., 2001). As part of the GCI, IIA and EH project on shelter assessment over mosaics, some shelters were found to enhance rather than reduce deterioration (Stewart et al., 2006). This suggests that there was still an incomplete understanding of the causes of deterioration and the performance of shelters and a lack of technical specifications for shelter design. Zaki Aslan (2007) put forward some suggestions for future research in his thesis. Among these were research on shelters with similar typology to provide comparative analysis; development of a methodology to guide shelter assessment for managers and

designers and field investigations to determine the main causes of deterioration. At the 9<sup>th</sup> Conference of the International Committee for the Conservation of Mosaics, S. Tringham and J. Stewart (2008) presented a review of assessment initiatives. They agreed that condition monitoring is rarely correlated with environmental data and more in-depth investigations into the causes and processes of deterioration are often lacking. In addition, they suggested studying possible materials which could be used as indicators of weathering effects. A recent literature review on conservation of mosaics established that the connection between deterioration mechanisms, environmental monitoring, and shelter design is still a challenge (Demas, 2013).

The knowledge gained from the literature has provided insight into the current situation of research on shelters and the scientific need to improve the field. This information, which has helped to design this current research project, can be summarised as follows: there is no full understanding of the influence of shelters on micro-environmental conditions, and more importantly, the scientific evidence of their influence on the deterioration of vulnerable materials is very limited. Furthermore, there have been no specific and rigorous studies on the effects of shelters on the decay of bioclastic limestone and there has been no attempt to establish a comparison between the performances of lightweight, open shelters in different climates. In addition, the design of a methodology for shelter assessment based on low-cost and easily carried out monitoring methods would be especially useful for site managers and shelter designers. However, there is a lack of proposals which take into consideration not only environmental factors and visual assessments but also a scientific evaluation of stone decay.

## **1.4. Aim and objectives**

This study aims to provide the first rigorous scientific assessment of the effect of lightweight, open shelters on bioclastic limestone deterioration at archaeological sites.

The objectives are the following:

1. Exhaustive assessment of the effect of a lightweight, open shelter on the preservation of limestone remains.

To meet this objective, a range of environmental parameters considered to be key factors in the decay of stone remains was monitored using low-cost environmental sensors inside (at the centre and towards the periphery) and outside the shelter at the Bishop's Palace (Witney, England). In addition, small limestone samples (blocks and tablets) of different vulnerability to decay were used to assess weathering mechanisms at different positions inside and outside the shelter.

2. Comparative assessment of the effects of lightweight, open shelters on the preservation of limestone remains at archaeological sites in contrasting climatic conditions.

To meet this objective, simultaneous monitoring of environmental causes of stone decay was undertaken at two comparable sites in different climate zones using low-cost, environmental sensors inside (at the centre and towards the periphery) and outside the shelter at Hagar Qim (Malta) and the Bishop's Palace (Witney, England). In addition, small blocks made of the same type of limestone were exposed simultaneously inside and outside the shelters to assess and compare weathering mechanisms.

3. Evaluation of the low-cost, simple but innovative method for shelter evaluation used to address objectives 1 and 2.

To meet this objective, the selection of environmental parameters, stone types and properties, and techniques for monitoring microclimatic conditions and the degree and nature of stone decay was critically assessed, based on the experience of the author. In addition, advantages and disadvantages of the use of exposure trials for shelter evaluation at archaeological sites were determined.

## **1.5. Chapter summaries**

### CHAPTER 1: RESEARCH CONTEXT

Archaeological sites can benefit from the control of environmental conditions through the construction of shelters, which aim to provide optimum conditions for the preservation of remains. However, some considerations must be taken into account in order to follow the Code of Ethics for Conservators (European Confederation of Conservator-Restorers' Organisations, 2003). This chapter explains the importance of the preservation of sites but also the scope of these recommendations. After defining some essential terms which underpin the research, summaries of the likely stone decay mechanisms at archaeological sites and methods commonly used for monitoring decay are presented. In addition, this chapter reviews research on shelters over archaeological sites and discusses the importance of this study in the context of heritage conservation. The knowledge gained from the literature reviewed in this chapter has provided insights into the current situation of research on shelters and the scientific need to improve the field of site management.

## CHAPTER 2: RESEARCH DESIGN

This chapter presents an explanation and justification of the experimental design in relation to the research aims and needs observed in the literature review. After an introduction to the overall approach, a detailed sampling strategy and data collection rationale is included. This part is divided into the same sections as the next chapter on materials and methods. It explains the approach related to the monitoring of microclimatic conditions, monitoring deterioration with stone blocks and monitoring dissolution, soiling and microbial growth with stone tablets. In addition, a summary of monitored locations is included. To conclude this chapter, a summary of the research design is presented.

## CHAPTER 3: MATERIALS AND METHODS

This chapter outlines the proposed methodology of study. After a brief introduction to the overall methodological approach, the chapter is divided into three sections. These are related to the different methods and materials used for the field experiments at the Bishop's Palace at Witney and at Hagar Qim in Malta. The first section deals with methods and materials to monitor microclimatic conditions inside and outside the field sites. The second section explains the use of limestone blocks to monitor stone decay inside and outside the shelters at the field sites. The third section focuses on the use of limestone tablets to monitor dissolution, soiling and microbial growth at the Bishop's Palace.

## CHAPTER 4: CONSERVATION STATUS OF THE FIELD SITES

An overview of the two case study sites (the Bishop's Palace at Witney and Hagar Qim in Malta) is presented. This section compiles information related to the sites and their shelters such as the history of the site condition and conservation interventions. A condition survey of the remains at the two field sites is presented in this chapter. In addition, the condition of the shelters is assessed. This introductory research was used to support the decision to monitor specific locations and to determine possible active weathering mechanisms in the remains and the influence of the shelters. This method builds on proposals from a large scale, rapid monitoring project on mosaics carried out by the Getty Conservation Institute and English Heritage (Stewart et al., 2006) (see section 1.3.2). This chapter addresses objectives number 1 and 2.

## CHAPTER 5: EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON MICROCLIMATIC CONDITIONS

This chapter reports on data collected from a year-long study of microclimatic conditions outside and inside the shelter at the Bishop's Palace (Witney). In addition to the outside and the centre of the shelter, a selected peripheral area was monitored to determine if there were differences in the protection provided by the shelter. In particular, the following environmental threats were monitored: temperature extremes and fluctuations, solar radiation, freeze-thaw events, relative humidity extremes and fluctuations and wetting events. The microclimatic conditions within the shelter experienced by upper, middle and lower portions of the ruined walls were also studied in order to determine which areas are at higher risk of decay at the Bishop's Palace. This chapter addresses objective number 1.

## CHAPTER 6: EVALUATING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON LIMESTONE DECAY WITH CHALK, COTSWOLD LIMESTONE AND PORTLAND STONE BLOCKS

This chapter reports on data collected using Chalk, Cotswold limestone and Portland stone blocks placed outside and under the shelter at the Bishop's Palace for a year. Changes in stone properties were documented periodically to provide information on the degree and nature of deterioration outside and inside the shelter (centre and periphery). The degree of deterioration of the stone blocks was quantified as changes in dry weight, elasticity, surface hardness and ultrasonic pulse velocity. The influence of the shelter on the nature of deterioration and soiling of the stone blocks was assessed by colour and macroscopic and microscopic surface changes. In addition, surface temperature (fluctuations and frost events) and moisture content of the stone blocks was monitored in order to examine the effectiveness of the shelter at reducing environmental causes of stone decay. This chapter addresses objective 1.

## CHAPTER 7: EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON DISSOLUTION, SOILING AND MICROBIAL GROWTH ON PORTLAND LIMESTONE TABLETS

Deterioration of Portland limestone tablets located outside and under the central part of the shelter at the Bishop's Palace was assessed periodically over 18 months by monitoring surface colour, microscopic changes, salt content and weight changes. The aim was to investigate dissolution, soiling and biological colonisation and their role in deterioration at this field site. The results were compared with those obtained by the

British National Materials Exposure Programme (NMEP) in unsheltered and sheltered Portland limestone tablets (Butlin et al., 1992). This chapter addresses objective 1.

#### CHAPTER 8: COMPARATIVE STUDY ON THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP'S PALACE (WITNEY) ON MICROCLIMATIC CONDITIONS

This chapter reports on data collected from a year-long study of microclimatic conditions outside and inside the shelter (centre and periphery) at Hagar Qim and the Bishop's Palace. The methodology follows the one proposed for Chapter 5. The following environmental conditions were monitored simultaneously at both sites: temperature extremes and fluctuations, freezing-thawing events, relative humidity extremes and fluctuations and dust deposition. The study of each site allowed the mitigating effect of the shelter to be determined in relation to the level of protection around their periphery as compared with towards the centre. The results were then compared between sites to establish differences in the degree of protection from open shelters at sites with Mediterranean and temperate maritime climates. This chapter addresses objective 2.

#### CHAPTER 9: EVALUATING THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP'S PALACE (WITNEY) ON LIMESTONE DECAY WITH GLOBIGERINA AND CORALLINE LIMESTONE BLOCKS

This chapter reports on data collected using Globigerina and Coralline limestone blocks, placed outside and under the central part of the shelter at Hagar Qim and the Bishop's Palace during the same year. The change in stone properties provided information on the degree and nature of deterioration at each site. The methodology follows the one proposed for Chapter 6. The degree of deterioration of the stone

blocks was quantified as changes in dry weight, elasticity, surface hardness and ultrasonic pulse velocity. The nature of deterioration and soiling of the stone blocks was assessed by colour and macroscopic and microscopic surface changes. In addition, surface temperature (fluctuations and frost events) and moisture content of the stone blocks was monitored to determine the effect of the shelter on environmental causes of stone deterioration. The results were compared to establish differences between the field sites in the degree and nature of deterioration of the stone blocks. This chapter addresses objective 2.

## CHAPTER 10: DISCUSSION AND CONCLUSIONS

Every chapter aims to explain different aspects of the effect of open shelters on the decay of limestone. A final discussion summarises the results and connects the findings from the previous chapters to establish general trends in shelter performance. This chapter also evaluates the proposed methodology in order for it to be applied extensively to different sites by heritage professionals (objective 3). Key results with respect to the stated objectives are identified in the conclusion.

## 2. RESEARCH DESIGN

Limestone is a commonly used stone for monuments across Europe due to its widespread availability and because it is relatively easy to quarry (Smith et al., 2010a). Studies on limestone have been, therefore, a priority for European restorers and conservators in order to propose preservation strategies for built cultural heritage (Smith et al., 2010b). Further research on bioclastic limestone is even more important because this stone type is considered particularly vulnerable under certain environmental conditions (section 1.2). In addition, the research community agrees that preventive conservation is fundamental for the long-term management of cultural heritage such as archaeological sites, and that shelters might be a suitable preservation strategy. However, limestone has been systematically ignored in the research on the impact of shelters in favour of decorative elements such as mosaics or wall paintings. On the other hand, lightweight membranes have been used for shelter design since the 1980s and, as explained in section 1.3, are becoming extremely popular because of numerous advantages such as their lower impact on the archaeological substrates. Further research is being carried out on this type of membrane, for example on the degradation factors that affect their lifespan (Rosina et al., 2011, Zanelli, 2015). However, there have been no rigorous, scientific assessments of the effect of lightweight, open shelters on the deterioration of bioclastic limestone.

Lightweight open shelters are very popular in the Mediterranean region. Some examples are the temple of Apollo in Bassae (Greece) built in 1987, the Roman villa Agrippa in Pianosa (Italy) in 1990, the terrace Houses in Ephesus (Turkey) in 1999 and Capo Soprano Walls (Greece) in 2009. However, these types of structures have been

used much less frequently in continental and temperate maritime climates where enclosed shelters are more popular. For example, in the case of England, there are no references in the published literature to open shelters made of lightweight membranes and only one site covered with this type of shelter, the Bishop's Palace at Witney, has been found by the author. The traditional belief is that open structures are not suitable for northern climates despite the fact that no attempt to compare their performance in different climates has been made.

Research to assess the suitability of open shelters in both Mediterranean and temperate maritime climates could be beneficial not only to widen the range of alternatives for the conservation of archaeological remains but also to fill the key knowledge gaps enumerated in section 1.3.3.

## **2.1. Overall approach of the research**

As detailed in the literature review (section 1.3.2), shelter assessments have been based on three categories summarised as follows: 1) environmental assessment by monitoring inside and/or outside the shelter or, less commonly, by computer modelling; 2) evaluation of the material decay by undertaking analytical investigations of archaeological materials or replicas; and 3) identification of risks connected with the preservation of the site through visual surveys of stone remains and shelters. Although the combination of all three is of vital importance to obtain a complete understanding of the effects of shelters (Tringham and Stewart, 2008), only a few cases have undertaken such holistic investigation of archaeological sites. This knowledge gap is even more evident in the case of stone remains (Tablet 1.2). Therefore, a methodology based on the collection of environmental data, analytical investigations on bioclastic

limestone samples before and after exposure and documentation of the sites has been designed for this project.

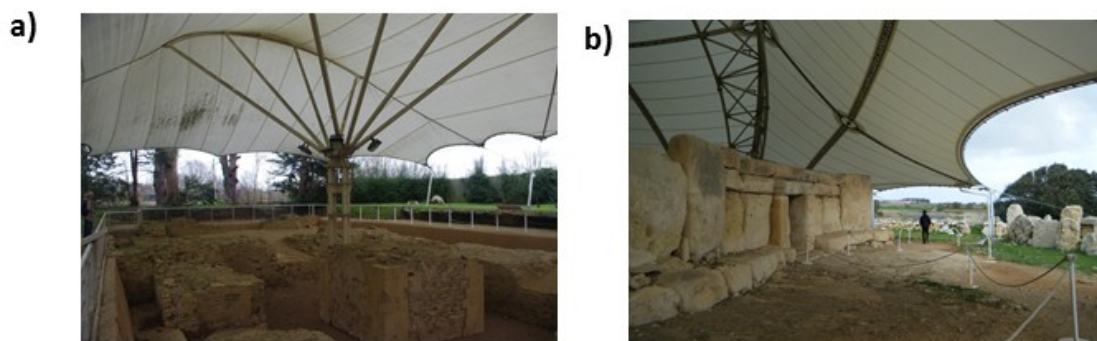
This study has used a practical, field-based approach in which two existing archaeological sites with lightweight, open shelters provide the major source of information through field observations and exposure trials. The main reason for this approach is to link science and conservation practice more closely by creating a practicable methodology for shelter assessment which can be applied extensively at different archaeological sites. This methodology can be used to support decisions regarding whether to implement shelters rather than other conservation strategies, and how to measure the impact of shelters over limestone remains.

The methodology is intended to be simple and low-cost so it could be applied by non-experts at a variety of sites ranging from high to low budgets. The focus was on field data collection with modelling used for solar radiation assessment to clarify data obtained by environmental monitoring in Chapter 5. In addition, direct investigations on archaeological materials were restricted to minimise damage to the site as recommended by international codes of conservation ethics (see section 1.1.2).

Exposure trials have been proven successful in the field of geomorphology and provide important advantages (see section 1.2.3). They are a useful method of obtaining some meaningful data which relate to real surfaces and reliable data which can be used to compare decay in different environments (Viles, 1996). Although there have been some attempts to implement this approach to the study of shelters, the result is of limited success because shelters are not similar in typology (see section 1.3.2). This is also one of the main limitations of previous projects which intended to compare sites

in different climates (Aslan, 2007). For example, the research undertaken on mosaics by the GCI, IAA and EH (Stewart et al., 2006).

The Bishop's Palace at Witney, England, and the Megalithic temples in Malta (Figure 2.1) were selected after a detailed literature review and interviews with a range of heritage professionals. Both have lightweight, open shelters of very similar design and are built with the same materials (fiberglass and polytetrafluoroethylene), and, in addition, both cover bioclastic limestone ruins.



**Figure 2.1:** a) Bishop's Palace (Witney, UK) and b) Hagar Qim (Malta). Images: C. Cabello-Briones

Logistical aspects like transport, proximity, availability of documentation, safety and security and the possibility of obtaining access permits were also taken into account for the selection. In addition, the Bishop's Palace is one of the few examples of this type of shelter that is not built in the Mediterranean region and in the case of Hagar Qim, heritage managers were especially keen on further research. In fact, this thesis provides a follow-up study to previous research on the conservation state of the unsheltered limestone remains at Hagar Qim, Malta (see section 1.3.1).

Visual assessments of the main decay phenomena on the ruins and the condition of the shelters helped to establish possible weathering mechanisms and problems with the shelter design at both sites (see Chapter 4). In addition, an exhaustive assessment

of the effects of the lightweight, open shelter at the Bishop's Palace was undertaken by monitoring environmental conditions and decay of stone blocks (90 x 30 x 30 mm) for a year (Chapter 5 and 6), and monitoring decay of stone tablets (50 x 50 x 20 mm) for 18 months (Chapter 7). This is the first scientific assessment of the effect of a lightweight, open shelter at an archaeological site in England. Furthermore, results obtained from the simultaneous monitoring at the two field sites (the Bishop's Palace and Hagar Qim) located in contrasting climatic conditions were analysed comparatively for the first time (Chapter 8 and 9). The intention was to validate the methodology at different sites, establish differences in shelter performance between sites in different climates and to the start towards developing dose-response functions. The study responds to the necessity of determining if the same sheltering solution is suitable for protecting limestone remains in different climates.

Fresh limestone samples were used because the state of conservation at the start of the experiment is known and it is the same for all the replicates. Samples are more homogeneous so it is easier and faster to document changes. In addition, using the same material for all samples allows the comparison between positions and sites.

Environmental impacts and the response of stone samples were determined by analysing a series of controlling factors, such as the number of freezing events in the case of environmental conditions and changes in dry weight in the case of stone decay. The potential risk for stone decay in relation to each controlling factor at different locations within the sites (i.e. outside, on the periphery and inside the shelter) and between sites was studied. This allowed establishment of possible limitations on the protective role of lightweight, open shelters in England and the Mediterranean.

## **2.2. Sampling strategy and data collection rationale**

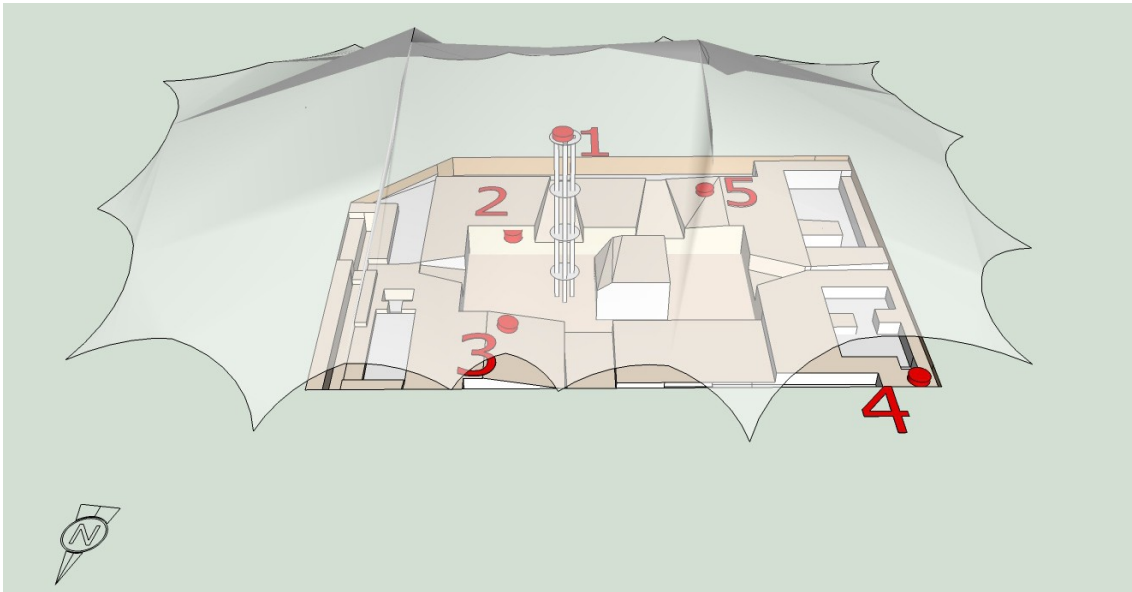
The first phase of the research corresponds to an exhaustive study of the effects of the shelter at the Bishop's Palace on the preservation of limestone remains. It is based on the monitoring of environmental conditions and decay in stone blocks inside and outside the shelter between 3<sup>rd</sup> August 2012 and 29<sup>th</sup> July 2013. To complete the study, specific research on dissolution, soiling and microbial growth inside and outside the shelter was undertaken by monitoring decay in stone tablets between 23<sup>rd</sup> January 2013 and 23<sup>rd</sup> July 2014. The second phase of the research corresponds to a comparative assessment of the effects of shelters on the preservation of limestone remains in England and the Mediterranean region. It is based on a simultaneous monitoring of environmental conditions and decay in stone blocks at the Bishop's Palace (Witney) and Hagar Qim (Malta) between 29<sup>th</sup> July 2013 and 22<sup>nd</sup> July 2014.

Short to medium exposure trials provide evidence of early stages of decay. They also represent a compromise between the time available for the project and the time necessary to obtain significant results (see section 1.2.3).

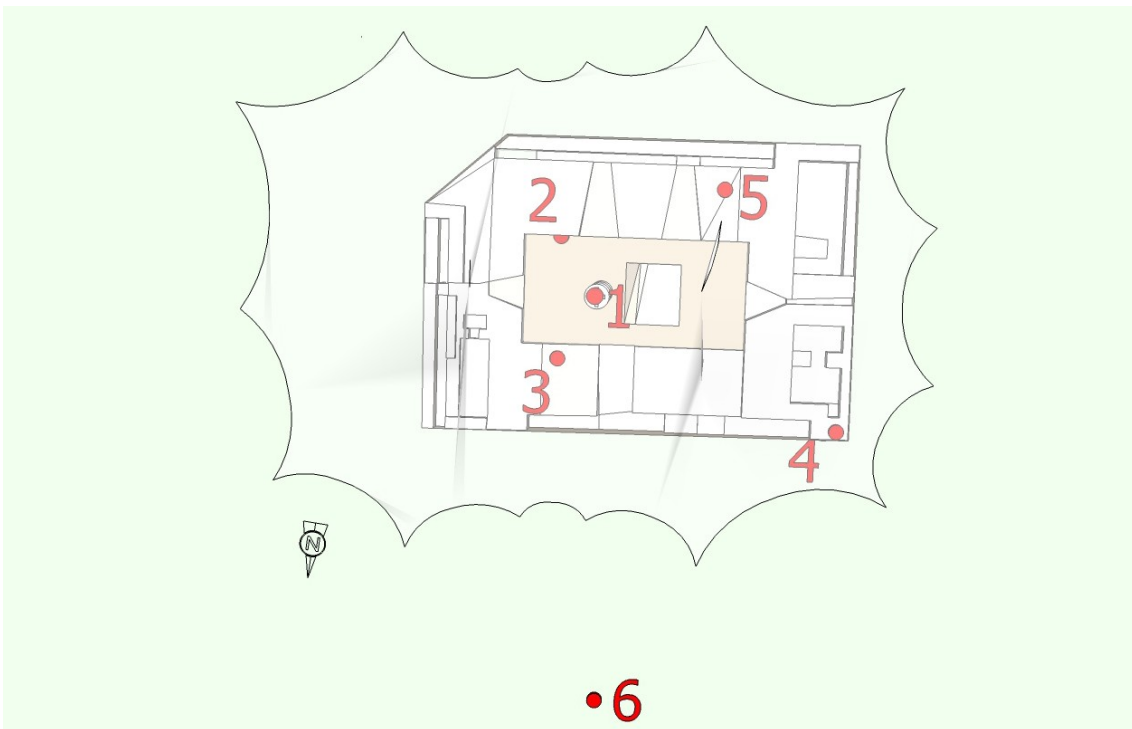
### **2.2.1. Summary of monitoring locations**

The position of sensors for environmental monitoring and stone samples was selected to determine how the degree of protection of the shelter varies across the site. Monitoring locations, which represent the centre, periphery and outside of the shelter, were selected at each site after undertaking condition surveys of remains and shelters (Chapter 4).

Figure 2.2 to Figure 2.5 illustrate the selected monitoring positions at each site. A detailed explanation can be found in following sections.



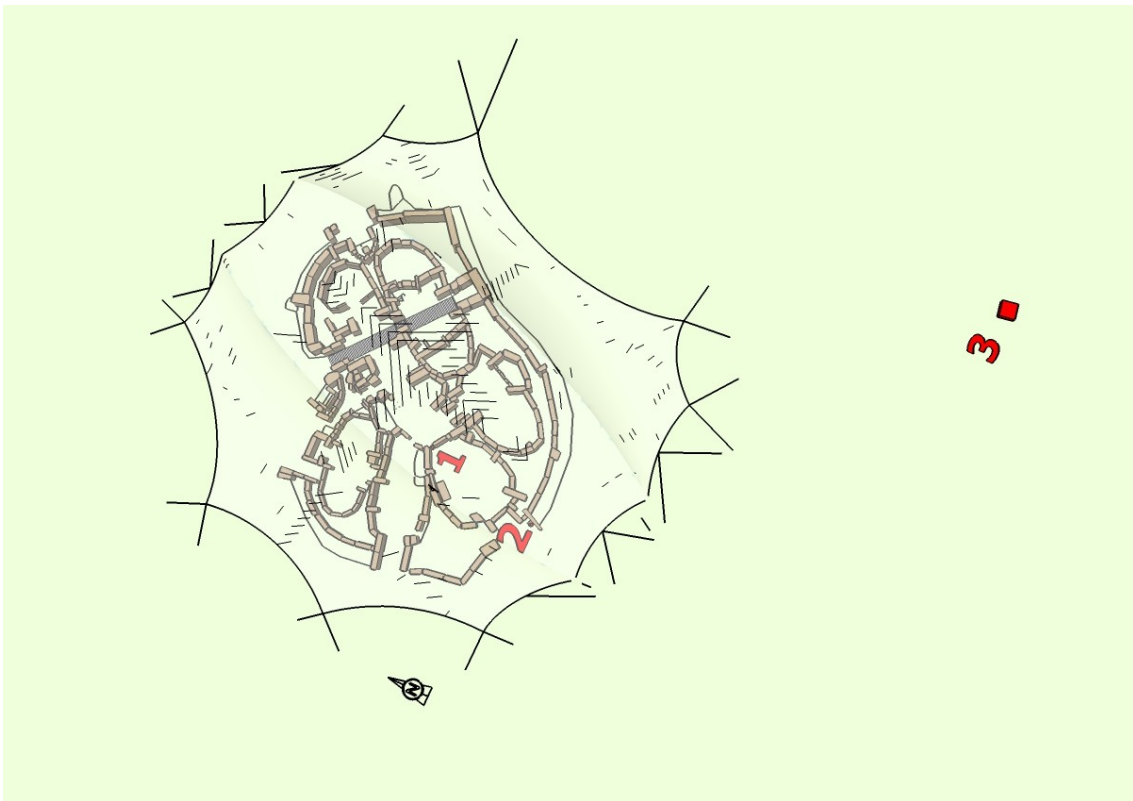
**Figure 2.2:** Position of the sensors inside the shelter at the Bishop's Palace (Witney) – 1: centre, 2: representative wall, 3: NE (periphery), 4: NW (periphery), 5: SW (periphery). Corresponding scale: 1:240



**Figure 2.3:** Position of the sensors at the Bishop's Palace – 1: centre, 2: representative wall, 3: NE (periphery), 4: NW (periphery), 5: SW (periphery) and 6: outside of the shelter. Scale: 1:240



**Figure 2.4:** Position of the sensors inside the shelter at Hagar Qim (Malta) – 1: centre, and 2: periphery (SW). Corresponding scale: 1:360

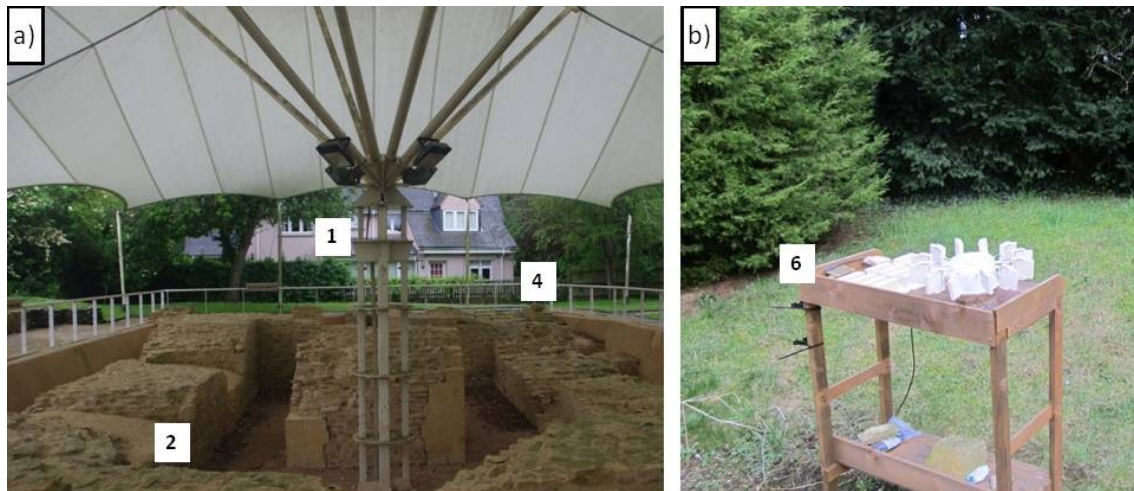


**Figure 2.5:** Position of the sensors at Hagar Qim – 1: centre, 2: periphery (SW) and 3: outside of the shelter. Scale: 1:720

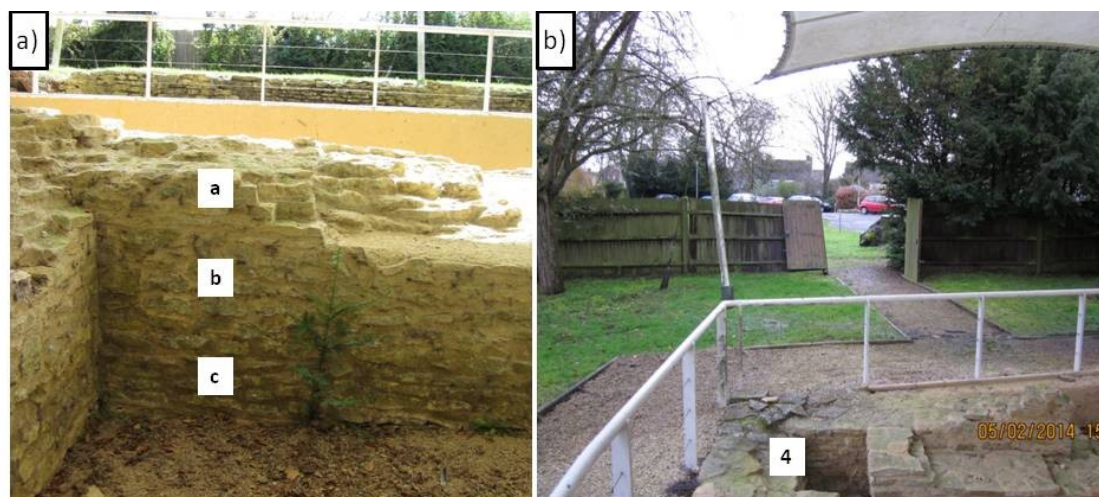
### **2.2.2. Monitoring of microclimatic conditions**

A shelter will effectively protect the remains if it is able to stabilise the microclimate, avoid extremes and reduce the amount of damaging environmental events, such as wetting-drying and freeze-thaw (Tringham and Stewart, 2008). Temperature (extremes and fluctuations), freeze-thaw cycles, relative humidity (extremes and fluctuations), salt crystallization events and wetting events were selected as key environmental causes of stone decay after a detailed literature review (Chapter 1). Temperature and relative humidity were measured using hygrochron dataloggers and surface wetness loggers with electrical impedance grids. Both dataloggers have proven successful in different projects related to stone decay (Viles, 2005, Sternberg et al., 2011, Coombes, 2011, Mol, 2014). The major advantages are that they are not only small but also low cost and reliable dataloggers (Hubbart et al., 2005). The number of NaCl crystallisation events and frost events were derived from temperature and relative humidity data following the model established by Sabbioni et al. (2010). Salt crystallisation events were determined by calculating the number of times relative humidity crosses 75% and frost events by the number of times the temperature went below 0°C. The microclimatic measurements were completed with data related to solar radiation (Chapter 5) determined by computer modelling, and dust deposition by image processing techniques (Chapter 8) (see section 3.2 for more information).

The first phase of microclimatic conditions monitoring (Witney only) is reported in Chapter 5. The study focused on the following positions: inside the shelter (centre, periphery and on a representative wall of the site) and outside.



**Figure 2.6:** Pictures of locations where sensors were placed at the Bishop's Palace (Witney): a) beneath the shelter (number 1=centre, number 2=representative site wall and number 4=NW) and b) outside (number 6). The numbers correspond to diagrams in section 2.2.1. Images: C. Cabello-Briones

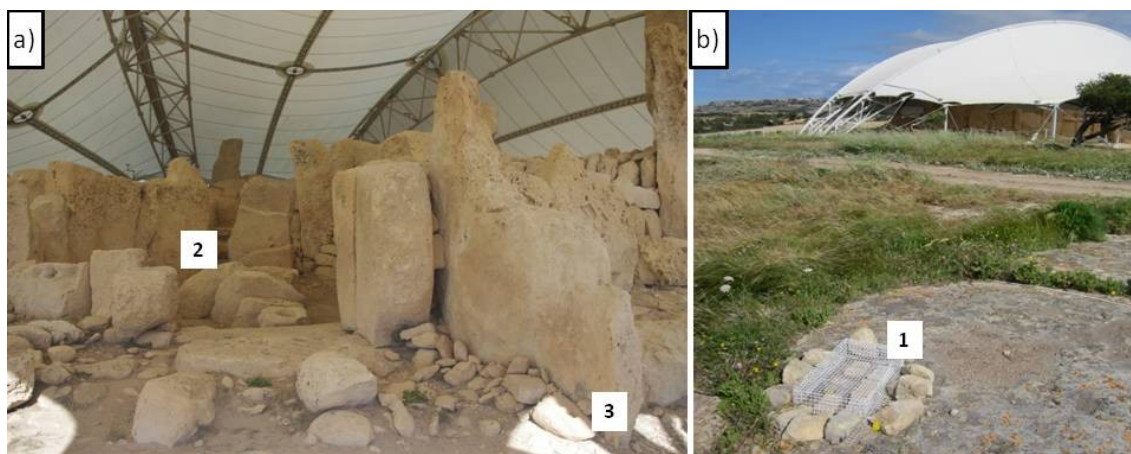


**Figure 2.7:** Detailed pictures of locations where sensors were placed at the Bishop's Palace (Witney): a) representative site wall (a=top part, b=middle part and c=bottom part) and NW (number 4). The numbers correspond to diagrams in section 2.2.1. Images: C. Cabello-Briones

The centre of the site refers to the central metal pole of the cover structure at approximately 3 metres high from the archaeological pit ground and 1.5 metres from the current ground (Figure 2.6, a). The peripheral location is the north-west corner of the site, where the ruins are at ground level (Figure 2.6, a and Figure 2.7, b). The selected portion of the wall is a vertical section of the medieval wall considered to be representative of the conservation state of the ruins. It is located under the shelter towards the centre and faces north (Figure 2.6, a). Three portions of the wall (top,

middle and bottom part of the wall) were monitored with hygrochrons, located in a vertical line, approximately 60 cm apart. The top hygrochron was placed on the wall head (horizontal) whilst middle and bottom ones were placed on the wall face (vertical). The hygrochron at the middle part of the wall was located just above the moisture stain on the wall (Figure 2.7, a). Recording at the site wall started one month later than in the centre, on the periphery and outside the shelter due to logistical constraints. A 1 metre high wooden support in a private garden adjacent to the north side of the site was used for the outside location (Figure 2.6, b).

The second phase of environmental monitoring (at Witney and in Malta simultaneously) is described in Chapter 8. The locations selected were the following: the outside, centre and periphery of the shelter. At Witney, the positions were the same as during the first phase. In Malta, the centre refers to the north section of the south-west apse of the temple (Figure 2.8, a). The location on the periphery is the vertical section on the south-west edge of the site (Figure 2.8, a) and the outside location, a rocky ground surface to the south, is around 20 metres away from the periphery of the shelter (Figure 2.8, b).



**Figure 2.8:** Pictures of locations where sensors were placed at Hagar Qim (Malta): a) beneath the shelter (number 2: centre and number 3=SW) and b) outside (number 1). The numbers correspond to diagrams in section 2.2.1. Images: C. Cabello-Briones

For both environmental sensors (explained in this section) and stone samples (explained in section 2.2.3), the most central location possible under the shelter was selected as a fully protected position and was compared with a fully exposed (outside) and a partly exposed location (periphery). The central position under the shelter and the outside were considered particularly important for the project. Therefore, the specific locations were chosen to represent conditions found around those parts of the site but also to avoid human interference and possible loss of equipment. The peripheral locations in Malta (SW) and at Witney (NW) are located towards the edge of the sites, where evident problems with shelter design were detected after a condition survey (Chapter 4). Selecting problematic areas is a common approach in studies of microclimatic conditions at archaeological sites to propose conservation strategies (Citterio and Giani, 2006a, Merello et al., 2013, Carcangiu G. et al., 2014). In addition, three different parts of a site wall were monitored to determine which areas of the vertical wall sections under the shelter are at higher risk of decay.

There are some potential impacts related to the use of monitoring locations at different heights. For example, the stratification of the air might lead to different temperatures between air layers. However, heritage sites are characterised by highly irregular structures and the selection of monitoring locations is conditioned by logistical constraints. As projects on archaeological materials should strive to protect the site integrity (see section 1.1.2), it is also essential that there is a low visibility of the sensors and a low impact on archaeological remains due to their manipulation.

The locations monitored at each site are summarised in Table 2.1 and illustrated in Figure 2.2 to Figure 2.5.

**Table 2.1:** Summary of locations where environmental conditions were monitored at each site and phase and the corresponding points in the diagrams in section 2.2.1

	1 <sup>st</sup> Phase (2012-2013)		2 <sup>nd</sup> Phase (2013-2014)	
	Witney	Witney	Witney	Malta
<b>Wall (top, middle and bottom)</b>	2			
<b>Outside</b>	6	6		1
<b>Centre</b>	1	1		2
<b>Periphery</b>	4	4		3

### 2.2.3. Monitoring deterioration with stone blocks

Stone blocks provide an indication of the relative aggressiveness of different environments across the sites. Replicates are used to minimise the influence of stone inhomogeneities and differences in mineralogical and chemical composition. The stone samples used in this study were made with limestone of varying sensitivity to decay (types and properties are explained in section 3.3.1). Samples were cut from the same block and washed with de-ionised water, before they were dried in the oven to calculate dry weight (see section 3.3.2). No additional surface finishing method was used. All replicates were manipulated with the same procedure to avoid differences due to quarrying methods, processing and surface finishing.

Samples used in the field of geomorphology are often medium sized blocks mounted on frames, but this approach is not particularly suitable for historic environments. Smaller blocks, which can be hidden between the ruins or the shelter's structure, are less unsightly and take less space. These make them more suitable for sites open to the public (Viles, 1996). The size and shape of the samples (90 x 30 x 30 mm) were selected to balance a range of requirements such as portability, unobtrusiveness in the field and equipment requirements.

Table 2.2 shows the techniques selected to determine physical, chemical and biological decay processes in the stone blocks, not only at surface level but also beneath the surface. This is especially important as many signs of decay may not be visible to the naked eye during medium exposure trials. Non-destructive techniques and relatively low-cost equipment was selected to reduce the amount of replicates and costs. Visual assessments provide information about the nature of stone deterioration while changes in dry weight, hardness, elastic modulus, ultrasonic pulse velocity and colour, were used to quantify change. These techniques have been extensively used to measure the degree of deterioration (see section 3.3).

**Table 2.2:** Techniques used to monitor stone samples in relation to type of decay mechanism

	<b>Dry weight</b>	<b>Surface hardness</b>	<b>Elastic modulus and UPV</b>	<b>Surface colour</b>	<b>Visual assessment</b>
<b>Physical</b>	A decrease indicates surface erosion and/or increase in inner space An increase indicates accumulation of salts/crusts	A decrease indicates surface erosion or decohesion An increase indicates accumulation of salts/crusts	A decrease indicates an increase in inner space (i.e. cracks or pores)		Surface erosion
<b>Chemical</b>	An increase indicates accumulation of crusts/soiling	An increase indicates accumulation of crusts/soiling		Soiling (darkening) and salt accumulation (lightening)	Soiling, dust deposition and salt accumulation at surface level
<b>Biological</b>				Biofilms (greening)	Biofilms at surface level

In addition, small and low-cost environmental sensors were attached to the stone blocks to monitor changes in surface temperature, and moisture content was measured periodically in the field (further information in section 3.3). Table 2.3 summarises the methods used for measuring moisture and surface temperature and how they have been used to address different decay processes.

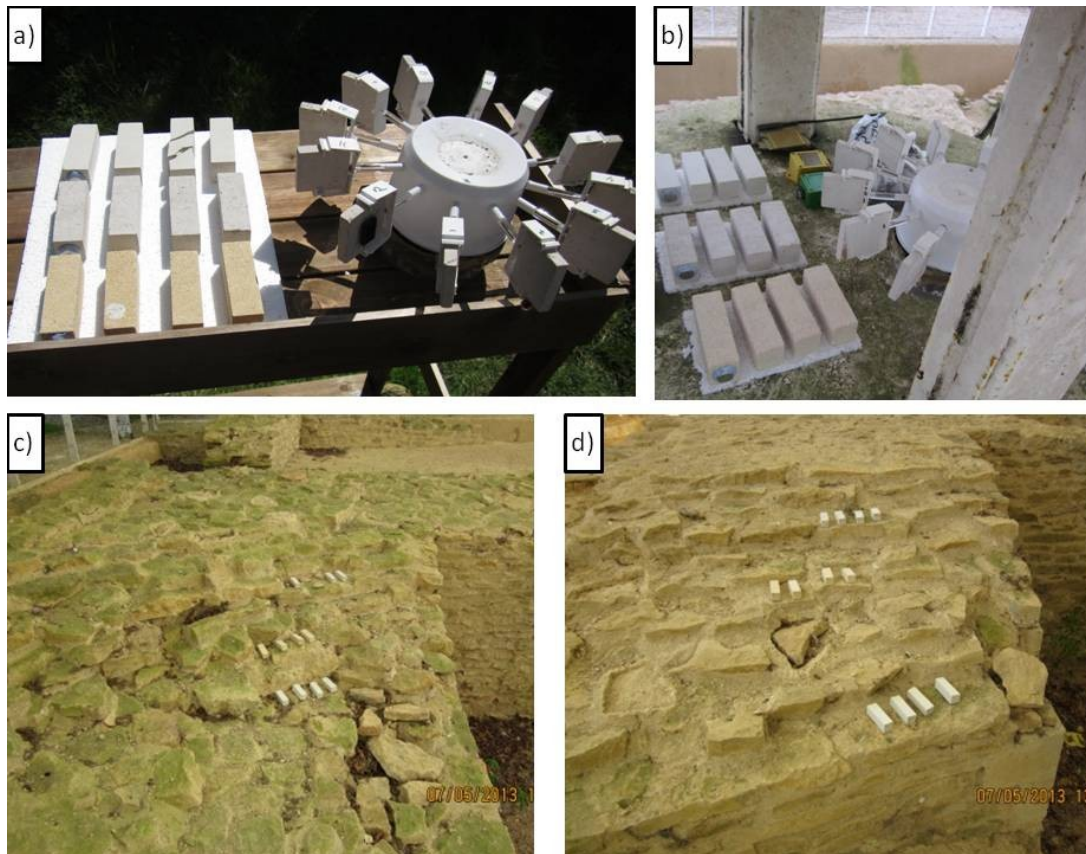
**Table 2.3:** Moisture and temperature data collection methods used in relation to the type of decay

	<b>FMW and balance</b>	<b>Hygrochrons</b>
<b>Physical</b>	Moisture content- risk for salt crystallisation and frost	Freezing cycles Temperature extremes and fluctuations
<b>Chemical</b>	Moisture content- risk for surface chemical reactions	
<b>Biological</b>	Moisture content – risk for biological growth	

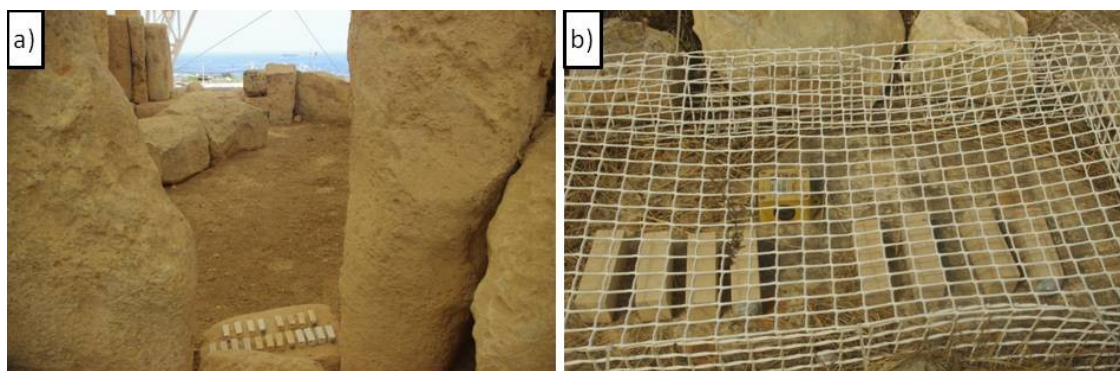
The first phase of stone decay monitoring (Witney only) is described in Chapter 6 and it was undertaken at regular intervals for a year. The locations selected for placement of the stone blocks were the following: the outside, centre and periphery of the shelter. The central part of the shelter and outside positions (Figure 2.9 a, and b) were the same as during the first phase of microclimatic monitoring (see section 2.2.2). In addition, two positions were selected for the periphery: the parts of the site located at the north-east and the south-west (Figure 2.9 c, and d). The reason was to determine the role of the shelter in the deterioration of specific areas of the limestone ruins. After the condition survey of the Bishop's Palace (Chapter 4), biofilms were seen predominantly at the north-east side of the site. In addition, wind driven rain was thought to affect the south-west area as this is the predominant wind direction in South England.

The second phase of stone decay monitoring (at Witney and in Malta simultaneously) is described in Chapter 9. At Witney, only the centre and outside were kept as monitoring positions and they were the same as in section 2.2.2 (Figure 2.9 a, and b). In Malta, stone blocks inside the shelter were placed on the ruins, slightly above the ground level at the north section of the south-west apse of the temple (Figure 2.10, a). Outside the shelter in Malta, blocks were located on the rocky ground surface, also

explained in the previous section (Figure 2.10, b). Monitoring was undertaken for a year but, in this case, measurements were not taken at periodical intervals due to logistical reasons.



**Figure 2.9:** Detailed pictures of locations where stone blocks were placed at the Bishop's Palace (Witney): a) outside the shelter (number 6), b) the centre of the shelter (number 1), c) NE (number 3) and d) SW (number 5). The numbers correspond to diagrams in section 2.2.1. Images: C. Cabello-Briones



**Figure 2.10:** Detailed pictures of locations where stone blocks were placed at Hagar Qim (Malta): a) the centre of the shelter (number 2) and b) outside (number 1). The numbers correspond to diagrams in section 2.2.1. Images: C. Cabello-Briones

The most central location possible under the shelter was selected in order to compare a protected location with an exposed one. No peripheral positions were used in the second phase (simultaneous monitoring) as site managers in Malta disapproved of the use of stone blocks because they might have been too visible. The locations and parameters measured at each site are summarised in Table 2.4 and illustrated in Figure 2.2 to Figure 2.5.

**Table 2.4:** Summary of locations where stone blocks were located at each site and phase, and the corresponding points in the diagrams in section 2.2.1

	1 <sup>st</sup> Phase (2012-2013)	2 <sup>nd</sup> Phase (2013-2014)	
	Witney	Witney	Malta
<b>Outside</b>	6	6	1
<b>Centre</b>	1	1	2
<b>Periphery</b>	3 (NE) and 5 (SW)		

#### **2.2.4. Monitoring dissolution, soiling and microbial growth using stone tablets**

An 18 month exposure trial based on Portland limestone tablets (50 x 50 x 20 mm) was used to investigate variations in specific weathering processes at the Bishop’s Palace (Chapter 7). After undertaking a condition survey (Chapter 4), dissolution, soiling and microbial growth were seen as important decay mechanisms at the site. In addition, these decay factors were also common at other archaeological sites (see Table 1.1 in Chapter 1) and could be further assessed adapting the methodology slightly.

In the literature it is possible to find a large number of studies on Portland limestone tablets used to monitor stone dissolution, soiling and microbial growth in different environments, for example A.T. Coote (1991) and H. Viles(2002), although they are

not specifically sheltered archaeological sites. Therefore, this thesis intends, firstly, to study the influence of the shelter at Witney in more detail, secondly, explore the potential of a methodology based on tablets instead of blocks to assess shelters, and finally, compare the results of these investigations with previous studies in other fields. In addition, the use of tablets allows including other analytical techniques, such as salt analysis, which is more difficult to undertake with blocks. Both non-destructive (optical examinations and changes in dry weight and surface colour) and destructive techniques (salt content) were used for this part of the project and monitored at regular intervals (Table 2.5). In addition, rainfall acidity and air pollution levels were determined and the decay rates were compared with results obtained from a large-scale UK programme (Butlin et al., 1995).

**Table 2.5:** Techniques used to monitor stone tablets in relation to type of decay mechanism

	<b>Dry weight</b>	<b>Salt analysis</b>	<b>Surface colour</b>	<b>Visual assessment</b>
<b>Dissolution</b>	Decrease			Surface dissolution
<b>Soiling</b>	Increase	Type and amount	Soiling (darkening) and salt accumulation (lightening)	Soiling and salt accumulation visible at surface level
<b>Microbial growth</b>			Greening and/or darkening	Biofilms visible at surface level

This study used small stone tablets (of 50 x 50 mm) attached to carousels, following the methodology of the Building Research Establishment for the UK programme mentioned above (Butlin et al., 1992). The tablets were located outside and under the central part of the shelter (Figure 2.9 a and b). The peripheral locations were not used due to the higher visibility of the carousels. In addition, the main focus was to compare the most protected area with a fully exposed one. This project required extending the

duration of the trial to match results with other studies, which was only possible at Witney. The locations are summarised in Table 2.6 and illustrated in Figure 2.3.

**Table 2.6:** Summary of locations where the carousels were located at the Bishop’s Palace (Witney) and the corresponding points in the diagrams in section 2.2.1

<b>1<sup>st</sup> Phase (2012-2014)</b>	
<b>Witney</b>	
<b>Outside</b>	6
<b>Centre</b>	1

### **2.3. Summary of the research design**

This project investigates the role of shelters in the preservation of limestone remains at archaeological sites by analysing data related to environmental factors of decay and decay processes over a 12-18 month period. Figure 2.11 summarises the research design.

Limestone samples were used as indicators of decay. They have been used successfully in geomorphology and have been adapted for use in this study on shelters instead of a direct monitoring of the ruins. They are an “early warning” method to detect the nature of deterioration rapidly and without the need for more intensive monitoring of the ruins. In order to provide a full picture of conditions within the shelter in comparison with the outside, both environmental dataloggers and stone samples were placed at different parts of the sites. In addition, the relevance of the data collected was maximised through comparisons between two different sites.

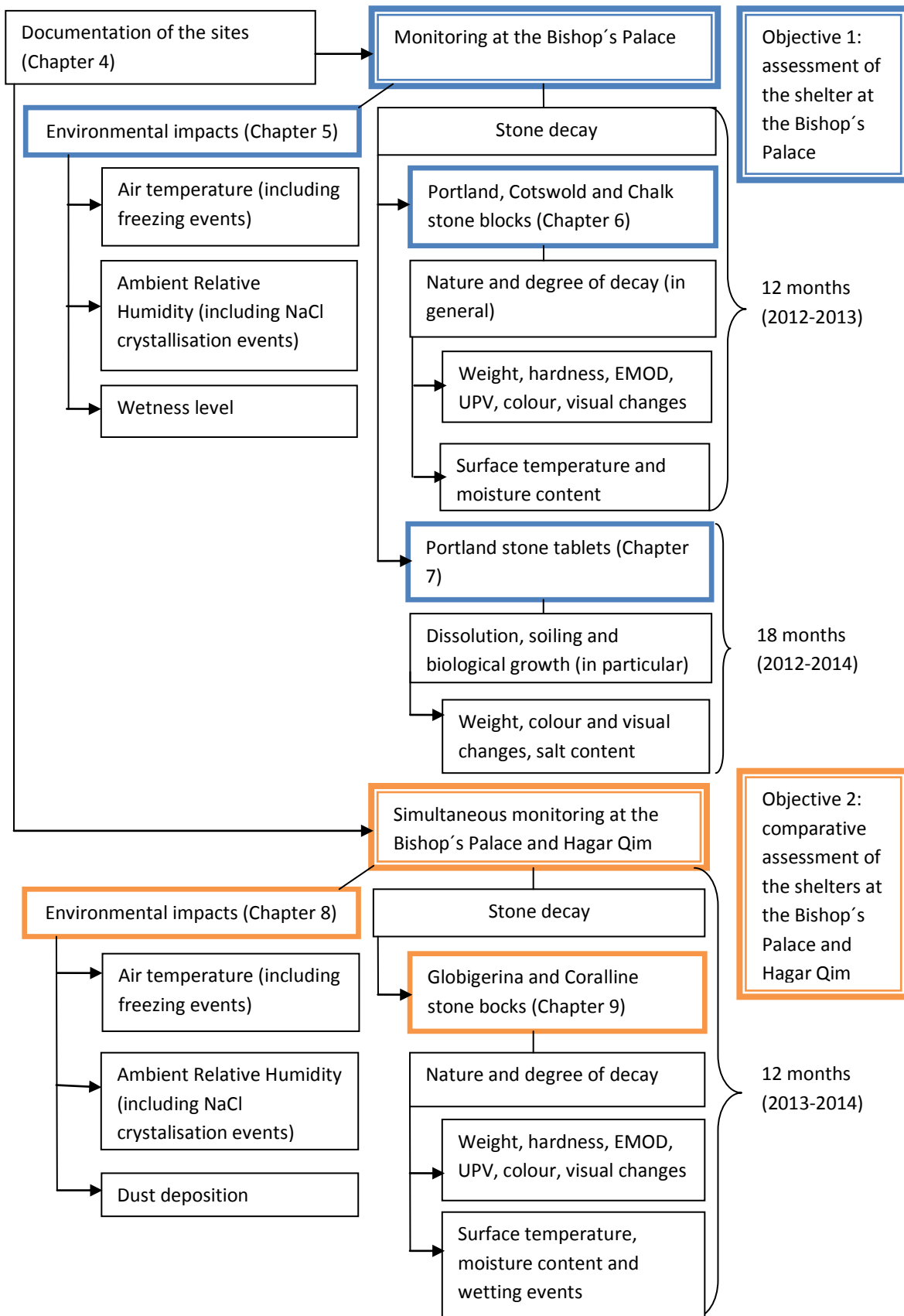


Figure 2.11: Flow chart of the research which summarises the experimental design

### **3. MATERIALS AND METHODS**

#### **3.1. Conservation state of field sites**

Visual assessments of the shelters and ruins were undertaken to determine the conservation state of the field sites. A general inspection of the shelters provided evidence of possible deficiencies in design and structure which could affect the preservation of the ruins. In addition, condition surveys of the stone remains were undertaken using standardised templates based on an international glossary of decay terms (ICOMOS International Scientific Committee for Stone ISCS, 2008). This information helped in selecting the monitoring positions and was analysed as part of an integrated monitoring program.

The three main types of surveys which have been used in the literature for effective research, conservation work and/or site management are detailed, preliminary and reconnaissance surveys (Letellier, 2007). Detailed surveys consist of accurate graphic records (between 2 and 5 mm) for highly significant building elements. They have been used mainly to record information before and after conservation activities on specific features or for creating permanent records. For example, three dimensional laser scanning technologies were used for a detailed dimensional record of eroding adobe walls of Tambo Colorado (Peru) (Addison, 2007). Preliminary surveys also include measured graphic records but with lower level of detail (approximately  $\pm 2$  cm). They are often used to define areas for further research or detailed recording. This is the case of the Buddhist temples in Spiti (India). The wall profiles were measured manually to determine levels of wall deformation and to devise a strategy for structural conservation (Sikka, 2007). Reconnaissance recording allows understanding

of the site's overall characteristics in sufficient detail to identify significant features and problematic areas. An example is the rapid assessment of the adobe buildings from the Colonial period in Los Angeles (USA). The survey intended to identify damaged structures after an earthquake and photographs of key wall elevations were used to plot crack damage (Crosby, 2007). Another example is the study of the stone statues on Rapa Nui (Easter Island). Although global positioning systems were used to record location and key features of the statues, reconnaissance recording was also used to determine structural problems and surface decay phenomena (Van Tilburg et al., 2007). In general, more time and/or more sophisticated recording tools are needed to undertake surveys with higher levels of detail, which leads to higher costs.

The condition surveys for this study were designed to determine general patterns of decay, establish possible differences between positions within the sites, and investigate any clear deterioration trend over time. The method selected was reconnaissance recording because it provides enough information to respond to the project's needs, taking into account the resources and time frame available.

Condition surveys were carried out in July 2012 and 2013 at the Bishop's Palace and in July 2013 and 2014 at the south apse of Hagar Qim. No significant change in condition was recorded at either site over the study period. The condition surveys include a qualitative estimation of the physical extent (as percentage of surface area affected by different phenomena), and severity (as degree to which the phenomenon impacts the integrity of the site) of deterioration (see APPENDIX A: CONDITION SURVEYS). This is a visual assessment based on the methodology proposed by IIA, EH and GCI to evaluate shelters over mosaics (Getty Conservation Institute, 2009, Stewart, 2008).

The main types of stone decay phenomena found at each site were determined after establishing a semiquantitative scale of deterioration. A value on a scale of 1 to 5 was connected to each type of decay phenomenon per area. A high value means that both severity and extent are high, and decay is both widespread and severe. On the other hand, when the value is low it means that decay phenomena are reduced to a specific and limited area and their severity is not remarkable (Table 3.1).

**Table 3.1:** Estimation of the degree of decay in relation to the severity and extent of the decay phenomena

Combination of severity and extent values	Degree of decay	
Both values are over 50%	High	5
One value is 30-40% and the other over 50%	Medium -high	4
One value is over 50% and the other up to 30%	High-Low	3
Both values are between 30 and 40%	Medium	3
One value is 30-40% and the other under 20%	Medium-low	2
Both values are under 20%	Low	1

### 3.2. Monitoring microclimatic conditions

Information on the likely causes of stone deterioration was obtained by comparing the microclimatic conditions inside (centre and periphery) and outside the shelter at each site. Microclimate refers to the surrounding ambient conditions which have a direct influence on the physical state of the site studied (Camuffo, 1998).

Ambient temperature and relative humidity (RH) were measured using i-button® hydrochron dataloggers (DS1923, Maxim Integrated Products, range = -20°C to +85°C and 0 to 100% RH) and surface wetness loggers with electrical impedance grids (TGP-0903, Tinytag leaf wetness logger, reading range = 0 to 100%). Relative Humidity (RH) is the ratio of the partial pressure of water vapour to its saturation vapour pressure at a prescribed temperature.

To avoid incident solar radiation artificially increasing the temperature readings, the hygrochrons placed outside were shaded with foil shields on the facing-out surfaces (Coombes, 2011). This was only possible for temperature readings. For RH, the hygrochrons placed outside were located vertically to avoid rain falling directly onto the sensors.

### **3.2.1. Data collection**

All the dataloggers (hygrochrons and surface wetness sensors) at the site were synchronized to take readings at the same time. Hygrochron dataloggers measure near-surface environmental conditions (Smith et al., 2001). They were placed inside (centre and periphery) and outside the shelters for both monitoring phases. The accuracy of the hygrochron dataloggers was verified at the start of the study. They were deployed in a desiccator with a saturated salt solution to control relative humidity. The efficiency of the sensors with high RH values was corroborated with NaCl, which keeps the environment at 75% RH, and with low RH values, with MgCl at 33% RH. The vessels were placed in an environmental cabinet (Sanyo-FE 300H/MP/R20, range = -20 to 100°C) for 24 hour cycles of low temperature (12°C) and high temperature (26°C). The accuracy of the hygrochrons was confirmed to be  $\pm 0.5\%$  RH and  $\pm 0.5^\circ\text{C}$  with higher accuracy at higher temperatures. During the first phase of the monitoring, measurements were taken every 15 min and during the second phase, every hour. The decision to reduce the number of data points was taken after analysing the first year's data. Data obtained every hour proved to be enough to obtain significant results.

The RH range stated by the hygrometron provider is 0-100%. However, values up to 120% were recorded. The saturation drift compensation provided by the manufacturer was applied (Equation 3.1). This depends on the amount of time the loggers are exposed to over 70% RH environments. In this study, because the sensors were exposed to very humid conditions for a very long time, there were humidity readings over 100% even after the correction factor was applied. Therefore, this compensation was not used and only data up to 100% RH was taken into account.

**Equation 3.1:** HScorr= humidity readings after compensation is applied. HTcorr= humidity reading at the end of the Nth hour; ARH<sub>k</sub> = humidity reading of the kth hour that the device is continuously exposed to 70%RH or higher; T<sub>k</sub>= temperature reading of the kth hour that the device is continuously exposed to 70% RH or higher; N=number of hours that the device is continuously exposed to 70%RH or higher

$$HScorr = HTcorr - \sum_{K=1}^N \frac{0.0156 \times ARH_K \times 2.54^{-3502 \times K}}{1 + (T_K - 25)/100}$$

Leaf wetness loggers were used in the first phase of the monitoring as a proxy for surface wetness occurrence. They were placed only in two positions (outside and under the central part of the shelter). These sensors were originally designed for agricultural purposes. They consist of artificial leaves (electrical impedance grids) calibrated by the manufacturer in arbitrary units of percent wetness based on the measured resistance (Table 3.2). As water droplets lower the sensor resistance, the method can be used to compare the level of wetness and duration of the events at the different locations. The accuracy according to the manufacturer is 0.5% (reading resolution) and ±2 units (sensor accuracy).

**Table 3.2:** Equivalence between wetness percentage and grid electrical resistance established by the manufacturer

Wetness	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Grid resistance (KΩ)	8200	2200	1160	720	478	326	221	144	86	40	3
	Dry										Wet

After having some difficulties analysing data from the wetness loggers during the first phase (explained in Chapter 5), the information on wetting events obtained from wetness loggers was validated with time-lapse cameras (TLC 200, Brinno, image sensor=1.3 MP) during the second phase of monitoring. The sensors and cameras were placed inside and outside the shelters over a week at each site in October 2013 and were synchronised to record information every 10 minutes. The cameras provide a continuous visual monitoring of wetting events which can be compared with data from wetness loggers.

In addition, a considerably great amount of dust was found over the surface of the wetness logger inside the shelter during the first phase. Dust deposition has been related to problems with shelter design in the literature (Table 1.1), so the amount of dust deposited on horizontal surfaces inside and outside both shelters was considered worthy of study during the second phase. Transparent 10x10 cm film patches (d-c-fix® self-adhesive vinyl film) were attached to rigid supports and located horizontally in the central part of the shelter and outside at both sites during the same period: one week in October 2013 and three months between October 2013 and January 2014. The adhesive part of the patch was left exposed and a small area (10 x 3.5 cm), which remained covered, was used as a control. The amount of dust deposited on the surface was calculated with a technique based on image processing, also used in other heritage studies (Thornbush and Viles, 2004, Proietti et al., 2014). The method employed in this study was developed by the Optics Department of Complutense University in Madrid. Pictures of the samples were taken with a camera (DFK 51BU02.H, Imaging Sources, sensor Sony CCD, sensibility 0.15 lx) set with a fixed exposure. An integrating sphere light source, which provides spatially uniform

luminance, was placed on the other side of the film. Mean opacity values were calculated by studying the amount of light that passed through the samples and in relation to the controls.

### 3.2.2. Data handling and aggregation

Environmental data from Witney and Malta (for the first and second monitoring phases) were summarised as means and standard deviations and compared between different locations taking into account they were recorded simultaneously. Occasionally some hygrochrons stopped working or malfunctioned giving constant values for more than 24 hours. These readings were not taken into account for the analysis. However, due to the amount of data collected, the small number of missing data points has not affected the results. The total number of readings per location during the first monitoring phase was 34435 (at Witney, measured every 15 min) and during the second monitoring phase (measured every hour), it was 8754 at Witney, and 8891, in Malta. Table 3.3 summarises the percentage of time the hygrochrons worked without incident.

**Table 3.3:** Mean percentage of time per location and site with valid temperature readings during the year of record

First phase (2012-2013)			Second phase (2013-2014)			
Witney			Witney		Malta	
Ambient	Stone surface	Wall surface	Ambient	Stone surface	Ambient	Stone surface
88.33%	80.34%	86.77%	91.97%	91.13%	87.07%	82.82%

For this study, the seasons have been defined as corresponding to the following periods (based on the astronomical calendar): spring from 21st March to 20th June; summer, from 21st June to 20th September; autumn between 21st September to 20th December and winter, from 21st December to 20th March, all dates inclusive.

Temperature and RH daily maximum and minimum values and diurnal differences between maxima and minima in all positions were used to calculate seasonal means and standard deviations, and monthly means. In addition, monthly means of the number of days when temperatures dropped below 0°C were used to estimate the risk from freeze-thaw cycles. The number of times the RH line crossed the NaCl threshold (75% RH) was used to calculate the number of salt crystallisation-dissolution events per day in every location (hereafter salt crystallisation events). NaCl crystallises at 75% RH independent of temperature, whereas phase transitions in hydrated salts, such as sodium sulphate, are always sensitive to both RH and temperature (Grossi et al., 2011). These thresholds have been frequently used in other weathering studies to determine potential frost and salt weathering events (Brimblecombe et al., 2006, Sabbioni et al., 2010). Additionally, synthetic representative days were profiled using hourly means of monthly RH and temperature values from the three hygrochrons on the wall at Witney. This allowed determining at what time of the day maximum and minimum values were recorded.

Similarly, the hourly wetness percentage means per month in the central part of the shelter and outside at Witney were used to estimate when condensation typically occurred in these locations. In addition, monthly means of the daily wetness percentage mean in the centre and outside the shelter at Witney were calculated to estimate seasonal variations.

A theoretical insolation analysis of the Bishop's Palace at Witney was carried out using the Autodesk Ecotect® Analysis programme. Total annual solar radiation inside the shelter was modelled using information on incident light collected with a light meter

placed outside and just beneath the lightweight membrane in November 2012 (YK-2005LX, Lutron, ISO-9001, range = 200/2000/20000/100000 Lux, accuracy =  $\pm 4\%$ +2 dgt). The light meter helped to determine the light transmittance capacity of the shelter. In addition, representative days in summer (one cloudy and the other sunny) were selected to explore in more detail the role of the shelter at the Bishop's Palace in reducing the effects of solar radiation.

The percentage of time between August 2012 and July 2013 when there should be condensation on the top, middle and bottom part of the wall and the periphery, centre and outside the Bishop's Palace shelter was calculated from the ambient temperature and RH measurements (hygrochrons). Condensation takes place when the difference between the dew point temperature (Tdp) and the surface temperature is positive. Dew point temperature is the temperature at which the water vapour in air at constant barometric pressure condenses into liquid water at the same rate at which it evaporates (Camuffo, 1998). The formula used to calculate the dew point is the Magnus formula, which only considers RH and air temperature (Equation 3.2), while other more complicated formulae also take into consideration data not collected in this study, such as saturated water pressure or wet bulb temperature.

**Equation 3.2:** Magnus formula. Constants  $b=17.67$  and  $c=243.5^{\circ}\text{C}$  (Bolton, 1980)

$$T_{dp} = \frac{c\gamma(T, RH)}{b - \gamma(T, RH)}; \gamma(T, RH) = \ln\left(\frac{RH}{100} \exp\left(\frac{bT}{c + T}\right)\right) = \ln\left(\frac{RH}{100}\right) + \frac{bT}{c + T}$$

The percentage of the total amount of time when condensation occurred was estimated for Witney after reducing the dataset to those days when there were values for all the positions.

### **3.2.3. Statistical analysis**

In order to determine if there were significant differences in the microclimatic conditions between the monitoring locations, a varied range of advanced statistical analysis tests were undertaken. Non-parametric Mann-Whitney-Wilcoxon tests were used to compare daily means and standard deviations of temperature and RH at different locations at Witney and in Malta. This test helped to determine if one location had significantly greater values than another. Mann-Whitney-Wilcoxon tests were also used for wetness percentages at Witney.

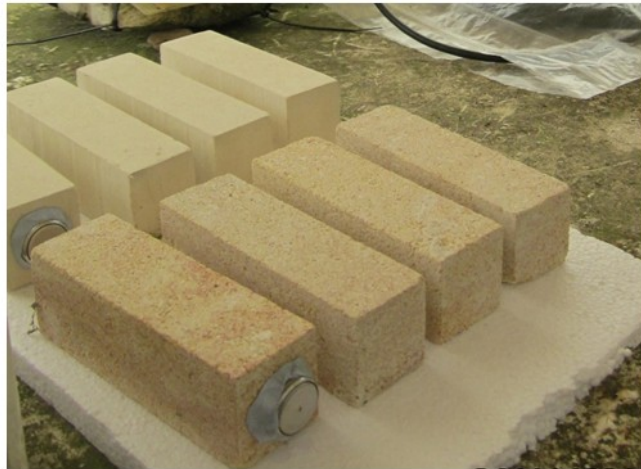
A multilevel linear model with day as random effect was fitted for the diurnal temperature range at Witney and in Malta to find out if temperature differences depended upon position. Multilevel models are particularly appropriate for research designs where data is organised at more than one level. Since there was within-Day correlation, the data have a 2-level structure. A linear model with day as random effect was also fitted to find out if daily wetness mean at Witney depended on temperature mean, RH mean and position of dataloggers. Transformations of the different datasets were carried out to produce acceptable normality and stability of variance in the model residuals. In addition, the number of times the temperature went below 0°C per day was fitted as the response in a 2-level Poisson Generalised Linear Model (GLM). Position of the dataloggers and daily minimum temperature were used as explanatory variables. Poisson GLM allows for Poisson counts rather than continuous normal responses.

### **3.3. Monitoring deterioration with stone blocks**

Four replicates of locally available stones (see section 3.3.1) were placed at each monitoring location (section 2.2.3). For the first monitoring phase (Witney only), blocks were located inside (the central part under the shelter, north-east and the south-west) and outside the shelter. For the second phase of monitoring (at Witney and in Malta), blocks were located under the central part of the shelter and outside. Changes in the following stone properties were studied: weight, elasticity, hardness, ultrasonic pulse velocity (UPV), colour and general appearance (as macroscopic and microscopic surface changes) in addition to moisture content of the stone blocks and surface temperature, monitored with hygrometers.

Hygrometer loggers were attached to the short vertical face of stone blocks to obtain information on surface temperature. They were placed on one of the stone blocks per set per position and all faced the same direction (north). A pressure-sensitive adhesive made of synthetic rubber (Blue-tack, Bostik), reversible and non-destructive, was used to keep hygrometers in place. It was located in a ring-shape around the loggers to allow full contact between it and the stone surface of the ruins and stone blocks (Figure 3.1). The samples under the centre of the shelter and outside at Witney were placed on Styrofoam to limit any influence of the support materials (see Figure 3.1). The NE and SW samples were placed directly on the remains, without an isolating intermediate layer between remains and samples, which could affect visitors' experience and conservation of the ruins. There are some potential impacts on the use of different supports. For example, the intermediate layer might affect the wetness levels or water movement in the samples. However, there were no significant

differences in changes in stone properties between both NE and SW samples and the samples under the central part of the shelter (see Chapter 5), which indicates that the differences in this exposure method are not important.



**Figure 3.1:** Stone blocks located under the central part of the shelter at Witney. Hygrochrons were attached to the vertical face of one block per set with synthetic rubber in a ring-shape

### **3.3.1. Selection of stone types**

The stone samples were cut from five types of fresh quarried bioclastic limestone. For the first phase at Witney, three types of limestone were selected: Portland, Cotswold and Chalk. Portland stone, from the Upper Jurassic period, is quarried on the Isle of Portland, Dorset. It is considered to be relatively durable. Famous buildings made with this stone type include the British Museum and the Bank of England in London. Portland limestone weathers at a rate of between 3 and 4 mm per 100 years but it could be greater if exposed to high concentrations of sulphur dioxide or severe frost (Building Research Establishment, 2001). Cotswold limestone is a Middle Jurassic limestone quarried from the Cotswold Hills. It has traditionally been used as building stone in South Central England, such as Hailes Abbey (Gloucestershire). The strength is towards the lower end of the range for limestones (Building Research Establishment,

2001). Typical decay of this type of stone is surface loss through contour scaling and flaking due to salt weathering or frost (Smith et al., 2001). Portland and Cotswold limestones are considered oolitic limestones as they are formed from ooids, spherical grains composed of concentric layers (Horsfield and Oxfordshire Geology Trust, 2011). On the other hand, Chalk is a Cretaceous limestone formed from the skeletal elements of minute planktonic green algae in circular groupings called coccoliths. The characteristic white colour is the result of the low iron and clay content in comparison with many limestones. It was used extensively in medieval churches such as Westminster Abbey. The blocking of the porous by salts lead to powdering and flaking of the surface. Further deterioration occurs through multiplane cracking due to differential thermal movement of the layers (Odgers et al., 2012). Chalk is one of the most susceptible stones to frost, mainly because it is soft, with low density and high porosity (Mortimore et al., 2004).

For the second phase at Witney and in Malta, two local Maltese limestones were selected: Globigerina and Coralline limestones. Globigerina is a pure limestone (calcite >92%) containing small amounts of quartz, feldspars, apatite, glauconite, and clay minerals (Cassar and Vannucci, 1999). It consists of a planktonic foraminiferal limestone from the Oligo-Miocene, quarried for this study from Gharb on Gozo Island. It is a very soft, fine-grained and homogeneous bioclastic limestone used as the main local building material in Malta and on Gozo. Examples of Globigerina can be seen in Hagar Qim and the fortified city of Valletta. There are two types of Globigerina limestone, Franka and Soll. Soll has been found to be richer in the non-carbonate portion, which also partially blocks the pores, reducing total porosity and increasing the percentage of small pores (Diana et al., 2014, Cassar, 2002). Soll is more easily and

rapidly deteriorated, mainly through the form of alveolar weathering, whereas Franka resists salt weathering better. However, it is very difficult to distinguish them visually prior to weathering (Cassar, 2004, Cassar, 2010). Coralline limestone contains broken fragments of coralline algae cemented together with calcite crystals. It is much harder than Globigerina and therefore more difficult to work. The samples used in this research are of Lower Coralline Limestone from the Lower Miocene period. It was used to build some Neolithic temples such as Ggantija and Mnajdra and some other buildings like the medieval Citadel in Gozo (Cassar, 2010). It contains over 95% of calcite and small amounts of quartz, feldspars and some clay minerals and it is characterised by a low porosity (Cassar and Vannucci, 1999). It typically weathers in the form of granular disintegration.

**Table 3.4:** Physical properties of the stone samples used during the first monitoring phase. The values obtained are in line with previous research (Bell, 1993, Building Research Establishment, 2001, Hancock, 1975, Leary, 1983)

Standard test	Property	Portland limestone	Cotswold limestone	Chalk
BS EN 3755:2008	Water absorption at atmospheric pressure ( $A_b$ )	6.96%	12.52%	18.51%
BS EN 1925:1999	Water absorption by capillarity (C1) - perpendicular to the planes of anisotropy	226.23 $\text{g/m}^2 \cdot \text{s}^{0.5}$	157.96 $\text{g/m}^2 \cdot \text{s}^{0.5}$	221.98 $\text{g/m}^2 \cdot \text{s}^{0.5}$
	Water absorption by capillarity (C2) - parallel to the planes of anisotropy	231.54 $\text{g/m}^2 \cdot \text{s}^{0.5}$	160.39 $\text{g/m}^2 \cdot \text{s}^{0.5}$	241.23 $\text{g/m}^2 \cdot \text{s}^{0.5}$
BS EN 1936:2006	Open porosity ( $P_o$ )	14.46%	22.02%	31.17%
BS EN 1936:2006	Apparent density ( $\rho_b$ )	2100 $\text{Kg/m}^3$	2375 $\text{Kg/m}^3$	1773 $\text{Kg/m}^3$

**Table 3.5:** Physical properties of the stone samples used during the second monitoring phase at Witney. WACC test results were not conclusive. Therefore they were omitted from this table

Standard test	Property	Globigerina limestone	Coralline limestone
BS EN 3755:2008	Water absorption at atmospheric pressure ( $A_b$ )	14.75%	3.36%
BS EN 1936:2006	Open porosity ( $P_o$ )	31.18%	11.01%
BS EN 1936:2006	Apparent density ( $\rho_b$ )	1789.72 $\text{Kg/m}^3$	2356.52 $\text{Kg/m}^3$

To complete the information on the selected stone types, standard tests (water absorption, open porosity and apparent density) were carried out at the Oxford University Rock Breakdown Laboratory. The results are shown in Table 3.4 and Table 3.5. The physical properties of the British limestones are very similar to the values obtained for Portland Whitbed Limestone, Cotswold Hill Quarry cream and Cambridgeshire Clunch by the Building Research Establishment (2001). The results obtained for the Maltese limestones are also in line with previous research carried out on these stone types (Cassar and Vannucci, 1999, Rothert et al., 2007).

These stone types were selected because they are local limestones, which are easy to obtain. In addition, the results can be applicable not only to the case study sites but also to other historical buildings in the area. Because the same types of stone were used simultaneously in Malta and at Witney in the second phase, the data can be used to compare decay in different climates and could increase understanding of how environment inside and outside the shelters affects the weathering process. In addition, these stone types represent different degrees of vulnerability to decay.

Low water absorption coefficients, low open porosity values and high apparent density indicate that the stone is less porous and more durable. The more strongly a stone is bonded together the greater its resistance to weathering (Bell, 1993). The porosity determines the amount of water it can hold, so the more porous the stone is the more susceptible it is to chemical attack and physical decay such as salt and freezing weathering. In addition, limestones with a coarse pore structure tend to be more durable than stones with finer pores because they tend to achieve higher saturation levels (Ross et al., 1991). Cotswold, Portland and Coralline limestones are less porous

(with lower water absorption and open porosity coefficients) and with higher apparent density (Table 3.4 and Table 3.5). Therefore, they are stronger and tend to be less sensitive to weathering and decay. The water absorption coefficient by capillarity indicates that Chalk is a more fine-grained stone than Cotswold and Portland limestone, and Cotswold stone has relatively larger pores than Portland (Table 3.4). Therefore, a greater degree of weathering is expected in Chalk samples, which are less dense and with more and thinner pores. On the other hand, higher level of resistance to decay is expected for Portland stone, which has high density, less number of open pores than Chalk and Cotswold limestone, although these are relatively thin, and a better cemented grain structure. The tests undertaken in Globigerina limestone are very similar to Chalk and in Coralline to Cotswold and Portland limestones (Table 3.5). Therefore, expected behaviours of these stones are in line with the explanation above.

### **3.3.2. Data collection**

Change in stone block's properties was documented periodically. For the first phase, the exposure periods were 0, 3, 9 and 12 months to detect seasonal changes in weight, elasticity, ultrasonic pulse velocity and surface colour. Pictures were taken and changes in hardness recorded only at 0 and 12 months, in the last case to avoid any excessive surface deterioration related to repeated impact measurements. The second monitoring phase was a before and after study (0 and 12 months). During both phases, the stone blocks were taken to the Oxford Rock Breakdown laboratory after each exposure interval and the tests were carried out on the top horizontal surface of the samples under laboratory conditions. Given that the results could depend on the degree of water saturation in the blocks, the stone samples were dried in an oven until

they reached a constant weight at the beginning of the experiment and after each exposure period. Portland, Cotswold and Coralline limestone samples were dried out at  $105\pm 5^{\circ}\text{C}$  following BS EN guidelines, whilst Chalk and Globigerina samples were dried at  $40\pm 5^{\circ}\text{C}$  to avoid any damage to these more vulnerable stone types. Before undertaking the tests, they were left in a desiccator at ambient temperature for two days. In addition, field measurements on the moisture content of the stone blocks were carried out every month at Witney during a two year period and every three months in Malta for one year.

Control blocks were left in a sealed container with silica gel in the Oxford Rock Breakdown laboratory during the time the other samples were exposed. They were tested with the stone blocks after each exposure period to check for inherent change in stone properties over time. Three control blocks per stone type were used. In addition, the calibration set provided by the manufacturer for each piece of equipment was also used prior to any experiment to check for any equipment drift.

### **3.3.2.1. Weight**

Monitoring of weight changes can be used to measure the extent of material detachment/deposition and the amount and rate of stone weathering (Chevalier, 1953, Trudgill, 1975, Butlin et al., 1992, Stefanis et al., 2009).

For this study, weight change was quantified as percentage of initial dry weight as indicated below:

$$\%W_{dry} = \frac{(\text{dry weight after exposure} - \text{dry weight before exposure})}{\text{dry weight after exposure}} \times 100$$

A balance (Sartorius AG Göttingen,  $\pm 0.01$  g accuracy) was used for this purpose.

### ***3.3.2.2. Elasticity***

The changes in elasticity were calculated using an impulse excitation technique device (M-K5, Grindosonic), a non-destructive method for measuring the dynamic modulus of elasticity. The stone blocks were subjected to a light mechanical impulse which produced a transient mechanical vibration. The dynamic modulus of elasticity (EMOD) of the material is the ratio of the applied stress (load) to the amount of strain (deformation) under vibratory conditions and it is expressed in GPa. EMOD is determined through the frequency of the vibration, the mass of the object and its shape and dimensions. In order for the calculations to be accurate, the samples were cut with a length to thickness ratio of three (Allison, 1988). EMOD values depend on the fabric and structure of the stone (e.g. grain size and porosity) (Prick A., 1997). Therefore, changes in EMOD values reflect changes in porosity and the development and microcracks and other faults.

### ***3.3.2.3. Hardness***

An electronic rebound hardness testing device (Equotip 3, Proceq) was used for monitoring change in stone surface hardness (Aoki and Matsukura, 2007). The Equotip consists of a hard sphere which impacts against the surface of the samples. The velocity of the impact and the rebound phase is measured by the induction voltage generated (Viles et al., 2011). The hardness value is expressed as a Leeb Hardness value (HL), which is the ratio of the rebound velocity to the impact velocity multiplied by 1000. Changes in, for example, density, porosity and surface roughness can affect the hardness values. A pilot study was carried out in advance for defining the appropriate sample size following the methodology of (Viles et al., 2011). Chalk,

Globigerina limestone and Portland stone have a more homogenous surface than the other stone types and more consistent values were obtained for them in the pilot study. It was determined that 18 single impacts for Chalk and Globigerina stone and 27 for Portland limestone would be enough for a good sample size. On the other hand, more than 100 impacts would be necessary for Cotswold and Coralline stones because they are much more heterogeneous. However, the surface of the samples is too small for such an amount. Taking into account that at least a distance of 3 mm should be left between impacts and between impacts and stone edges (according to the manufacturer), 36 single impacts were undertaken, which are the maximum possible number for that surface. The median of the hardness readings in each stone block was used to summarise the data.

#### ***3.3.2.4. Ultrasonic pulse velocity (UPV)***

The velocity of ultrasound waves through the stone blocks (m/s) can be used to calculate change in void space and to estimate the degree of physical degradation in a non-destructive way. The decrease of ultrasonic velocities corresponds to an increase in porosity and decrease in density (Heinrichs and Fitzner, 2007). The ultrasonic testing equipment (Pundit Lab, Proceq) was used with 54 KHz transmitters placed on either side of the stone blocks (longitudinal direction). Four measurements were taken per stone block and the median was used for the data analysis.

#### ***3.3.2.5. Colour***

Colour changes were measured with a spectrophotometer (CM-700d, Konica Minolta) and the results were expressed using the International Commission on Illumination

(CIE)  $L^*a^*b$  system. This is an international standard for colour measurement where the colour difference ( $dE^*ab$ ) is stated as a single numerical value.

$dE^*ab = [(dL^*)^2 + (da^*)^2 + (db^*)^2]^{1/2}$ , where:

$dL^* = L^*_2 - L^*_1$  difference in lightness/darkness value

$da^* = a^*_2 - a^*_1$  difference on red/green axis

$db^* = b^*_2 - b^*_1$  difference on yellow/blue axis

$L^*$  indicates lightness and  $a^*$  and  $b^*$  are the chromatic coordinates of the colour space.

This non-destructive technique has been used extensively for stone weathering studies (Viles et al., 2002, Grossi et al., 2003, Thornbush and Viles, 2004). The measurement area used was MAV ( $\Phi 8$  mm/ $\Phi 11$  mm), the illuminant D65, the viewing system  $di:8^\circ$  (diffused illumination,  $8^\circ$  viewing angle) and the illumination SCE (specular component excluded). Ten measurements per stone block were taken on different points of the top horizontal surface and the mean was used to summarise the data set.

### ***3.3.2.6. Macroscopic and microscopic surface changes***

Pictures of each block were taken at the beginning of each monitoring phase and after twelve months of exposure with a DSLR camera (Pentax K-x) and a 35x optical microscope (VMS-001, Veho USB microscope) used under similar conditions in the laboratory. By using this method, morphological characteristics of the surface can be examined, at macroscopic and microscopic level (Moropoulou et al., 1996). A template was made to relocate the exact point on the stone surface after a year of exposure.

### ***3.3.2.7. Environmental causes of decay in stone blocks***

Moisture content of the stone blocks was recorded frequently at different times of the year by changes in weight (field balance OHAUS Compact Series Scale,  $\pm 0.1$ g accuracy)

and using a hand held capacitance-based moisture content meter (FMW-T, Brookhuis). The moisture meter, designed to determine wood moisture, was placed lengthwise on the top surface of each stone sample and configured to measure to a depth of 20 mm, as it recommended by Eklund et al. (2013). The results were used to compare the moisture content of the different samples and of the same sample at different dates. Diurnal temperature ranges and the number of times surface temperature dropped below 0°C per day were used to estimate the risk of decay due to temperature fluctuations and freeze-thaw cycles respectively.

### **3.3.3. Data handling and aggregation**

Data from all techniques described in section 3.3.2 was checked for outliers and averages calculated for hardness, UPV and colour. The information from the change in properties is presented as raw data and also as means and standard deviations of the four replicates per same stone type and location. In addition, the reflectance (%) in relation to each wavelength for specific replicates was studied for colour change. Additionally, monthly mean values were calculated for daily surface temperature ranges and the number of times per day surface temperature went below 0°C.

The means and standard deviations of the control blocks for each property and stone type are presented below (Table 3.6). These values refer to the intrinsic characteristics of each stone type. In evaluating change over time in these properties during the field monitoring phases, only differences greater than the standard deviations shown in Table 3.6 were taken as significant.

**Table 3.6:** Means (n=3) and standard deviations (in brackets) of weight loss (as percentage of initial dry weight) and elasticity (EMOD), hardness (HL), ultrasonic pulse velocity (UPV) and colour change (dE\*ab) of the control blocks after a year

	<b>%Wdry</b>	<b>EMOD (GPa)</b>	<b>HL</b>	<b>UPV (m/s)</b>	<b>dE*ab(D65)</b>
<b>Chalk</b>	-0.05 (0.01)	11.1 (0.9)	182.4 (8.2)	2570.8 (41.0)	0.18 (0.07)
<b>Cotswold</b>	-0.02 (0.01)	13.5 (0.5)	304.2 (12.7)	2853.4 (111.3)	0.38 (0.26)
<b>Portland</b>	-0.02 (0.00)	26.4 (0.4)	337.2 (23.6)	4064.7 (41.3)	0.22 (0.03)
<b>Globigerina</b>	-0.07 (0.01)	12.0 (0.4)	270.6 (19.0)	2886.5 (12.4)	0.43 (0.18)
<b>Coralline</b>	-0.03 (0.01)	19.7 (0.5)	273.3 (22.6)	3644.5 (252.7)	1.33 (0.56)

### 3.3.4. Statistical analysis

For the first monitoring phase, three-way ANOVA tests were used to determine if there were statistically significant differences in weight change means, EMOD means, HL values and UPV means between positions, time of exposure and stone type. Post-hoc all pairwise multiple comparison tests (Holm-Sidak method) were used to isolate which group(s) differ from the others. In addition, two-way ANOVA tests were undertaken for dry weight (%Wdry) and overall colour (dE\*ab) values in order to obtain more detailed information on changes between same stone type.

For the second phase of monitoring, two-way ANOVA tests for the same stone type and site were undertaken to define if there were statically significant differences in dry weight, EMOD, HL, UPV and dE\*ab values between positions and time of exposure. Additionally, three-way ANOVA tests were undertaken to evaluate if there were statistically significant differences in dry weight (%Wdry) and overall colour (dE\*ab) changes between positions, sites and types of stone. These analyses were also complemented with post-hoc all multiple comparison tests (Holm-Sidak method).

In addition, a multilevel linear model with day as random effect for diurnal surface temperature ranges was undertaken to find out if the differences between positions,

stone types and sites were statistically significant. The number of times stone surface temperature went below 0°C per day was fitted as the response in a Poisson Generalised Linear Model (GLM) with position, stone type and daily minimum temperature as explanatory variables.

### 3.3.5. Validation of the dataset

Statistical analysis tests were carried out to establish if there were significant differences between the control and exposed blocks. The purpose was to determine if the changes in stone properties after a year of exposure were due to weathering and not due to natural, inherent variability of the stone types.

For the first monitoring phase, three-way ANOVA tests indicate that there were statistically significant differences in initial dry weight ( $F = 72.05$ ,  $DF=4$ ,  $P<0.001$ ), EMOD ( $F=56.87$ ,  $DF=4$ ,  $P<0.001$ ) and  $dE^*ab$  ( $F = 72.68$ ,  $DF=4$ ,  $P <0.001$ ) between positions (outside, under the shelter, south-east, north-west and controls).

**Table 3.7:** Results of the multiple comparisons tests on dry weight change (%Wdry), colour change ( $dE^*ab$ ) and EMOD in the exposed samples at different locations versus control group (Holm-Sidak method). Overall significance level = 0.05. Comparisons for factor: Position

	Comparison	Diff of Means	t	P	P<0.050
Weight	Control vs. Outside	0.507	16.692	<0.001	Yes
	Control vs Centre	0.261	8.576	<0.001	Yes
	Control vs. NE	0.233	7.662	<0.001	Yes
	Control vs. SW	0.180	5.908	<0.001	Yes
$dE^*ab$	Control vs. Outside	2.843	16.888	<0.001	Yes
	Control vs. NE	1.444	8.574	<0.001	Yes
	Control vs. SW	1.425	8.466	<0.001	Yes
	Control vs. Centre	1.116	6.626	<0.001	Yes
EMOD	Control vs. NE	1.133	8.123	<0.001	Yes
	Control vs. Centre	1.121	8.033	<0.001	Yes
	Control vs. Outside	0.556	3.989	0.002	Yes
	Control vs. SW	0.099	0.711	0.487	No

Post-hoc multiple comparison tests (Holm-Sidak method) showed that overall weight and colour changes and EMOD values were significantly higher for most of the exposed samples in comparison to controls after 3, 6 and 12 months (Table 3.7). This suggests that handling and storage of the control blocks did not affect the stone properties significantly as has also been shown by Inkpen (1995) and the main cause of the change in the stone blocks is the microenvironment to within they were exposed during the study. However, two-way ANOVA tests showed that there were no significant differences in hardness values between positions ( $F= 0.516$ ,  $DF=4$ ,  $P=0.727$ ) in Chalk, Cotswold and Portland samples after a year of exposure, and for UPV, it depended on the type of stone (Table 3.8). This means that changes in hardness and UPV were not as good indicators of stone weathering as the other properties mentioned above in this case.

**Table 3.8:** Results of the multiple comparison tests on UPV between positions and the control group after a year (Holm-Sidak method). Overall significance level = 0.05. Comparisons for Position within Stone type

	Comparison	Diff of Means	t	P	P<0.050
Position within Chalk	Control vs. NE	132.438	1.207	0.658	No
	Control vs. OUT	100.687	0.918	0.744	No
	Control vs. Centre	84.063	0.766	0.696	No
	Control vs. SW	59.813	0.545	0.589	No
Position within Cotswold	Control vs. NE	365.500	3.332	0.008	Yes
	Control vs. SW	308.000	2.808	0.024	Yes
	Control vs. Centre	199.875	1.822	0.148	No
	Control vs. Outside	24.625	0.225	0.824	No
Position within Portland	Control vs. NE	73.375	0.669	0.941	No
	Control vs. Centre	72.125	0.658	0.886	No
	Control vs. Outside	62.250	0.568	0.818	No
	Control vs. SW	30.750	0.280	0.781	No

For the second monitoring phase, three-way ANOVA tests indicate that the difference in EMOD ( $F=0.763$ ,  $DF=2$ ,  $P=0.477$ ) and UPV ( $F=0.894$ ,  $DF=2$ ,  $P=0.422$ ) in *Globigerina* and Coralline samples at the different locations at Witney (outside, under the shelter and controls) before and after a year of exposure were not statistically significant. In addition, the differences in hardness depended on the type of stone. Post-hoc multiple comparison tests (Holm-Sidak method) showed that controls differed from sheltered ( $t=3.004$ ,  $P=0.005$ ) and unsheltered ( $t=3.066$ ,  $P=0.008$ ) Coralline samples but not from *Globigerina* samples either inside ( $t=0.713$ ,  $P=0.730$ ) or outside the shelter ( $t=0.187$ ,  $P=0.852$ ). For Malta, three-way ANOVA tests shows that there are no significant differences in EMOD ( $F=1.762$ ,  $DF=2$ ,  $P=0.193$ ), UPV ( $F=1.762$ ,  $DF=2$ ,  $P=0.193$ ) or hardness values ( $F=2.516$ ,  $DF=2$ ,  $P=0.095$ ) between controls and exposed Coralline and *Globigerina* samples before and after a year.

**Table 3.9:** Results of the multiple comparisons tests on  $dE^{*ab}$  and dry weight change (%Wdry) between positions (outside the shelter, under the central part of the shelter and the control group) (Holm-Sidak method). Overall significance level = 0.05. Comparisons for Position within Site

		Comparison	Diff of Means	t	P	P<0.050
$dE^{*ab}$	Malta	Control vs. Outside	12.438	18.423	<0.001	Yes
		Control vs. Centre	6.152	9.113	<0.001	Yes
	Witney	Control vs. Outside	4.067	8.520	<0.001	Yes
		Control vs. Centre	1.006	2.108	0.042	Yes
Weight	Malta	Control vs. Centre	0.037	1.121	0.467	No
		Control vs. Outside	0.032	0.976	0.336	No
	Witney	Control vs. Outside	0.160	4.770	<0.001	Yes
		Control vs. Centre	0.092	2.770	0.009	Yes

A three-way ANOVA tests in  $dE^{*ab}$  and weight changes in *Globigerina* and Coralline samples in Malta and at Witney after a year showed that there is a significant interaction between position and site for both  $dE^{*ab}$  ( $F=22.884$ ,  $DF=2$ ,  $P<0.001$ ) and %Wdry ( $F=8.755$ ,  $DF=2$ ,  $P<0.001$ ). Results of the post-hoc multiple comparison tests

(Holm-Sidak method) are shown in Table 3.9. Sheltered and unsheltered samples differed significantly in colour change from the controls at both Witney and in Malta whereas the differences in weight change between controls and exposed samples are only significant at Witney.

### **3.4. Monitoring dissolution, soiling and microbial growth with stone tablets**

In order to assess the influence of shelters on stone dissolution, soiling and microbial colonisation, two sets of twelve Portland limestone tablets (50 x 50 x 20 mm) were exposed vertically, attached to carousels (Figure 3.2) similar to those used in previous research (Jaynes and Cooke, 1987, Butlin et al., 1992).



**Figure 3.2:** Image of the free rotating carousel used in this study

The tablets were located outside and under the shelter at the Bishop's Palace at Witney from 23<sup>rd</sup> January 2013 to 23<sup>rd</sup> July 2014 (see section 2.2). Three tablets per set were exposed for 6 months, another three for 12 months and the remaining six, 18 months. In addition, three tablets were left in a sealed container with silica gel in the Oxford Rock Breakdown laboratory to act as controls. Before exposure, each stone

tablet was washed in deionised water and then dried in a ventilated oven at  $105\pm 5^{\circ}\text{C}$  until the tablets reached constant weight. The same drying procedure was used after each exposure period.

#### **3.4.1. Data collection, handling and aggregation**

Decay rates in terms of weight change were calculated for each tablet by percentage of initial dry weight (balance Sartorius AG Gottingen, accuracy 0.01g). Colour changes due to soiling and/or microbial colonisation were measured with a spectrophotometer (CM- 700d, Konica Minolta). An average of 10 measurements on the unweathered tablets was used as reference value. The baseline measurements of overall colour change ( $dE^*_{ab}$ ) were compared with those taken after each exposure period (also an average of 10 measurements). In addition, deviations on the red-green scale ( $da^*$ ) and light-dark scale ( $dL^*$ ) were established. The settings used in this study were the same as explained previously for the stone blocks (see 3.3.2.5). Detailed examination by optical microscope and scanning electron microscope (JSM 5910 SEM, Jeol) was used to corroborate the presence of microorganisms on the stone surface after the exposure period and establish their role in the weathering process. Salt contents in Portland tablets after 6, 12 and 18 months were measured using a Dionex ion chromatograph. The major anions (sulphate, nitrate, nitrite, chloride, fluoride and phosphate) and cations (sodium, ammonium, potassium, magnesium and calcium) were extracted using deionised water. Salt concentrations were measured in 5g of stone cut from the corner of the tablet to ensure a good sample of the exposed surface. In addition, a surface analysis was carried out on the samples exposed for a year. Concentrations at surface level were measured in 1g of sample cut from the first

2mm of stone. The concentrations were compared with the mean salt content recorded from the control tablets. The pH of the rain (pH meter Orion Model 410A) was measured in April 2014 to obtain a representative sample of rainfall acidity during the exposure period.

Combined NO<sub>2</sub> and SO<sub>2</sub> diffusion tubes (Gradko International Ltd) were used to monitor air pollution for 4 weeks in October/November 2013 as autumn provides more stable values of pollution conditions in comparison with the winter peaks and summer troughs in NO<sub>2</sub> (Hargreaves et al., 2000). Diffusion tubes are a passive technique for monitoring gaseous pollutants in the air. They are cheap, simple and efficient and have been used extensively in environmental studies for heritage preservation (Gysels et al., 2004, Camuffo et al., 1999, Viles and Gorbushina, 2003). The tubes were placed vertically attached to the same support used for the carousels. Three tubes were left at each location and an extra tube was added to each set. It consisted of an unopened tube to determine if sunlight affected the results (Krochmal and Kalina, 1997). A laboratory blank with closed caps was placed in a dark and cold room over the same period. After exposure, analysis was carried out with Dionex ion chromatograph, and the concentration level of pollutants in both the unopened tube and the laboratory blank were found to be under levels of detection. The air pollution levels and salt content of the tablets at the Bishop's Palace was compared with the results obtained from four NMEP sites in 1980s with low rainfall acidity and air pollution: Wells (South West England), Bovington Camp (South East England), Lough Navar (Northern Ireland) and Strath Vaich Dam (Scotland) (Butlin et al., 1993).

The weight, colour and salt content values were presented as means and standard deviations of the replicates located at the same position and exposed during the same amount of time. Changes above the standard deviations of the control tables are considered to be caused by the environment and not a result of the, inherent variability of the Portland stone (Table 3.10).

**Table 3.10:** Means (n=3) and standard deviations (in brackets) of weight loss (as percentage of initial dry weight) and colour change (as dE\*ab, da\* and dL\*) and salt content in the Portland stone control tablets after 18 months

%Wdry	dE*ab(D65)	da*(D65)	dL*(D65)	Sulphate (ppm)	Nitrate (ppm)	Chloride (ppm)
-0.02 (0.01)	0.37 (0.11)	0.00 (0.03)	0.24 (0.22)	0.26 (0.07)	0.05 (0.02)	0.13 (0.06)

### 3.4.2. Statistical analysis

Two-way ANOVA tests were used to determine if there were statically significant differences in weight change, salt content (nitrates and sulphates) and colour change (dE\*ab, da\* and dL\* values) between positions and time of exposure. In addition, post-hoc all pairwise multiple comparison tests (Holm-Sidak method) were used to isolate which group differed from the others. T-tests were undertaken to determine if the differences between inside and outside the shelter in mean air pollution levels (SO<sub>2</sub> and NO<sub>2</sub>) and nitrate and sulphate concentration on the stone surface (as recorded to a depth of 2 mm) after a year were significant.

### 3.4.3. Validation of the dataset

To understand if there were significant differences between the control and exposed tablets after 6, 12 and 18 months, two-way ANOVA tests were undertaken. There were significant differences between positions (outside the shelter, central part under the shelter and control tablets) regarding weight (F=7.654, DF=2, P=0.005), dE\*ab

(F=20.740, DF=2, P<0.001), da\* (F=28.996, DF=2, P<0.001), dL\* (F=15.043, DF=2, P<0.001) and sulphate (F=18.004, DF=2, P<0.001), nitrate (F=21.556, DF=2, P<0.001) and chloride content (F=69.181, DF=2, P<0.001).

**Table 3.11:** Multiple comparisons tests on weight and dL\* changes and sulphate, nitrate and chloride contents versus the control group (Holm-Sidak method). Overall significance level = 0.05. Comparisons for factor: Position

	Comparison	Diff of Means	t	P	P<0.050
Weight	Control vs. Outside	0.035	2.929	0.020	Yes
	Control vs. Centre	0.006	0.557	0.585	No
dL*	Control vs. Outside	1.759	3.058	0.013	Yes
	Control vs. Centre	0.254	0.441	0.664	No
Sulphates	Control vs. Outside	0.182	4.487	<0.001	Yes
	Control vs. Centre	0.243	5.995	<0.001	Yes
Nitrates	Control vs. Outside	0.065	1.988	0.064	No
	Control vs. Centre	0.292	0.292	<0.001	Yes
Chlorides	Control vs. Outside	0.0208	1.870	0.080	No
	Control vs. Centre	0.036	3.311	0.009	Yes

**Table 3.12:** Multiple comparisons tests versus the control group (Holm-Sidak method) for dE\*ab. Overall significance level = 0.05. Comparisons for Position within Months

	Comparison	Diff of Means	t	P	P<0.050
Position within 6 months	Control vs. Outside	0.128	0.114	0.911	No
	Control vs. Centre	0.558	0.495	0.861	No
Position within 12 months	Control vs. Outside	5.580	4.947	<0.001	Yes
	Control vs. Centre	0.607	0.538	0.597	No
Position within 18 months	Control vs. Outside	3.327	3.153	0.011	Yes
	Control vs. Centre	0.693	0.657	0.519	No

**Table 3.13:** Multiple comparisons tests versus the control group (Holm-Sidak method) for da\*. Overall significance level = 0.05. Comparisons for Position within Months

	Comparison	Diff of Means	t	P	P<0.050
Position within 6 months	Control vs. Outside	0.120	0.819	0.547	No
	Control vs. Centre	0.160	0.614	0.668	No
Position within 12 months	Control vs. Outside	1.400	7.166	<0.001	Yes
	Control vs. Centre	0.213	1.092	0.289	No
Position within 18 months	Control vs. Outside	0.430	2.353	0.059	No
	Control vs. Centre	0.157	0.857	0.403	No

Post-hoc pairwise multiple comparison tests (Holm-Sidak method) showed that control tablets differed significantly from at least one other set of samples in weight loss, dL\*and sulphate, chloride and nitrate contents (see Table 3.11). However, the changes in the different positions depended on time of exposure for dE\*ab and da\* (see Table 3.12 and Table 3.13 respectively). In these cases, the tablets exposed changed significantly more than the control blocks only at certain times of the year.

## 4. CONSERVATION STATE OF THE FIELD SITES

### 4.1. Introduction to the Bishop's Palace, Witney

The palace of the Bishop of Winchester (Figure 4.1) was built at Witney, Oxfordshire, England, in the early 12<sup>th</sup> century. It is located 90 metres east of St Mary's Church, in the centre of the present day town (location: lat. 51.7805, long. -1.4834).



**Figure 4.1:** Open shelter built over the Bishop's Palace remains at Witney (Oxfordshire, England). Image: C. Cabello-Briones

In geological terms, Witney is situated near the western margin of the London Platform. The surface of the Platform is of low relief and was submerged during Upper Devonian, Upper Carboniferous and Jurassic times (Kempt et al., 1982). The Bishop's Palace rests on Mesozoic rocks, in particular Cornbrash limestone (0 to 5 m deep). It consists of fine grained shell-debris limestones from the Middle Jurassic with some evidence of reworking and bioturbation in the area (Kempt et al., 1982).

The palace was built with Cotswold stone, a local oolitic limestone often found to be susceptible to deterioration under wet and frosty conditions (Wainwright, 1984). However, little is known about the exact quarry location. The site was excavated in 1984 and the majority of the remains, on the western and northern sides of the monument, were re-buried after excavation (Oxfordshire Historic Environment Record). Only a small part of the total extent (a walled and moated enclosure), which was considered to be the most important from a historical point of view, was left open and sheltered with a shelter in 1991 (Figure 4.1).

Some interventions were carried out on the exposed Palace masonry and clay embankment after the excavation (Historic Buildings and Monuments Commission for England, 1992). Among them was treatment with biocide to remove organic growth, repointing and filling with lime mortar, dismantling of wall tops down to a level where the mortar bed was solid and reconstruction of wall tops with hard capping. Other interventions, related to the shelter construction, were the introduction of land drains in a gravel filled trench to direct water sideways, construction of the shelter's concrete foundations and soft landscaping consisting of grass and planting in the surroundings carried out at the end of the 1980s. These actions were disruptive and require regular maintenance. The documents compiled in the report (Historic Buildings and Monuments Commission for England, 1992) enumerate the interventions and describe the products used for the restoration. However, there is a lack of information related to where these treatments were applied specifically.

Environmental data from the area where the field site is located exemplify a typical temperature maritime climate, with moderate temperatures but some hot summer

days and cold winter nights. The coldest months are in winter, with mean daily minimum temperatures around 0°C. On the other hand, the warmest months are in summertime with mean daily maximum temperatures between 20 and 25 °C. Air temperatures show both seasonal and diurnal variations. Minimum temperatures are around sunrise and maximum ones, 2 to 3 hours after midday. Table 4.1 shows the monthly averages of temperature, precipitation and rainfall days at Brize Norton (location: lat. 51.760, long.-1.553), located around 6 km from the Bishop’s Palace, from 2000 to 2012.

**Table 4.1:** Monthly average of temperature (°C), precipitation (mm) and rainfall days at Brize Norton between 2000 and 2012

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<b>Average Max. Temperature (°C)</b>	8	9	11	13	17	20	23	23	19	15	11	8
<b>Average Min. Temperature (°C)</b>	2	1	2	3	7	9	11	11	9	9	3	1
<b>Precipitation (mm)</b>	49.8	38.5	36.6	46.3	56.9	37	40.3	45.1	50.1	65	64.9	16.8
<b>Average Rainfall days</b>	21	18	19	18	18	16	16	16	16	21	21	19

In Southern England, the annual average of days of rain  $\geq 1$  mm between 1971 and 2000 varied from 100 to 130 and the average of days of ground frost in the same period was between 85 and 110 (Met Office, 2013). In addition, there are prevailing south-westerly winds from the Atlantic Ocean. At Minster Lovell (location: lat. 51.812, long. -1.536), located approximately 3 miles from the Bishop’s Palace, the prevalent wind direction recorded between January 2010 and 2015 was south and average wind speed for the same period was of 11.3 Km/h. Therefore, high risk of stone decay due to frost and high moisture levels is expected at this location, together with wind driven rain at southern surfaces. In fact, four years after the excavation, salts had

accumulated on the site surfaces and stones were visibly eroded. In addition, the wide joints of weak lime mortar, which was at that time also crumbling, accelerated the movement of water through the surfaces (Historic Buildings and Monuments Commission for England, 1988). The Bishop's Palace was sheltered to slow down deterioration by excluding frost and extreme temperatures and minimising water entry and movement (Historic Buildings and Monuments Commission for England, 1988). However, no further study was undertaken to determine the effect of the shelter and to assess whether it had succeeded in these aims.

#### **4.2. Introduction to Hagar Qim, Malta**

The prehistoric site of Hagar Qim (Figure 4.2) consists of megalithic buildings called temples. However, there is no evidence of religious use (Stroud, 2010)..



**Figure 4.2:** Shelter over the megalithic temples at Hagar Qim, Malta. Image: C. Cabello-Briones

The complex was built between 3600 and 3200 BC (Neolithic period). It is situated at the top of a hill, less than 1 km away from the sea, on the south western coast of Malta, 2 km from the village of Qrendi (location: lat. 35.827, long. 14.441). The site was inscribed on the UNESCO World Heritage list in 1992 because of its significance for human history.

The Maltese archipelago, situated on the unit of the Hyblean Plateau, consists of an accumulation of Oligo-Miocene limestones and marls. The stratigraphical sequence is divided into five formations (from oldest to youngest): Lower Coralline, Globigerina, Blue Clay, Greensand and Upper Coralline limestones (Pedley et al., 1976). Hagar Qim rests on outcrops of Lower Globigerina Limestone (0 to 60 m deep), a planktonic foraminiferal wackstone from the Miocene. Bioturbated levels occur locally, shown by a honeycomb like structure (Cassar, 2010).

The temple was built exclusively with Globigerina limestone, probably quarried near the site. The same limestone was also used to cover the flooring after crushing the stone (Cassar, 2010). Globigerina limestone is a relatively soft bioclastic limestone still widely used for construction in Malta. It is prone to powdering and alveolisation, mainly due to salt weathering (Cassar, 2007a).

The remains were never completely buried and remained partially visible. The first archaeological excavation took place in 1839 followed by some reconstructions with dry-stone walling. However, no systematic studies were made until the beginning of the 20<sup>th</sup> century (Stroud, 2010). In the restoration campaigns in 1910 and 1950s, fallen megaliths were lifted and supported by modern pillars. In addition, cement (on its own or mixed with Globigerina limestone chippings) and metal dowels were used for

reconstructions with subsequent damage to the original stones. Portland cement gives rise to salt deterioration, especially when locally concentrated, and can lead to irreversible damage to stone and mortar (Arnold and Zehnder, 1991). More recent restoration interventions were undertaken after collapses of temple walls in 1996 and 2001. The replacements of the stone blocks were done with locally quarried Globigerina limestone. The remains were sheltered in 2008 in order to reduce environmental and anthropogenic risks (Figure 4.2). Before this time, collapse and vandalism had become more frequent and severe.

Malta has a Mediterranean climate, with dry and hot summers and little probably of frost in winter. Maximum average temperatures are above 25°C in July and August. In winter, temperature rarely drops below 0°C. Table 4.2 shows the monthly averages of temperature, precipitation and rainfall days at Malta airport in Luqa (location: lat.35.854, long.14.481), located around 4 km from Hagar Qim. This area is characterised by low precipitation rates during summer, high monthly rainfall from November to January and mean monthly temperatures between 13 and 28°C (Bonazza et al., 2009).

**Table 4.2:** Monthly average of temperature (°C), precipitation (mm) and rainfall days at Malta airport in Luqa between 2000 and 2012

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<b>Average Max. Temperature (°C)</b>	15	15	17	19	23	27	30	31	27	24	20	17
<b>Average Min. Temperature (°C)</b>	10	10	11	13	16	20	23	24	21	19	15	11
<b>Precipitation (mm)</b>	83.1	45.9	34.3	49.9	20	11.1	2.2	19.4	84.6	76.8	75.5	137
<b>Average Rainfall days</b>	12	9	7	6	4	2	1	1	5	7	11	13

The island is exposed to strong winds. The mean annual wind speed between 1961 and 1990 was 16.3 km/hr. During this period, January had the highest maximum mean of 26.1 km/hr. The most common wind direction is the North-west, which blows on an average of 20.7% days in a year, followed by West Southwest (8.9%) (Galdies, 2011). In addition, there is a high content of soluble salts in the air, mainly chlorides (Cassar et al., 2011). Therefore, stone decay due to high temperatures in summer, high rainfall in winter, wind erosion and deposition of marine aerosols is expected in this area.

Heritage Malta decided that a lightweight, open shelter was the best solution for the main decay factors affecting Hagar Qim. These were high levels of direct solar radiation, which led to thermal expansion and contraction; rainwater, which washed away the infills of the walls and increased their structural instability and wind impact; which affected evaporation rates and increased erosion of the surfaces (Cassar et al., 2011). However, further research was encouraged to determine if the shelter is fulfilling its protective role (Stroud, 2010).

### **4.3. Condition state of the remains**

#### **4.3.1. Definitions**

The decay phenomena identified in this study are defined as follows (ICOMOS International Scientific Committee for Stone ISCS, 2008):

- Cracks or fissures: separation of one part of the stone from another at a macroscopic level
- Detachment processes include fragmentation, disintegration, delamination and scaling:
  - a. Fragmentation: breaking of a stone into portions of variable dimensions

- b. Disintegration: detachment of single grains or aggregates of grains
- c. Delamination: separation into layers following the stone laminae
- d. Scaling: detachment of stone layers, not following any stone structure but usually parallel to the stone surface
- Processes related to material loss are missing parts, alveolisation and erosion:
  - a. Missing parts: empty spaces, located in the place of some formerly existing stone parts
  - b. Alveolisation: formation of cavities on the stone surface (alveoles) due to differential weathering
  - c. Erosion: loss of original surface leading to smoothed shapes
- Discoloration is the change of the stone colour. This could be due to crusts, soiling and/or patina:
  - a. Crusts: coherent accumulation of exogenic and stone-derived materials on the stone surface with a visible thickness
  - b. Deposits: accumulation of exogenic material at surface level with lack of adhesion to the stone
  - c. Soiling: deposit of a very thin layer of exogenous particles giving a dirty appearance to the stone surface
  - d. Patina: chromatic alteration of the material, generally resulting from ageing and without involving visible surface deterioration
- Biological colonisation: presence of plants and/or micro-organisms such as bacteria, cyanobacteria, algae, fungi and lichen on the stone surface

The main decay phenomena described above are illustrated in Table 4.3.

**Table 4.3:** Examples of decay phenomena according to the ICOMOS-ISCS Illustrated glossary on stone deterioration patterns (ICOMOS International Scientific Committee for Stone ISCS, 2008). Cracks, missing parts and discoloration: Castle Park (Versailles, France), author: V. Vergès-Belmin (LRMH). Detachment: Pernstejn Castle (Nedvedice, Czech Republic), author: D. Michoinova (National Heritage of the Czech Rep). Biocolonisation: Bourges Cathedral (France), author: V. Vergès-Belmin (LRMH).



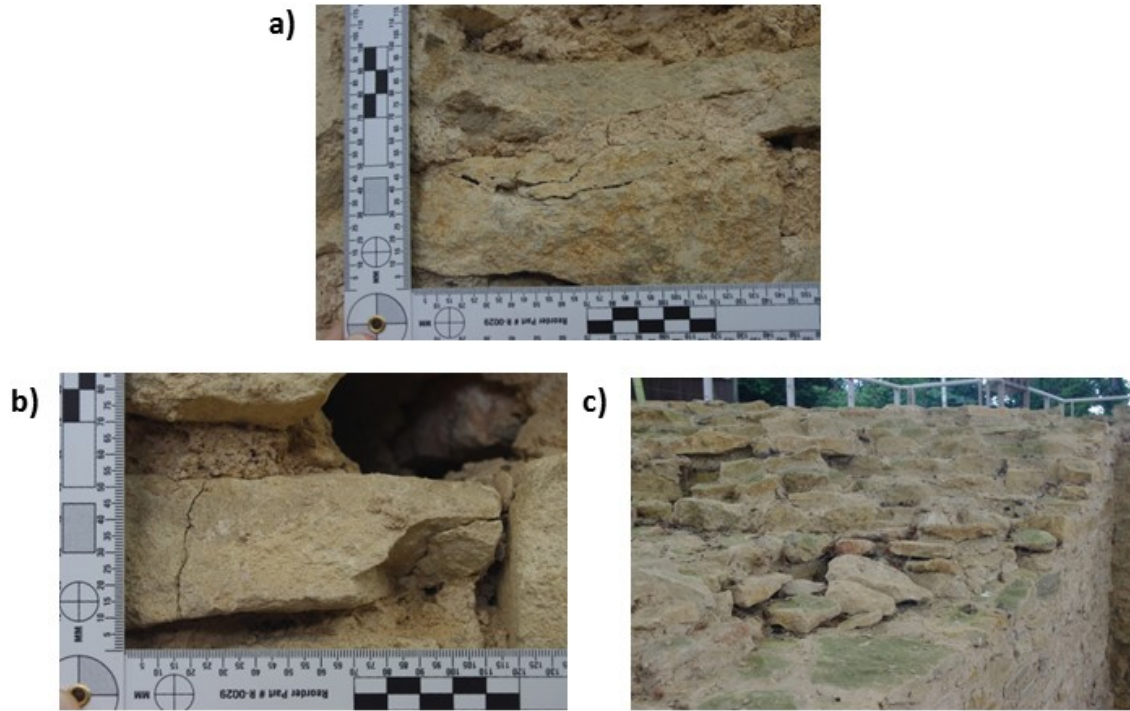
#### 4.3.2. Condition survey of the Bishop's Palace, Witney

Biofilms are insignificant on the west and south vertical surfaces in comparison to those found on the north and east side where biocolonisation could be considered the main problem. Soiling and deposits are extensive on every wall of the site. Also found are fragmentation and missing parts but these are concentrated mainly on the south and west sides. There are several deterioration phenomena widespread across the entire site, for example cracks, crusts and delamination, mainly on the south, but the damaged caused is not as high as the phenomena mentioned previously. On horizontal surfaces, fragmentation, missing parts and deposits are also significant but their degree of severity and extent is less than on the vertical faces. Biocolonisation, mainly in the form of surface greening, is found on the east and north areas where it becomes the main problem. In addition, if a comparison is made between decay phenomena found on the ruins at the centre of the site and those on the periphery, it is clear that one of the most notable patterns on peripheral walls is biocolonisation, present at a high level in terms of both severity and extent. On the other hand, soiling is predominant towards the centre of the site. Other phenomena such as fragmentation, missing parts and deposits, are found in both areas.

The restoration treatments have also had an influence on the conservation of the original remains. In places where filling and pointing have failed to keep the stone attached to the wall, stone fragments have become loose, mainly at the corners and other irregular surfaces on the top walls. Although these interventions were designed to minimise water access, the increase in the exposed surface accelerates the damage. In addition, consolidation products could have introduced other damage factors such as the presence of salts. Therefore, the main decay phenomena as identified in the survey were: cracking, detachment and material loss, discoloration and biocolonisation.

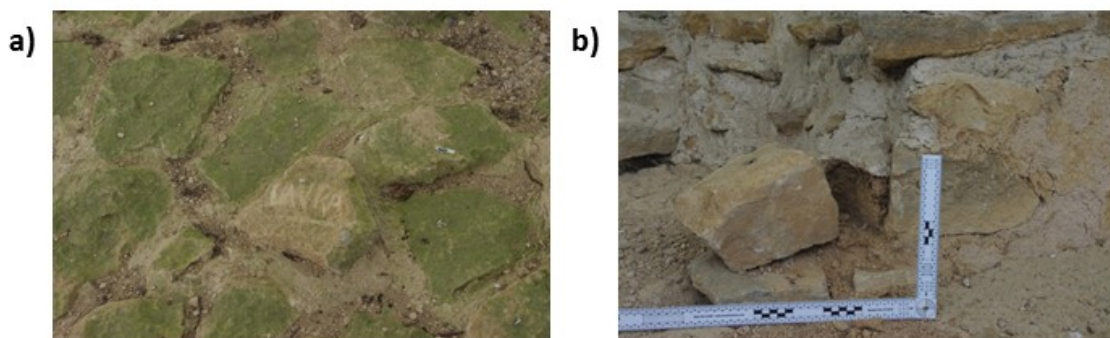
A detailed explanation of the decay phenomena at the Bishop's Palace is presented below:

- a) The main cause of cracking is presumed to be physical weathering, especially frost weathering and salt crystallisation. Cracks are localized mainly on vertical walls where mortar has already been degraded and is detached from the stone (Figure 4.3, a)
- a) Delamination and fragmentation are detachment processes, which often lead to missing parts and deposits (Figure 4.3, b). Detachment can be the result of the action of salts or repeated freeze-thaw cycles and it can be seen as the second step after the formation of cracks. Salt efflorescences and biological colonisation can also be found on the new exposed surfaces after fragmentation has taken place leading to further decay. Areas not effectively protected either by the hard capping on the horizontal surfaces or repointing on the vertical ones, are very vulnerable. The high quantity of stone fragments on the ground and over the upper surface of the walls indicates the severe extent and degree of the detachment process (Figure 4.3, c).



**Figure 4.3:** a) Cracks on the vertical wall facing west at the central part of the Bishop's Palace (detail), b) cracks, fragmentation and missing parts on the same wall as before (detail), and c) accumulation of fragments and loose stones on the upper part of the walls (detail of the north-east side of the site). Image: C. Cabello-Briones

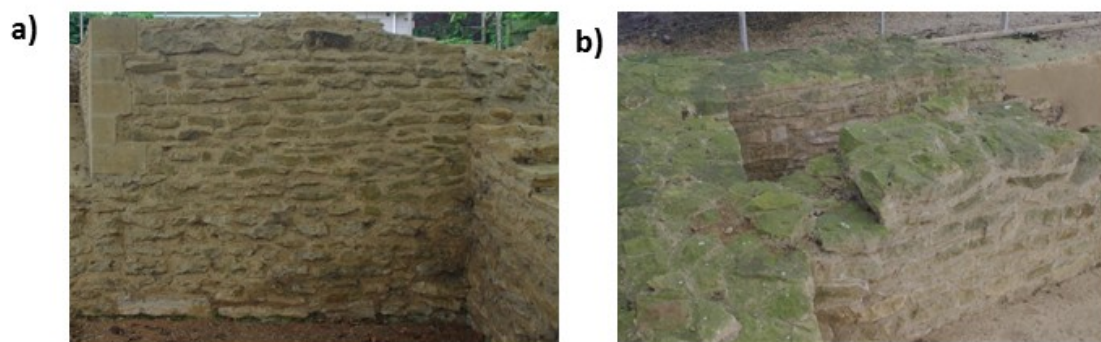
b) Loss of material may have anthropogenic or natural causes. There are several graffiti on the ruins' walls made by scratching (Figure 4.4, a). Additionally, the original mortar is very soft and easily detached from the wall leading eventually to missing parts (Figure 4.4, b). Particularly exposed parts of stone blocks, such as corners and edges, are typical locations for material loss.



**Figure 4.4:** a) Detail of greening, accumulation of dirt and graffiti on the horizontal top surface at the north part of the site and b) detachment on the east side of the Bishop's Palace (detail). Image: C. Cabello-Briones

c) The stones which form the Bishop's palace ruins are very heterogeneous, with different colours due to different petrology and mineralogy, and perhaps presence of clays, in addition to the change in colour due to natural ageing. However, the main causes of stone discoloration at the site seem to be salts, microorganisms and moistening.

The presence of salts crusts is extensive. They are concentrated on the medium height of the vertical walls (around 1 metre from the ground), where the evaporation of rising damp takes place. Salt crusts are firmly adhered to the stone substrate and their formation is supported by environmental conditions such as frequent wetting and drying cycles. Microorganisms cover the stone surface as biofilms mainly on the north and east sides (see section d). In addition, moisture stains are visible on the lower part of the vertical walls and corners due to water uptake from the ground (Figure 4.5, a). The accumulation of fallen leaves and deposits on the ground can exacerbate the problem.



**Figure 4.5:** a) Moisture stain on inner part of the corner on the north-west side of the site, and b) biofilm over the top part of the walls on the north-east side of the Bishop's Palace. Image: C. Cabello-Briones

d) Biological colonisation (algae, fungi and lichen) occurs in very thin layers and mainly concentrated close to ground level and at the corners of vertical walls, where water supply may be greater. There are also significant amounts of biofilms covering

north-facing walls. Greening on the north and north-east horizontal surfaces is remarkable (Figure 4.5, b) and some higher plants are also found on the south and east side.

#### **4.3.3. Condition survey of Hagar Qim, Malta**

Five phases of damage have been distinguished at the site in previous studies (Cassar, 2007a). The initial stage is a formation of a superficial crust by precipitation of dissolved calcite, which is followed by the formation of cavities and back-weathering. In the next stage, material loss is severe due to the connection of the cavities. Finally, the surface is totally back-weathered, the surface is flat and the edges rounded. On some stone monoliths the processes have taken place several times creating pronounced scaling. It is possible that the decay slowed down after the building of the shelter and that dissolution of calcite has been reduced since then. However, the effects of wind or salts could still be responsible for the alveolisation process on some already decayed surfaces.

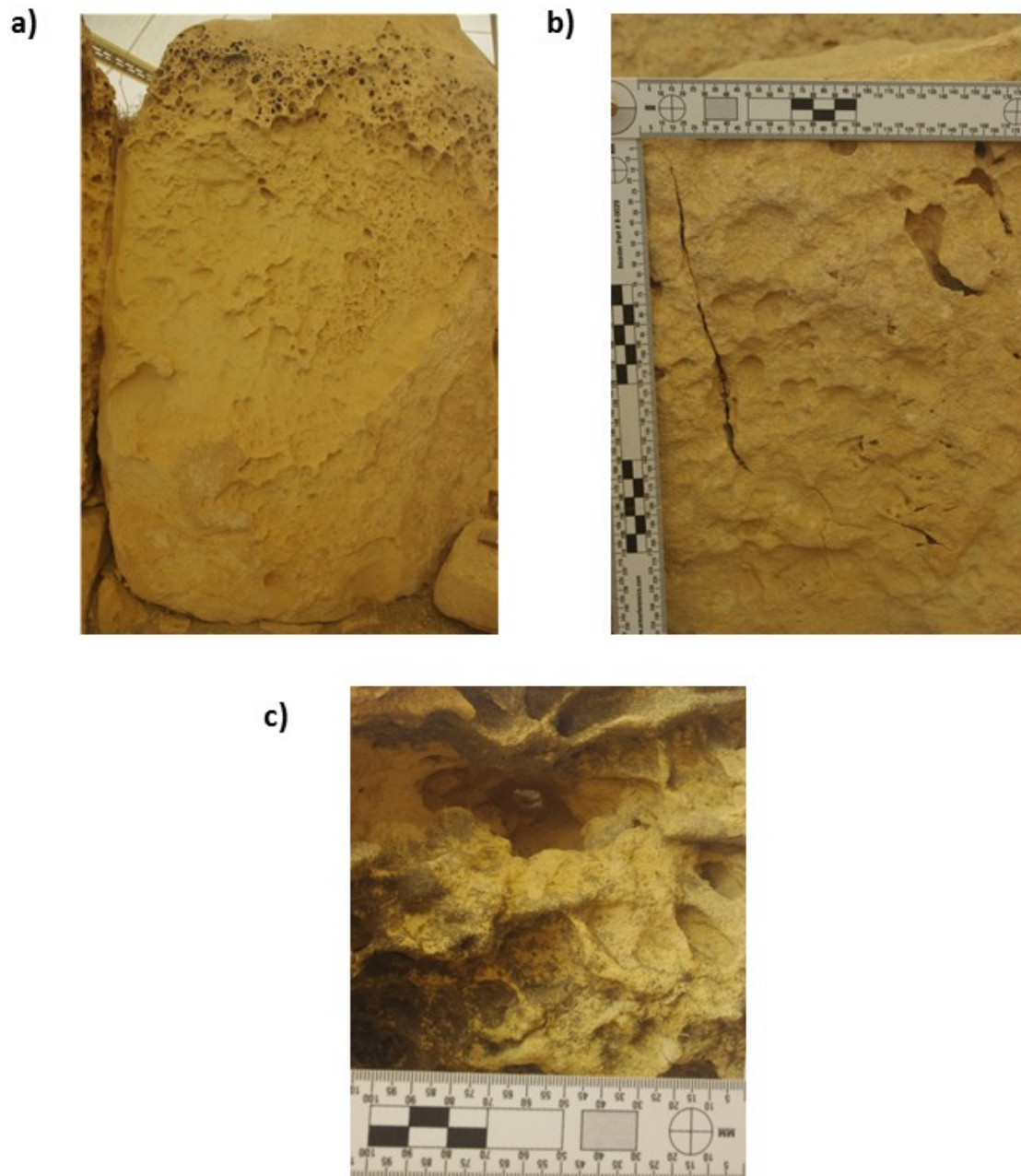
The condition survey carried out in this study showed that the main decay phenomena at Hagar Qim are cracking, scaling, alveolisation and soiling (see APPENDIX A). Alveolisation is the main decay phenomenon usually connected with scaling. The severity of decay is quite homogeneous but vertical walls facing east and south, orientated towards the sea, are the most affected. Cracking, fragmentation, crusts and soiling are also widespread and their severity has been classified as medium-high.

A detailed explanation of the decay phenomena at Hagar Qim is presented below:

a) Cracks are inferred to form on the stone surface due to physical weathering. As discussed above, calcite, previously dissolved from within the stone by rain water, rising damp or condensation, re-precipitates in the stone pores (Cassar, 2007a). The repeated process produces several layers of a compact and hard crust, parallel to the surface. The crust has different properties to the stone core. Thermal movement and salt weathering are most probably responsible for the cracking and subsequent detachment of the crust here, which leaves a decayed surface exposed. The new exposed surface is very vulnerable. It has a high porosity due to the dissolution of calcite. The lack of cohesion makes it prone to disintegration and other types of material loss processes such as alveolisation and scaling (Figure 4.6 a and b).

The process depends on the number, orientation and size of the sedimentary structures (Cassar and Vannucci, 1999). Due to this type of deterioration, a new crust is not able to form but salt weathering and wind erosion can make alveoles interconnect resulting in a back-weathered surface.

b) Biological crusts are mainly concentrated on newly exposed surfaces, between cracks and inside alveoles, and surfaces facing north and west (Figure 4.6, c), probably due to the higher levels of humidity (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). Horizontal surfaces have higher biological diversity than the vertical ones. However, there are no differences in terms of cover (Llop et al., 2013).



**Figure 4.6:** a) alveoles and severe scaling on one of the monoliths in the south apse at Hagar Qim, b) cracks, alveoles and erosion on the stone surface (detail of previous picture), c) biofilm on monolith facing north in the south apse at Hagar Qim. Image: C. Cabello-Briones

#### **4.4. Condition state of the shelters**

##### **4.4.1. The shelter at the Bishop's Palace, Witney**

The open shelter, made of a fiberglass and polytetrafluoroethylene (PTFE) fabric, was built in 1991 and has a life expectancy of 25 years (Allen, 1991). Lightweight shelters

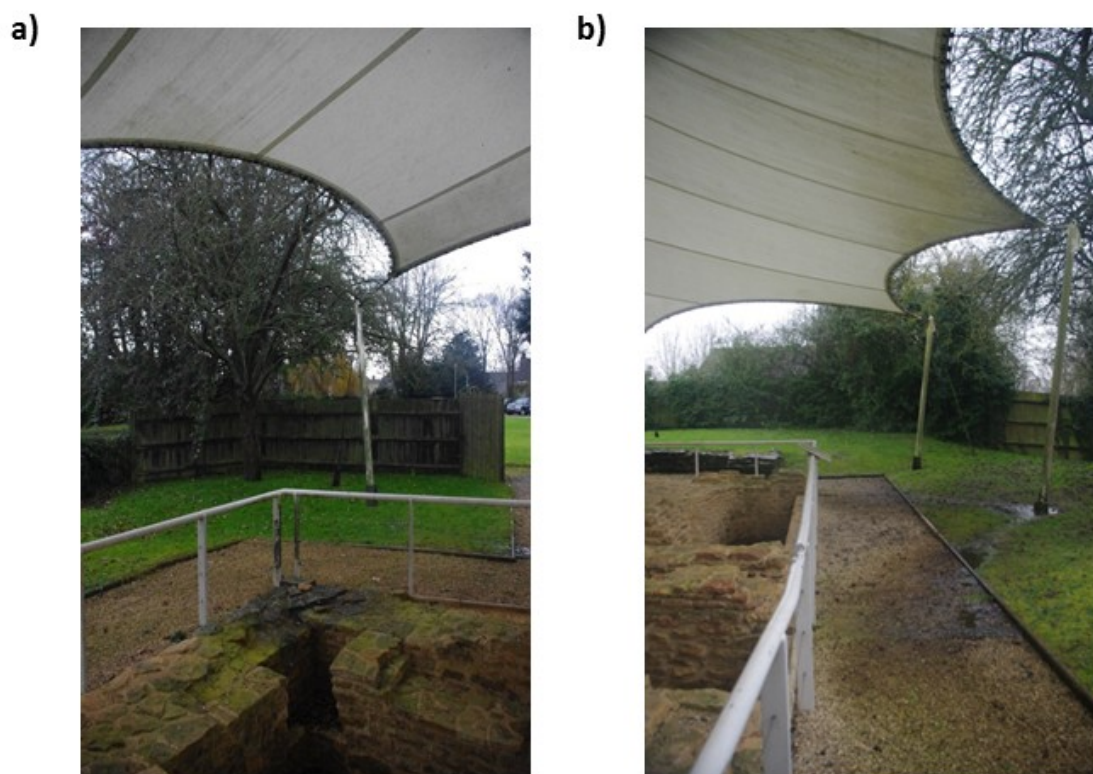
reduce the amount of solar radiation reaching the ruins without blocking light completely. Therefore, light transmission is an important value to define the materials' characteristics. For this study, the light transmission (%) of the shelter was calculated using a light meter (Lutron, YK-2005LX, accuracy  $\pm 4\%$   $\pm 2$  dgt) in November 2012 at midday. It was established that shelter at the Bishop's Palace transmits 11.5% of the incoming light.

The open lightweight shelter was built to provide better protection against rain and frost than a temporal or seasonal cover and incur less initial and maintenance costs than an enclosure (Historic Buildings and Monuments Commission for England, 1988). However, only a small part of the palace was selected for display. The reason was to minimise the impact that this type of structure can cause to the site aesthetically and in relation to damage to the archaeological substrate (Historic Buildings and Monuments Commission for England, 1988).

The shelter that covers the remains at the Bishop's Palace at Witney most probably buffers the thermal expansion of the stone given that air temperature changes are mainly due to the heating effect of the sun. In addition, it prevents direct rainfall onto the stone remains and thus reduces mineral dissolution. However, moisture (condensation and from the soil) seems to be one of the main damaging factors under the shelter. Frost damage, hydric swelling, salt precipitation and biological colonisation are external causes of stone decay related to material dampness. Water can access the site directly, through leaks and wind driven rain, as the shelter is not well maintained and big enough. In addition water can access the site indirectly, through rising damp, condensation and high relative humidity. The land drains and

soakaways were built to intercept the water from the sides (Historic Buildings and Monuments Commission for England, 1988). However, the drainage system has been less effective than expected. Soon after the construction of the shelter, some problems were detected. Water coming from the shelter was reported to saturate the higher ground (Adams, 1995). This is important as damp masonry could increase the risk of frost damage (Figure 4.7, b).

The shelter presented in the original plans was reduced in size at the north-west corner in its final construction, although the reason is not explained in the literature (Kendall and English Heritage South East Local Office, 1992). The deficiency with the shelter coverage in this area is clearly visible, where rain and snow fall directly onto the ruins (Figure 4.7, a).



**Figure 4.7:** a) Rain falling over the ruins at the north-west corner in November 2012 due to shelter cover deficiency and b) rainwater running off the shelter over the ground on the north side of the site in February 2012. Image: C. Cabello-Briones

The shelter is close to the end of its designed life span. There is no deformation in its shape indicating that the tensioning devices still work properly. However, the membrane has some visible tears and leakages. In addition, the shelter has not been cleaned recently. Dirt has accumulated both inside and outside the membrane (Figure 4.8). The possible sources are biological colonies which require high humidity and light to live, fallen leaves and sticky pollen from close trees, and pollution.



**Figure 4.8:** Dirt patches on the shelter membrane in October 2012. Image: C. Cabello-Briones

#### **4.4.2. The shelter at Hagar Qim, Malta**

The shelter was built in 2009. It is a fiberglass and polytetrafluoroethylene (PTFE) membrane with a life span of 25-30 years. It was selected due to its expected good behaviour under UV exposure and salt sprays (Cassar et al., 2011). The translucency of the membrane is 12% at 550 nm (Form TL ingenieure für tragwerk und leichtbau gmbh, 2007). It is able to reduce the incoming solar radiation inside the shelter to a range between 25 and 40% (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). As solar radiation increases the evaporation rate, the risk of salt weathering is also potentially reduced. The shelter reduces the intensity of sun irradiation mainly under the central part; however, solar radiation affects the

periphery of the site when the sun is low in the sky (Figure 4.9). Therefore, this area could still be subjected to thermoclastic and salt weathering. Additionally, around 20-30% of the incident radiation can also be reflected by the surrounding soil and vegetation inside a shelter (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006).



**Figure 4.9:** Sun irradiation on the ruins facing the south-west in the afternoons in October 2013. Image: C. Cabello-Briones

The shelter protects against rainfall avoiding accumulation of water inside the site after short and heavy rain episodes. Rain could still affect the erosion of dry surrounding ground and enter the site through capillarity. However, the risk is low as the drains are in good condition.

The temple is made of Globigerina limestone, a type of stone which has high water absorption properties (see Table 3.5). Before the construction of the shelter, rainwater was absorbed by the monoliths and evaporated due to thermal irradiation after each

rain episode (Cassar, 2007a). These humidity fluctuations most probably exacerbated salt weathering. After the construction of the shelter, marine aerosols deposited on the stone surface are not removed anymore by the washing effect of the rain but moisture fluctuation and sea salt deposition are reduced by the covering effect of the shelter in the centre. However, the most exposed stone surfaces and those facing the main wind direction can still be affected. In addition, the shelter might influence wind turbulence underneath it. This might enhance concentration of marine aerosols and pollutants on specific areas inside the shelter. The shelter was built recently and is in good condition. There are no signs of tears and leakages. Nevertheless, the microclimate inside the shelter is suitable for birds' nesting. In addition, biological growth is visible on the membrane following the lines of water streaks. The water is due to condensation and probably washes off the accumulated dust on the inner side of the shelter's membrane (Galea, 2014).

#### **4.5. Discussion**

The use of translucent membranes can be a sustainable option for medium-term coverings, provided that the membrane keeps its properties. Such membranes can offer the necessary amount of light to visitors for site contemplation without the need for artificial light. In addition, to some extent, they can reduce wavelengths dangerous for deterioration, i.e. ultraviolet and infrared radiation. However, they can lead to the disappearance of microorganism colonies in the long term (Llop et al., 2013). Although biological crusts can change the appearance and colour of the stone surfaces and cause physical and chemical weathering, they can also prevent stone deterioration

altering the microclimatic conditions and acting as agents of bioprotection (Viles, 2012).

After the construction of a shelter, wind dynamics are most probably modified. At Hagar Qim, it has been shown that speed decreased and turbulence was modified within the site (Farrugia and Schembri, 2008). This is important as wind might have altered dust deposition rates. Wind and wind driven particles, such as sand or dust, are responsible for stone erosion. In addition, it is most probable that wind action, together with salt crystallisation, cause the deepening of alveoli in the Maltese stones (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). In Witney, the effects of wind are not as clear.

The levels of dirt on the shelter surface depend on material properties, slope and orientation of the shelter (Rosina et al., 2011) and environmental conditions of the site, mainly rainfall intensity and frequency, but also pollution, proximity of trees (leaf fall and sticky pollen) and bird droppings. If not frequently cleaned, dirt accumulates on the shelter surface with time. Periodic cleaning with water and natural soaps is highly recommended by manufacturers at least every 18 months, in order to remove airborne pollutants and dirt (KOIT High-tech GmbH Konstruktive Membranene (UK) LTD, 1993). However, this could be expensive and also dangerous for the preservation of the site. Water could fall directly on the remains and also increase the ambient humidity levels inside the shelter. The lack of cleaning, on the other hand, could affect the life span of the membrane and its properties.

The ageing of the lightweight membranes usually leads to a change in colour; a yellowing due to the deterioration of the textile. Light reflection and diffusion decrease

then and the absorbed heat increases, making the membrane deteriorate faster (Rosina et al., 2011). Although no dramatic change in colour was observed at either of the sites, a regular visual inspection of the shelter condition is important. The tensioned structure provides a stable system capable of resisting strong winds and other climate episodes. Distortion of the shelter's shape could indicate that the tensioning devices are damaged (Historic Buildings and Monuments Commission for England, 1992). In addition, cuts or tears can affect the isolating properties of the membrane and increase the accumulation of dirt. These elements are more frequent in old membranes (See section 4.4). Regular inspection of the preservation state of the site is also beneficial. The accumulation of deposits, leaves and plants leads to a change of the site's appearance. Biological growth, formation of crusts, soiling, dampness stains, and increase in relative humidity are some consequences. In addition, the amount of missing parts could be reduced if repointing tasks and periodical checking of de-cohesive parts are done at the site.

Although material loss and cracking are decay phenomena found in both sites, the deterioration processes are different. Frost weathering seemed to be the main cause at the Bishop's Palace whereas salt weathering is likely to play an important role in the decay at Hagar Qim. Low temperatures and presence of water are necessary for frost weathering. Water entry might be intensified by the shelter, which is not properly maintained and has a small covering area and inefficient drainage system. These problems are not present in the shelter at Hagar Qim. Moisture fluctuations could have been reduced since the construction of the shelter but salt and dust deposition may be exacerbated.

Summary comparison of all the aspects reviewed in this chapter between the Bishop's Palace and Hagar Qim is presented in Table 4.4.

**Table 4.4:** Comparative summary of the Bishop's Palace and Hagar Qim in relation to location, characteristics, conservation state of the sites and type and condition of the shelters

		<b>The Bishop's Palace</b>	<b>Hagar Qim</b>
<b>Location/ characteristics</b>	Location	Witney, South England	Qrendi, South Malta
	Climate	Temperate maritime	Mediterranean
	Materials	Cotswold limestone	Globigerina limestone
	Decay mechanisms	Granular disintegration	Alveolar weathering
	Wind direction	South-west	North-west
<b>Conservation state of remains</b>	Main decay phenomena	Cracking, detachment, material loss and biocolonisation	Cracking, scaling, alveolisation and soiling
	Likely decay causes	Freeze-thaw and wet-dry cycles	Salt weathering and wind
<b>History and condition of shelter</b>	Dimensions	Height: approx. 9.5m from archaeological pit level and 8m over ground level. Dimensions: approx. 22x29m	Height: approx. 12m over ground level. Dimensions: approx. 54x43m
	Shape	Open shelter. Umbrella-like with one main pole in the centre. Faceted perimeter	Open shelter. Ovate shape with two main diagonal poles. Faceted perimeter
	Materials and light transmission	Fiberglass and PTFE (11.5%)	Fiberglass and PTFE (12%)
	Construction and life span	1991 (25 years)	2009 (25-30 years)
	Condition state	Lack of maintenance, water infiltration, limited coverage, limited lateral protection, inadequate drainage	Good condition of maintenance, limited lateral protection
	Possible effects on site preservation	Unstable climatic conditions, wind and wind driven rain access, direct rainwater and sunlight access, pollutants deposition, dust accumulation, bird nesting	Unstable climatic conditions, wind access, direct sunlight access, aerosols deposition, dust accumulation, bird nesting

The comparison between the microclimate and stone decay processes inside and outside the shelter will clarify to what extent the shelter is affecting the preservation of the remains at Hagar Qim and Bishop's Palace. The location of the stone samples described in following chapters (Chapters 5, 6, 7, 8 and 9) was selected taking into the

account the problematic areas observed at the sites in the condition surveys recorded in this chapter. The periphery is susceptible to being affected by sun irradiation, wind action and rainwater, redirected by the shelter towards the perimeter of the covering area. In addition, problems with shelter design and faulty drains could aggravate some decay processes.

## **5. EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON THE MICROCLIMATIC CONDITIONS**

### **5.1. Introduction and aims**

Uncovered archaeological remains are likely to be affected by extreme and fluctuating climatic conditions. Shelters should provide thermal insulation and reduce temperature extremes. They also should help to decrease the number and extent of damaging temperature and relative humidity fluctuations, reduce the number and severity of freeze-thaw cycles and minimise direct water entry (Villari, 2004, Maekawa, 2006, Getty Conservation Institute and Instituto Hondureño de Antropología e Historia, 2006). On the other hand, shelters could enhance salt crystallisation damage and biocolonisation due to changes in relative humidity and moisture content (Aslan, 1997, Stewart, 2008, Neguer and Alef, 2008) and frequency and duration of condensation events (Kotlík and Heidingsfeld, 2002, Stewart et al., 2004, Neguer and Alef, 2008). The main decay phenomena identified at Witney were cracking, material loss and biocolonisation probably because of frost weathering and high moisture content (see Chapter 4). Open shelters rarely completely prevent water entry and movement (Agnew and Coffman, 1991, Buccellati and Bonetti, 2003, Citterio and Giani, 2006c). Moisture may enter the shelter through wind driven rain or from the ground. Shelters can cause rainwater to be deposited around their perimeter, saturating higher ground (Tringham and Stewart, 2008). In addition, they could also present some construction problems which may reduce their theoretical effectiveness, such as inadequate rainwater dispersal because of faulty site drainage or roof cover (Rizzi, 2008).

This chapter aims to provide an assessment of the effect of the lightweight, open shelter at the Bishop's Palace on the microclimate of the archaeological site. The following research questions have been addressed:

1. How effective is the shelter (in the centre and towards the periphery) on reducing the outside microclimatic conditions in terms of:
  - 1.1. Temperature extremes and fluctuations
  - 1.2. Solar radiation
  - 1.3. Freeze-thaw cycles
  - 1.4. Relative humidity extremes and fluctuations
  - 1.5. NaCl crystallisation events
  - 1.6. Wetting events
2. What is the difference in microclimatic conditions between upper, middle and lower portions of the ruined walls, which can make some areas of the site under the central part of the shelter at higher risk of decay?

## **5.2. Materials and methods**

In order to address the two aims stated above, two sets of data collection were carried out each for one year, i.e. a) monitoring microclimatic conditions in the centre, the periphery (NW side of the site) and outside the shelter, and b) monitoring microclimatic conditions as experienced at the top, middle and bottom portions of one of the ruined walls within the shelter (central part of the shelter slightly towards the north-east and facing north) (see Chapter 2). The monitoring positions were selected after literature was examined and a visual assessment of the decay patterns and conservation state of the remains at the Bishop's Palace was undertaken (Chapter 4).

For a) outside, centre and periphery of the shelter, temperature, RH and surface wetness were monitored from 3<sup>rd</sup> August 2012 to 29<sup>th</sup> July 2013. For the top, middle and bottom part of the wall, temperature and RH were monitored from 5<sup>th</sup> September to 29<sup>th</sup> July 2013. Temperature and RH (i-button® hygrometers, accuracy=±0.5%RH and ±0.5°C) and wetness loggers (Tinytag leaf wetness logger, accuracy=0.4%, ±2 units) were synchronised and readings taken every 15 minutes. Table 5.1 summarises the methods used to produce the different sets of information (for more information see Chapter 3).

**Table 5.1:** Data collection, handling and analysis methods used for the microenvironmental conditions able to affect stone decay

	<b>Data collection</b>	<b>Data handling</b>	<b>Data analysis</b>
<b>Temperature</b>	Hygrochrons (i-button) – every 15 mins	Whole dataset, seasonal means of max and min T per day, monthly mean of daily T range and representative months (calculated with hourly means)	Mann Whitney Wilcoxon tests on annual and seasonal T means and standard deviations, and linear model for diurnal T range
<b>Solar radiation</b>	Light meter	Representative days (real days)	Theoretical insolation model of total annual radiation (Autodesk Ecotect® Analysis)
<b>Freezing-thaw cycles</b>	Number of times a day $T \leq 0^\circ\text{C}$	Monthly mean of number of events	Poisson Generalized Linear Model for mean number of events per day in a year
<b>RH</b>	Hygrochrons (i-button) – every 15 mins	Whole dataset and monthly mean of daily RH range	Mann Whitney Wilcoxon tests on annual and seasonal RH means and standard deviations
<b>Salt crystallisation events</b>	Number of times a day RH crosses 75%	Monthly mean of number of events and representative months (hourly means)	Means and 95% confidence intervals and linear model for mean number of events per day in a year
<b>Wetting events</b>	Wetness loggers	Monthly mean of daily wetness and representative months (hourly means)	Mann Whitney Wilcoxon tests on annual and seasonal wetness means and standard deviations, and linear model for daily wetness mean
	Dew point temperature	Representative months (hourly means)	Percentage of time with condensation events

Microclimatic conditions, especially temperature and RH cycles and wetting events, affect the preservation of the stone remains at the site. The shelter should be able to reduce some of them in terms of frequency and/or range and, therefore, reduce the risk of stone decay. The degree of protection that the shelter gives will depend on the location within the shelter, such as central or peripheral, and at the top, middle or bottom of the ruined walls. Based on the literature review, a number of predictions about the likely microclimatic conditions at different locations were established (Table 5.2 and Table 5.3). Specific ranges were assigned to the high, medium and low categories after data collection to know the variability of real data. The categories were delimited taking into account also climate characteristics. The outside was considered to be the group at higher risk of decay.

**Table 5.2:** Predictions of the range of specific microclimatic conditions outside and inside the shelter (periphery and in the centre)\*

	<b>Outside</b>	<b>Periphery</b>	<b>Centre</b>
<b>Mean daily T in summer</b>	High	Medium	Low
<b>Mean daily T in winter</b>	Low	Medium	Medium
<b>Mean diurnal T range in summer</b>	High	Medium	Low
<b>Mean diurnal T range in winter</b>	High	Medium	Low
<b>Total annual solar radiation</b>	High	Medium	Low
<b>Freezing events in a year</b>	High	Medium	Low
<b>Mean daily RH</b>	High	Medium	Medium
<b>Mean diurnal RH range in summer</b>	High	Medium	Medium
<b>Mean diurnal RH range in winter</b>	Medium	Low	Low
<b>NaCl crystallisation events (mean number per day)</b>	Medium	Low	Low
<b>Time in a year (%) with condensation events</b>	High	Medium	Medium

\* For daily T in summer: HIGH=above 20°C, MEDIUM=20-10°C, LOW= below 10°C. For daily T in winter: above 5 °C, MEDIUM=5 to -5°C, LOW= below -5°C. For diurnal T ranges: HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For solar radiation: HIGH=above 500 Kw/h, MEDIUM=500-100 Kw/h, LOW= below 100 Kw/h. For number of freezing events: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For daily RH: HIGH=above 90%, MEDIUM=90-60%, LOW= below 60%. For diurnal RH ranges: HIGH=above 30%, MEDIUM=30-15%, LOW= below 15%. For annual mean NaCl crystallisation events per day: HIGH=above 3, MEDIUM=3-1, LOW= 1. For condensation events (%time): HIGH=above 60%, MEDIUM=60-30%, LOW= below 30%.

Table 5.2 shows that temperature and RH fluctuations outside the shelter are likely to be frequent and with a higher range, enhancing frost weathering risk. The peripheral areas under the shelter are likely to be affected by a transitional environment between a fully covered central space and exposed environment. The top of the wall, as a horizontal surface, will be the most exposed to the sheltered environment (Table 5.3). The bottom part of the wall will probably be affected by water uptake from the soil and the middle area characterised by evaporation events. The moisture content of lower locations, such as the bottom part of the wall, tends to be greater in archaeological remains (Maekawa, 2006, Kotlík and Heidingsfeld, 2002). However, condensation is more likely to occur on horizontal surfaces at night (Camuffo and Giorio, 2003); therefore, the top part of the wall is also likely to be affected by high moisture levels and this area will probably be most at risk from decay.

**Table 5.3:** Predictions of the range of specific microclimatic conditions on the top, middle and bottom part of the representative wall\*

	<b>Top</b>	<b>Middle</b>	<b>Bottom</b>
<b>Mean daily T in summer</b>	Low	Low	Low
<b>Mean daily T in winter</b>	Medium	High	High
<b>Mean diurnal T range in summer</b>	Low	Low	Low
<b>Mean diurnal T range in winter</b>	Low	Low	Low
<b>Freezing events in a year</b>	Low	Low	Low
<b>Mean daily RH</b>	Medium	Medium	Medium
<b>Mean diurnal RH range in summer</b>	Medium	Medium	Low
<b>Mean diurnal RH range in winter</b>	Low	Low	Low
<b>NaCl crystallisation events (mean number per day)</b>	Low	Medium	Low
<b>Time in a year (%) with condensation events</b>	Medium	Low	Low

\* For daily T in summer: HIGH=above 20°C, MEDIUM=20-10°C, LOW= below 10°C. For daily T in winter: HIGH= above 5 °C, MEDIUM=5 to -5°C, LOW= below -5°C. For diurnal T ranges: HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For solar radiation: HIGH=above 500 Kw/h, MEDIUM=500-100 Kw/h, LOW= below 100 Kw/h. For number of freezing events: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For daily RH: HIGH=above 90%, MEDIUM=90-60%, LOW= below 60%. For diurnal RH ranges: HIGH=above 30%, MEDIUM=30-15%, LOW= below 15%. For annual mean NaCl crystallisation events per day: HIGH=above 3, MEDIUM=3-1, LOW= 1. For condensation events (%time): HIGH=above 60%, MEDIUM=60-30%, LOW= below 30%.

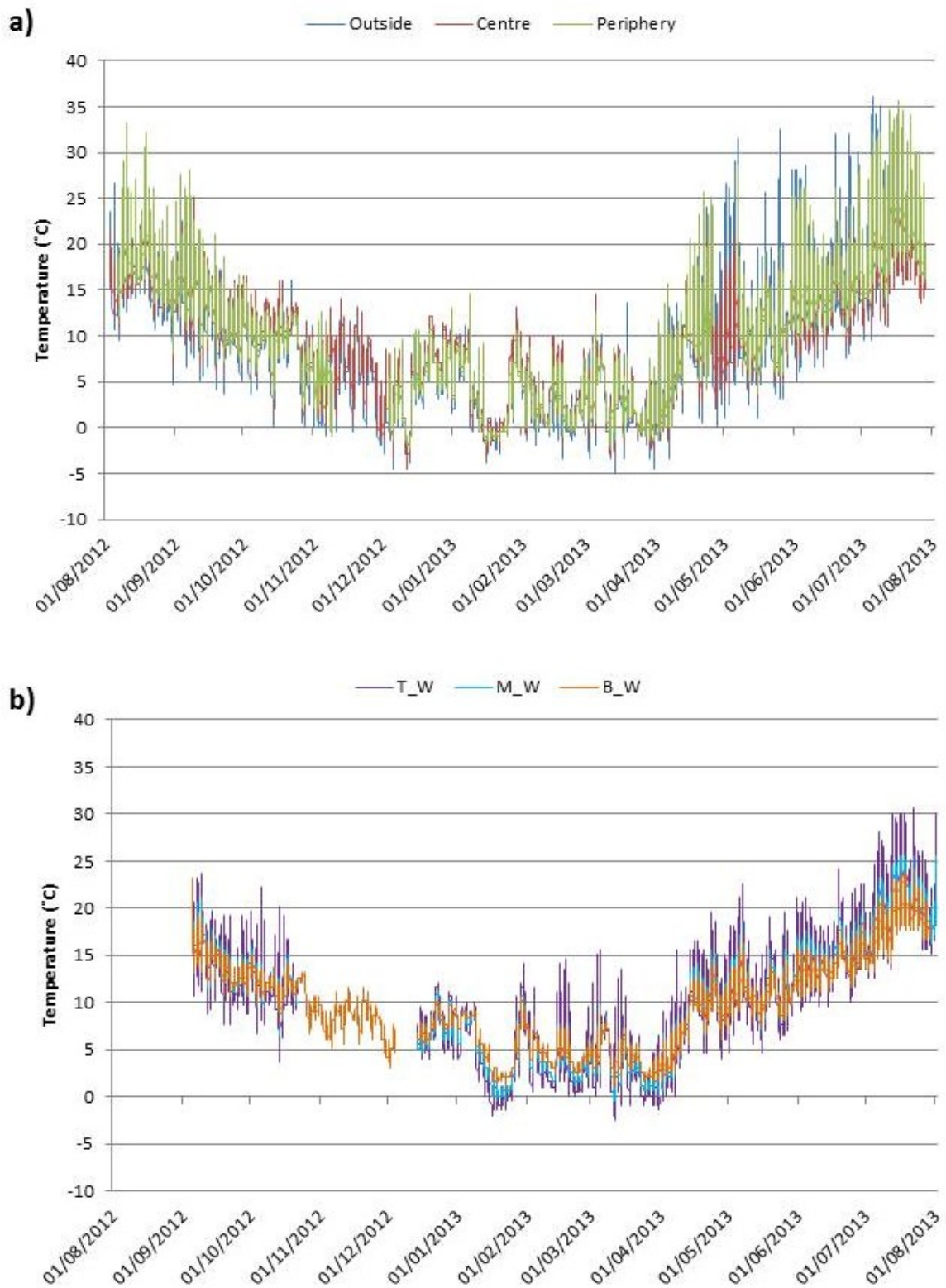
### 5.3. Results

In this section, results are presented on the impact of the shelter on temperature (extremes and fluctuations), solar radiation, freeze-thaw cycles, RH (including NaCl crystallisation events) and wetting events. For each factor, results are firstly presented to address research aim 1 (comparing results from centre, periphery and outside the shelter) and secondly to address research aim 2 (comparing results from the top, middle and bottom parts of the ruined walls).

#### 5.3.1. Temperature

Figure 5.1, a) shows the temperatures outside and inside the shelter (centre and NW periphery) for the year of record. Data was recorded using hygrometers. Both daily and seasonal variations are demonstrated. As expected, temperatures were highest in summer going up to  $36.6 (\pm 0.5)^\circ\text{C}$  outside and  $31.6 (\pm 0.5)^\circ\text{C}$  in the central part of the shelter, and below  $0^\circ\text{C}$  values were recorded in winter. The temperature outside the shelter showed more variability in comparison with the periphery and the centre. However, both inside locations tracked the outer environment, as expected in an open shelter. Figure 5.1, b) illustrates the temperatures on the different parts of the site wall (top, middle and bottom) for the 11 months of record. Recording at this location started one month later than in Figure 5.1, a). In addition, there were some problems with the dataloggers between October and December 2012 leading to missing data. The temperatures on the wall followed the temperature outside and exhibited similar daily and seasonal fluctuations. The temperature at the top of the wall went up to  $30.6 (\pm 0.5)^\circ\text{C}$  and at the bottom to  $24.2 (\pm 0.5)^\circ\text{C}$  in summer and dropped in winter below  $0^\circ\text{C}$  but less frequently than any of the locations in Figure 5.1, a). In general, the

temperature range on the wall was smaller than at the centre of the shelter with the bottom part of the wall being the most stable.



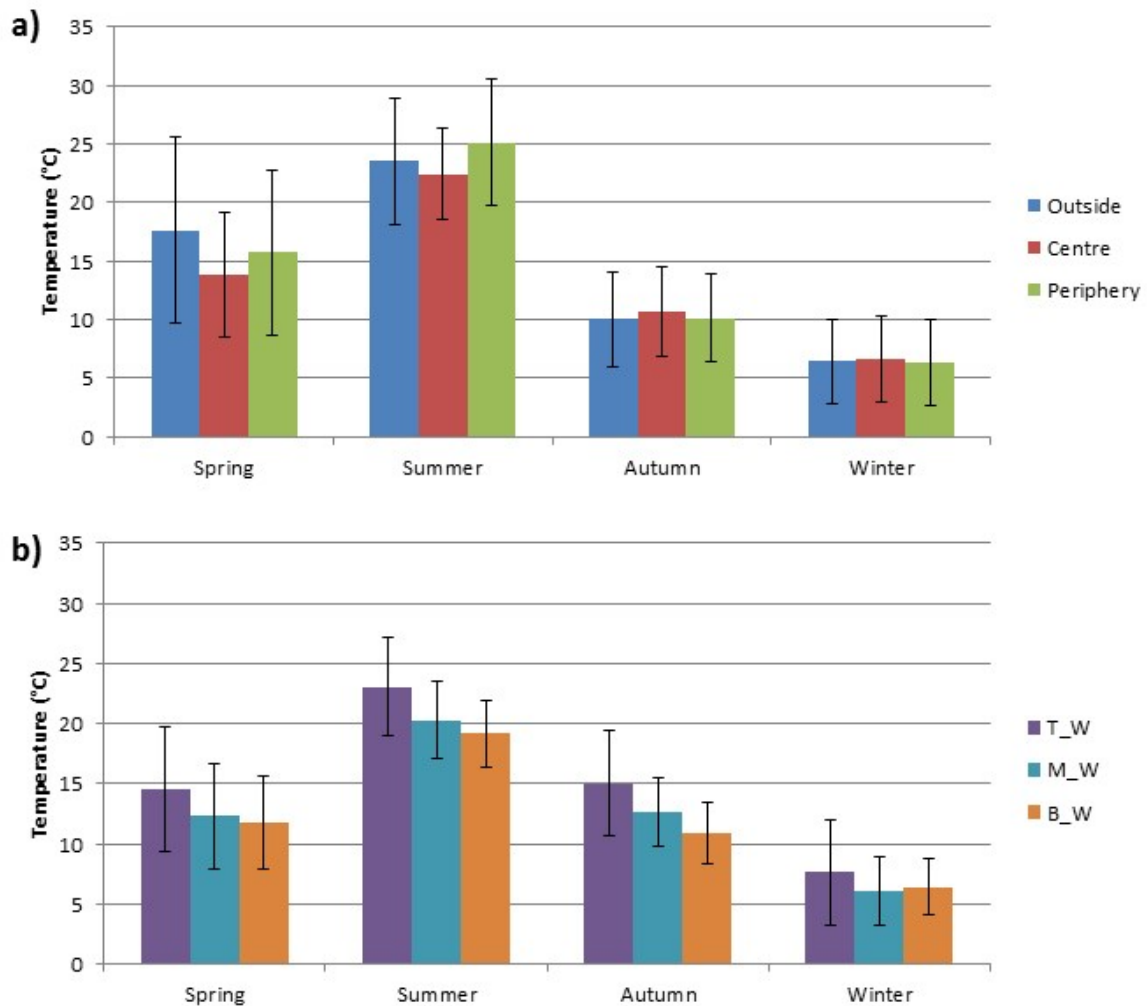
**Figure 5.1:** Temperature records a) outside the shelter, centre and periphery of the shelter and b) top, (T\_W), middle (M\_W) and bottom (B\_W) part of the wall between 2012 and 2013

Non-parametric Mann-Whitney-Wilcoxon tests on daily mean temperatures extracted from the raw data in Figure 5.1 a) showed that the periphery of the shelter was significantly warmer than outside ( $U=16629$ ,  $P=1.137e^{-09}$ ) but cooler than the centre of the shelter ( $U=34329.5$ ,  $P=0.0347$ ). In general, the central part of the shelter had higher daily mean temperatures compared with both the periphery and outside. These general findings obscure seasonal trends. For example, if the test is restricted for daily mean temperatures in summer (from 21<sup>st</sup> June to 20<sup>th</sup> September), Mann-Whitney-Wilcoxon tests showed that the periphery was significantly warmer than both centre ( $U=390$ ,  $P=3.042e^{-10}$ ) and outside the shelter ( $U=30$ ,  $P=4.377e^{-12}$ ). In addition, outside was warmer than the centre of the shelter in summer ( $U=1864$ ,  $P=0.0002$ ). On the other hand, in winter (from 21<sup>st</sup> December to 20<sup>th</sup> March), the centre of the shelter was warmer than the periphery ( $U=15347.5$ ,  $P<2.2e^{-16}$ ) and outside ( $U=208.5$ ,  $P<2.2e^{-16}$ ). At this time, there is no significant difference in daily mean temperatures between the periphery and outside ( $U= 8146$ ,  $P=0.899$ ). These results show that there was an unpredicted increase in temperature on the periphery during the hottest months.

The analysis of daily mean data from Figure 5.1, b) showed that the top part had significantly higher daily mean temperatures than the middle ( $U=23326.5$ ,  $P=0.001$ ) and bottom ( $U=21961.5$ ,  $P=0.017$ ) during the 11 months of record. The difference between the temperatures experienced by the middle and bottom parts of the wall was not significant ( $U=20582$ ,  $P=0.184$ ).

### 5.3.1.1. Maximum and minimum temperatures

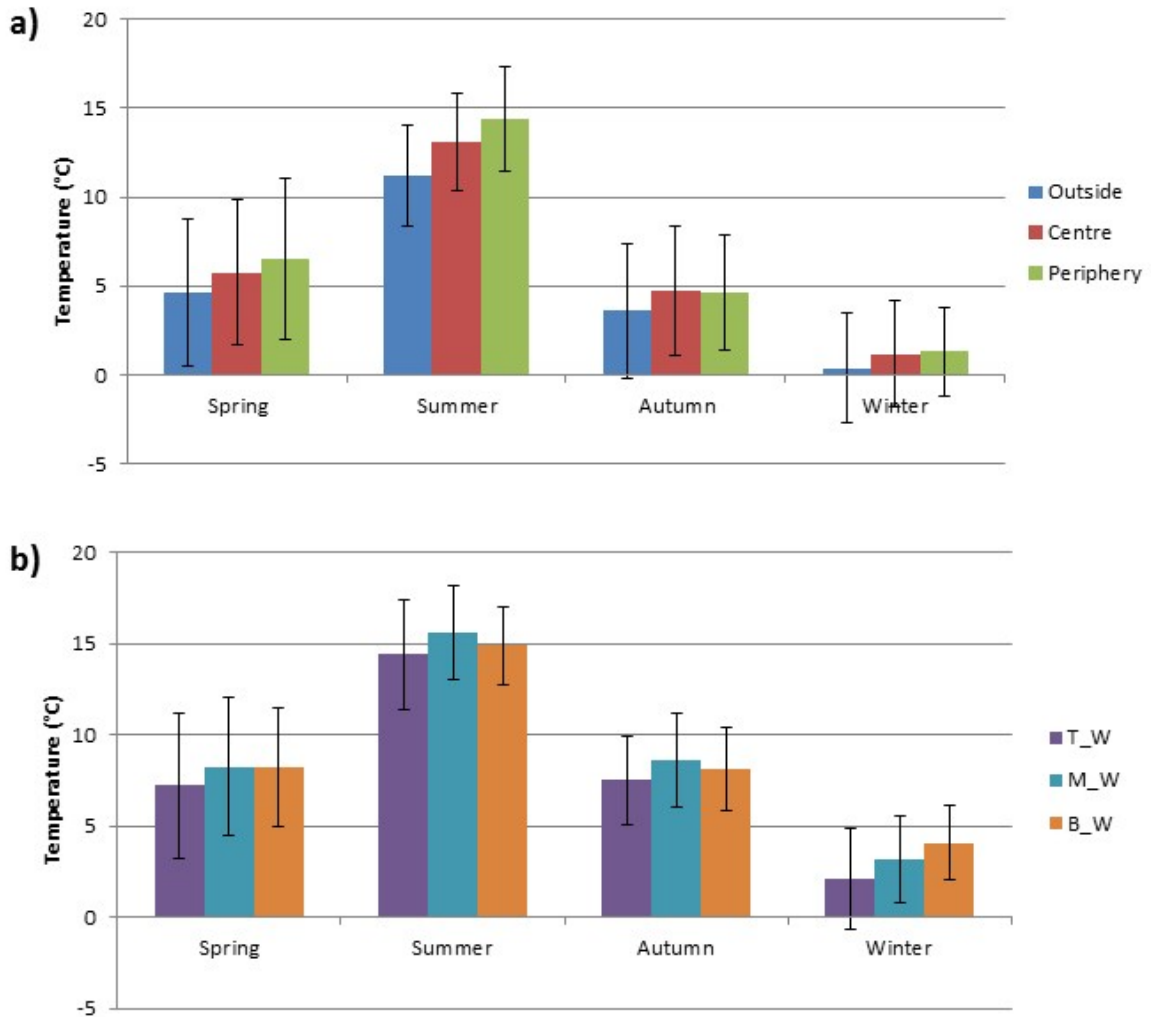
Figure 5.2 and Figure 5.3 show the seasonal means and standard deviations of daily maximum and minimum temperatures for the outside, centre and periphery of the shelter and top, middle and bottom parts of the wall respectively.



**Figure 5.2:** Mean and standard deviations of daily maximum temperature per season (a) outside, centre, periphery and (b) on the site wall (T\_W= top part of the wall; M\_W=middle part of the wall; B\_W= bottom part of the wall)

In autumn and winter, there were no clear differences in maximum temperatures between outside, the centre and the periphery of the shelter (Figure 5.2, a), whereas there was an increase in minimum temperatures in the centre and on the periphery in relation to outside during that period (Figure 5.3, a). In spring and summer, maximum

temperatures were lower in the centre than on the periphery and outside (Figure 5.2, a), and minimum temperatures on the periphery were greater than outside and in the centre (Figure 5.3, a).



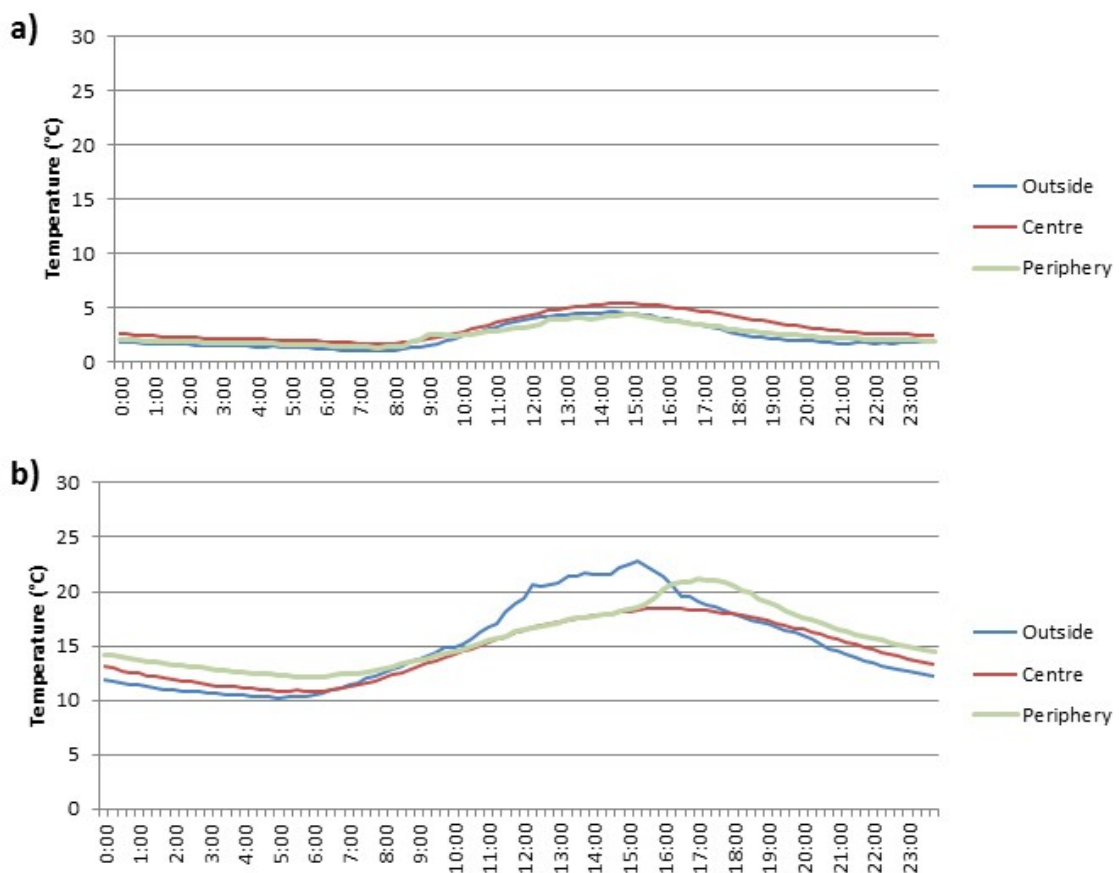
**Figure 5.3:** Mean and standard deviations of daily minimum temperature per season (a) outside, centre, periphery of the shelter and (b) at site wall (T\_W= top part of the wall; M\_W=middle part of the wall; B\_W= bottom part of the wall)

The outside had the greatest temperature range with high maximum and low minimum temperatures. The periphery had the warmest conditions with high maximum and minimum temperatures. The most stable position was the centre with low maximum and high minimum temperatures. In relation to the elevation of the wall, the top part had higher maximum and lower minimum temperatures than the

middle and bottom parts during the whole year (Figure 5.2, b and Figure 5.3, b). The middle and mainly the bottom parts of the wall were more stable than the top.

### 5.3.1.2. Hourly temperature

A synthetic representative day was calculated per every month with the hourly means to depict the impact of the shelter on temperature at different times of the day and year.

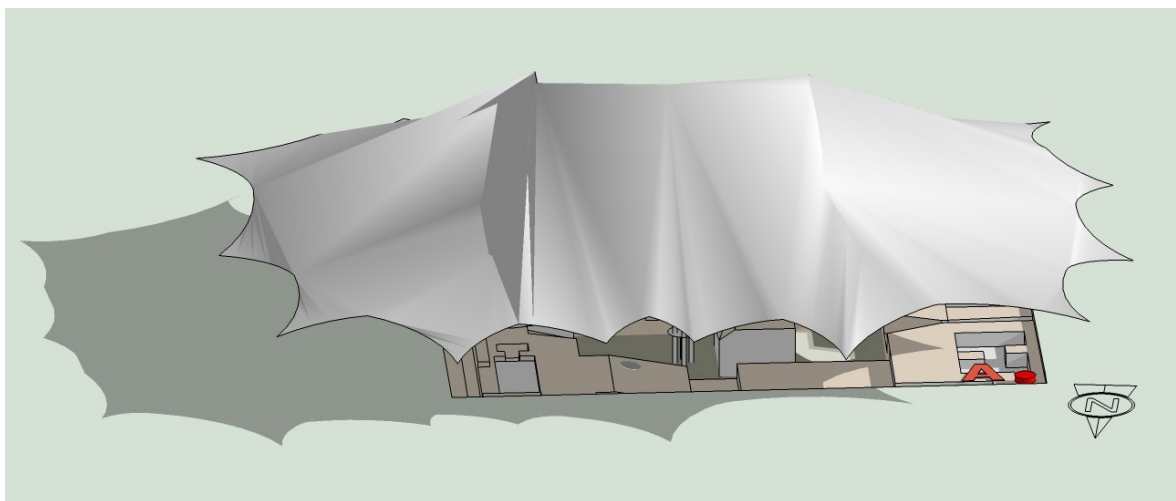


**Figure 5.4:** Hourly means of temperature outside, centre and periphery of the shelter in a) February 2013 and b) June 2013

Figure 5.4 a) represents the hourly means of temperature outside, in the centre and on the periphery of the shelter in February 2013. In winter, the central part of the shelter is slightly warmer than the other two positions; however, the difference is not as big as

in spring and summer. Figure 5.4 b) shows the hourly means of temperature outside, in the centre and on the periphery of the shelter in June 2013. The central part of the shelter experienced reduced maximum temperatures as expected. This can be related to the protective effect of the shelter against direct solar radiation. Figure 5.4 b) also shows that the outside was colder than the periphery and central part of the shelter at night in June 2013. These differences were even greater in July and August. These results are in line with Figure 5.3. The centre and periphery of the shelter had higher minimum temperatures than outside in summer. It is most probable that the shelter protected the environment from radiation heat loss during the night also seen by Maekawa (2006) in open shelters in El Salvador. On the other hand, the periphery showed higher temperatures than the centre of the shelter around 5 pm. This could be due to direct solar gain at this point in the early hours in the afternoon.

Figure 5.5 shows a representation of the shadows projected by the shelter on the site in June 2013 at 5 pm. The model was undertaken with Google SketchUp® and takes into account the real latitude, longitude, time zone and orientation of the site.



**Figure 5.5:** Simulation of shadows projected by the shelter at the Bishop's Palace on the 12<sup>th</sup> June 2013 at 5 pm. Point A is the location of the sensors on the periphery

Figure 5.6, a) and b) show the hourly means of temperature at the top, middle and bottom parts of the wall in February 2013 and June 2013 respectively. The top horizontal part of the wall had higher temperatures than the vertical middle or bottom sections around 11 am in winter and in day time in summer (Figure 5.6, b). Differences in the receipt of solar radiation between these locations may have been a key factor. Figure 5.7 shows how the shelter design allows solar radiation to hit the top part of the wall in the morning in winter.

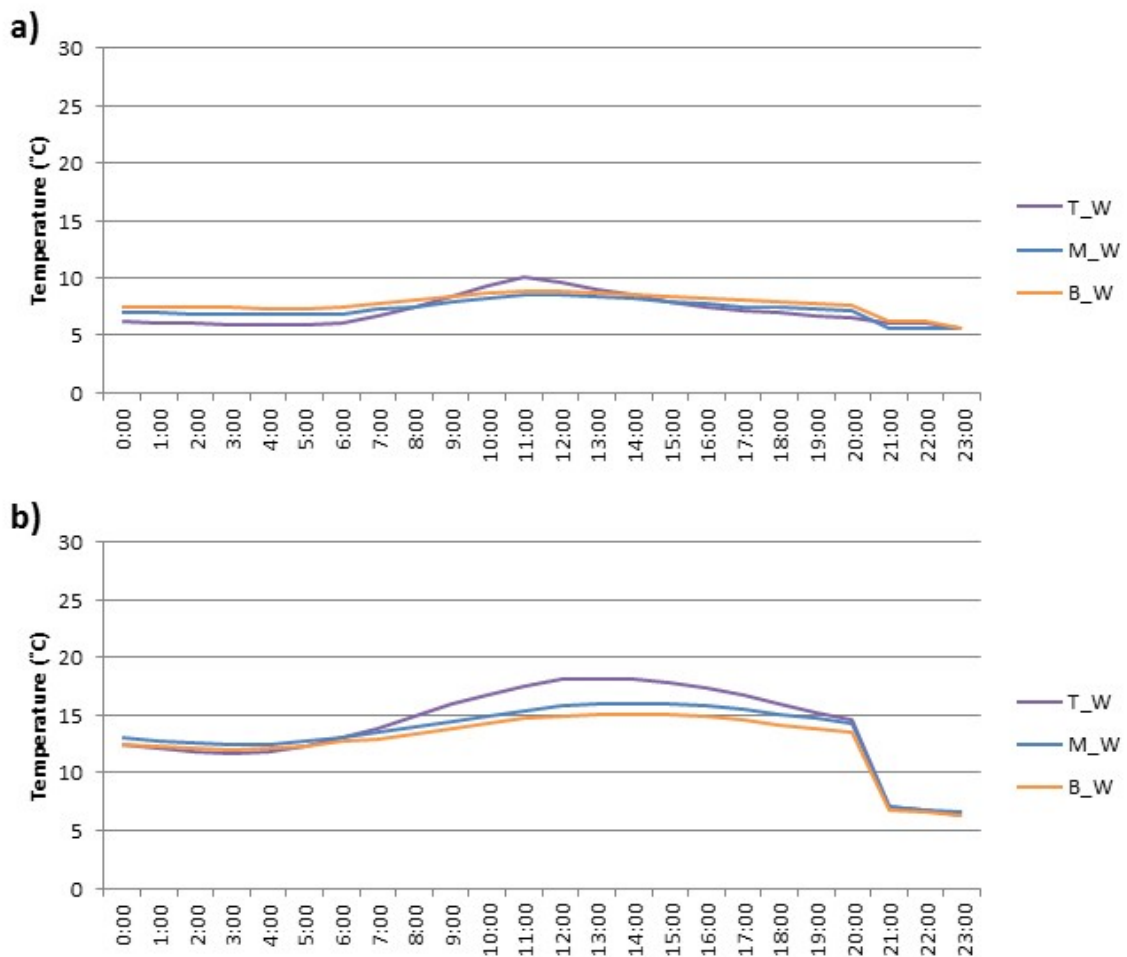
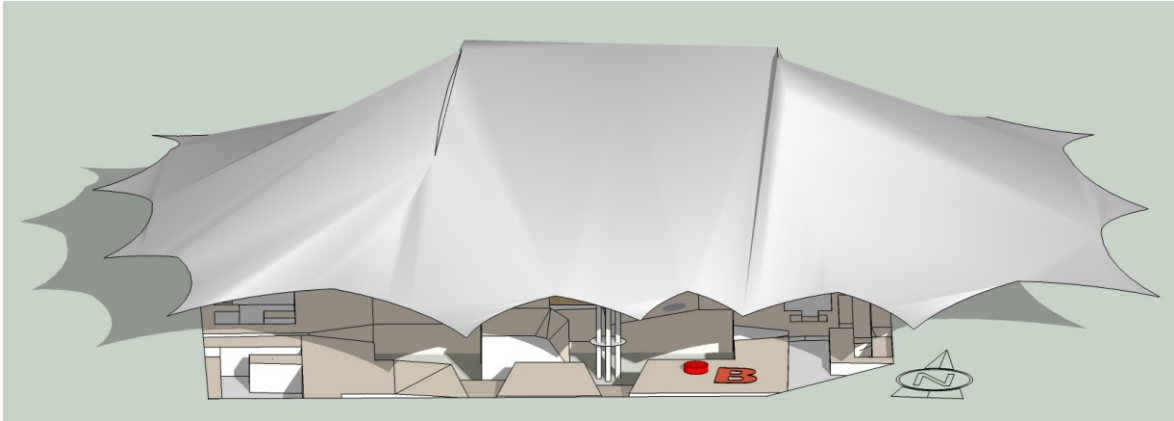


Figure 5.6: Hourly means of temperature at the top, middle and bottom parts of the wall in a) February 2013 and b) June 2013.



**Figure 5.7:** Simulation of shadows projected by the shelter at the Bishop's Palace on the 12<sup>th</sup> February 2013 at 11 am. Point B is the location of the sensor on the top horizontal surface of the site wall

As shown in Figure 5.4 b), the site walls showed lower temperatures than outside during the day and higher at night in summer. With an inner environment warmer than the outside, freezing-thaw cycles should be reduced, but if temperature sharply decreased at night (as in Figure 5.6, b) condensation might occur.

### ***5.3.1.3. Daily temperature fluctuations***

Non-parametric Mann-Whitney-Wilcoxon tests on the standard deviations of daily mean temperatures extracted from the annual raw data in Figure 5.1, show that the temperature outside varied significantly more than under the central part of the shelter ( $U=51613$ ,  $P<2.2e^{-16}$ ) and on the periphery ( $U=49657$ ,  $P<2.2e^{-16}$ ), while the periphery was more stable than the centre ( $U=45450.5$ ,  $P=3.323e^{-16}$ ). In addition, the temperature at the top part of the wall fluctuated significantly more than at the middle ( $U=37944$ ,  $P<2.2e^{-16}$ ) and the temperature at the middle varied significantly more than at the bottom ( $U=37080.5$ ,  $P<2.2e^{-16}$ ).

Another way to examine temperature fluctuations is to calculate the difference between maximum and minimum temperatures per day (i.e. the diurnal range). Monthly mean values for the diurnal temperature range outside, in the centre and on

the periphery of the shelter and at the top, middle and bottom parts of the wall are shown in Figure 5.8. Figure 5.8, a) shows that the diurnal temperature range in the central part of the shelter was smaller than the outside in summer. This is related to a reduction in daily maximum temperatures at this location (as seen in Figure 5.2), and it is probably because the shelter created a shadow effect. Daily temperature ranges on the periphery were similar to those in the centre of the shelter but with a wider range in April and July. There were particularly large differences outside. In addition, diurnal temperature ranges on the bottom and the middle parts of the wall were lower than on the top (Figure 5.8, b).



**Figure 5.8:** Mean of diurnal temperature difference per month (a) outside, centre and periphery of the shelter and (b) at the different parts of the wall (T\_W= top part of the wall; M\_W=middle part of the wall; B\_W= bottom part of the wall)

Table 5.4 shows the annual mean and 95% confidence intervals of diurnal temperature ranges for outside, centre and periphery of the shelter as well as on the site wall. The diurnal temperature range outside the shelter was highest with an annual mean of 8°C. On the other hand, the bottom part of the wall was the most stable, with a mean diurnal temperature range of only 1.3°C.

**Table 5.4:** Means and 95% confidence intervals for diurnal temperature differences (°C) outside, centre and periphery of the shelter and top, middle and bottom parts of the site wall in a year (2012-2013)

	Lower 95%	Mean	Upper 95%
Outside	7.59	8.04	8.50
Centre	5.87	6.23	6.61
Periphery	5.92	6.29	6.67
Top wall	2.93	3.16	3.40
Middle wall	1.40	1.53	1.67
Bottom wall	1.19	1.30	1.43

In order to find out if diurnal temperature ranges depended upon location, a multilevel linear model was fitted to the data, taking into account correlation for same day. Transformation of the daily temperature difference by raising it to the power  $\frac{1}{4}$  was found to produce acceptable normality and stability of variance in the model residuals. The statistical analysis indicates that there was no significant difference in diurnal temperature range between the central part of the shelter and periphery ( $t=0.451$ ,  $DF= 1557$ ,  $P=0.652$ ). However, both of them differed significantly from the range outside (Table 5.5). In addition, the bottom part of the wall differs significantly from the middle and top parts of the wall (Table 5.6) and all of them are significantly different from outside (Table 5.5).

**Table 5.5:** Results of the multilevel linear model with day as random effect for the diurnal temperature range values. Reference position: outside.

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.684	0.012	1557	139.075	<0.001
Centre	-0.104	0.008	1557	-13.348	<0.001
Periphery	-0.100	0.008	1557	-12.752	<0.001
Bottom wall	-0.615	0.008	1557	-75.976	<0.001
Middle wall	-0.571	0.008	1557	-67.355	<0.001
Top wall	-0.350	0.0085	1557	-41.321	<0.001

**Table 5.6:** Results of the multilevel linear model with day as random effect for the diurnal temperature values. Reference position: bottom part of the wall.

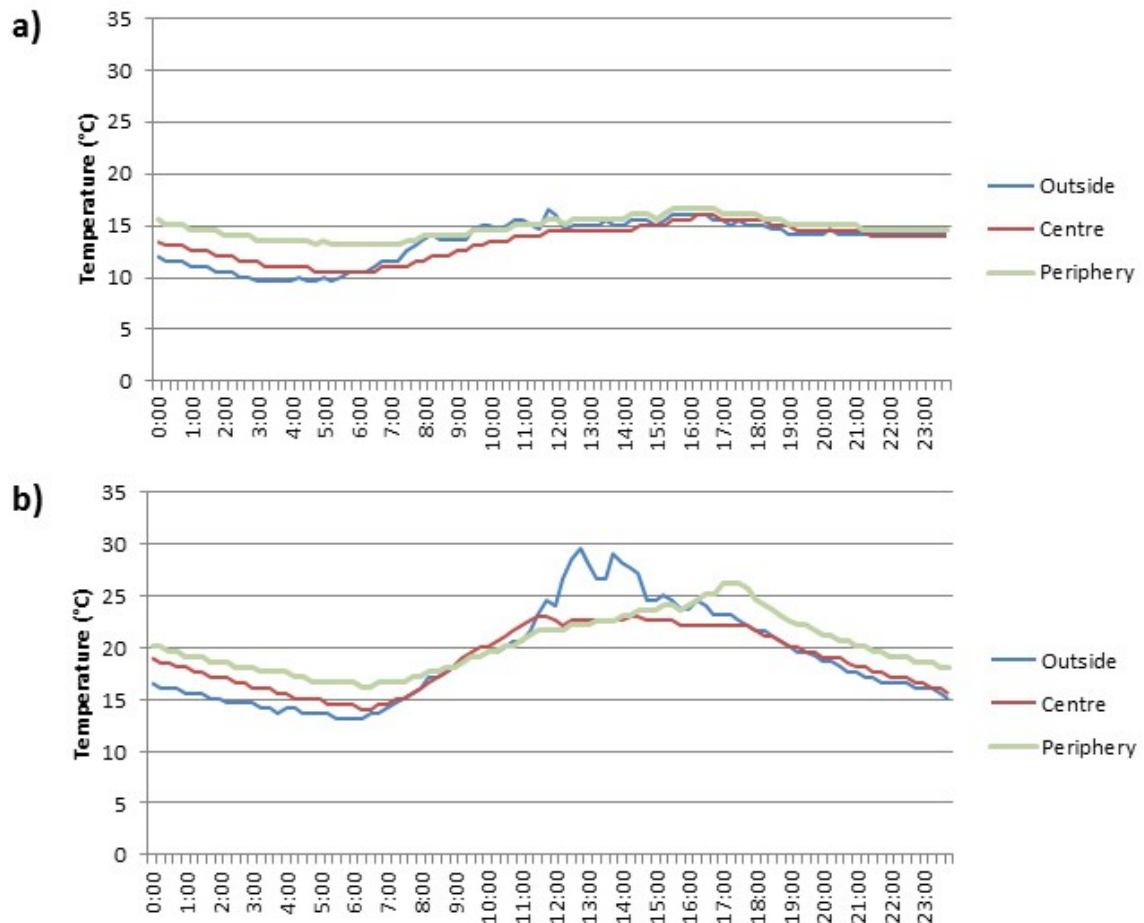
Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.069	0.012	1557	87.337	<0.001
Middle wall	0.043	0.009	1557	5.079	<0.001
Top wall	0.264	0.009	1557	31.026	<0.001

### 5.3.2. Solar radiation

Relatively small daily temperature ranges in winter indicate constant low temperatures, whereas diurnal temperature ranges increased in summer most probably because the maximum temperatures went up during the day, mainly outside (Figure 5.8). The reason could be the effect of solar radiation.

Figure 5.9 illustrates the changes in temperature outside, centre and periphery of the shelter on a cloudy and a sunny day in July 2013. These representative days were selected to explore in more detail the role of the shelter in reducing the effects of solar radiation. The differences in temperature between cloudy days (Figure 5.9, a) and sunny days (Figure 5.9, b) in the same month in summer show that during cloudy days, the diurnal temperature range was smaller and the temperature at all locations was very similar. Therefore, reduction in direct solar radiation under the shelter during

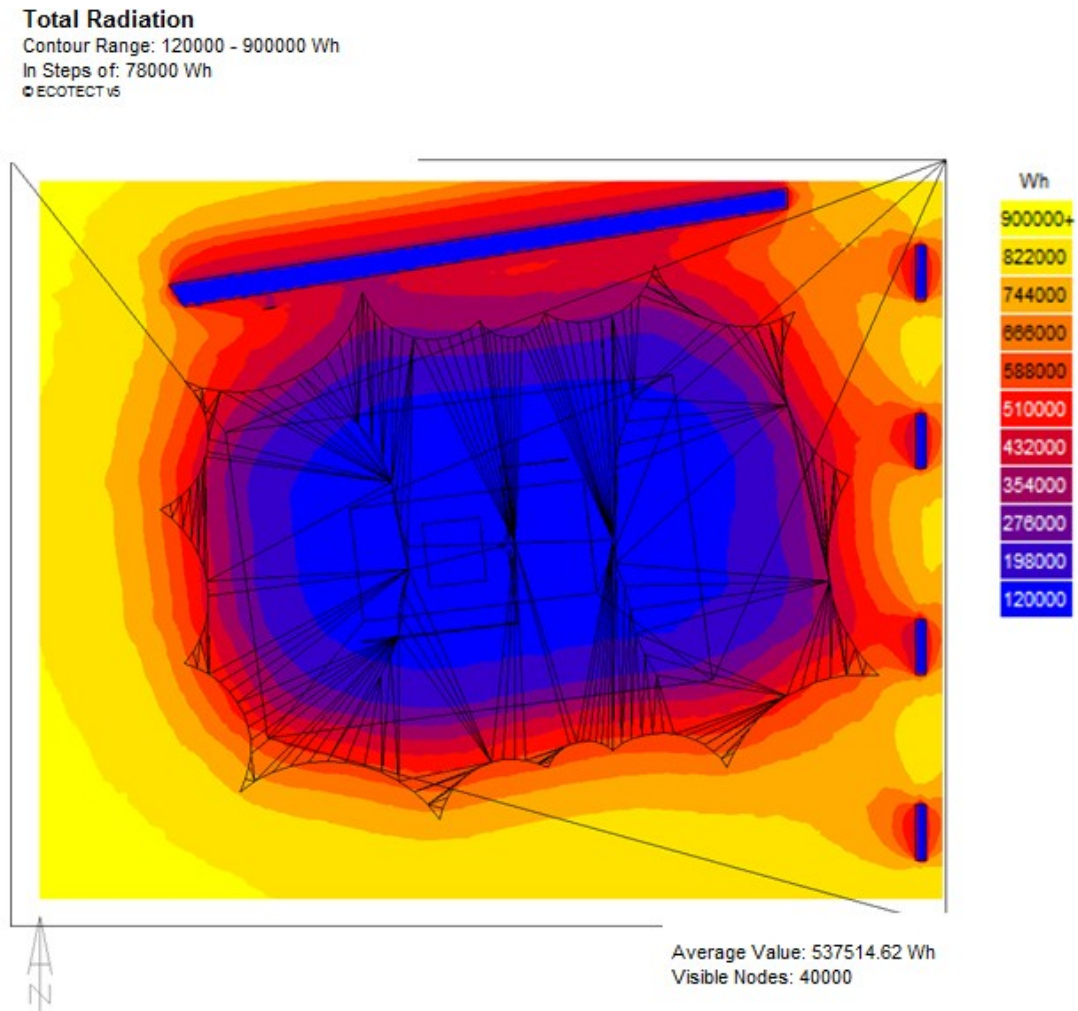
sunny days, mainly in summer, seems to be the main factor affecting the differences between daily temperature range inside and outside the shelter.



**Figure 5.9:** Temperature outside, in the centre and on the periphery of the shelter in summer on a) cloudy day (02/07/13) and b) a sunny day (10/07/13)

A theoretical insolation analysis for the Bishop’s Palace was undertaken in order to quantify the impact of the shelter on solar radiation. The results are illustrated in Figure 5.10. Total annual solar radiation inside the shelter is between 198000 and 120000 W/h, being for example 185700 W/h at the south-west point and 147200 W/h at the north-east. However, all points would receive 920000 W/h without a shelter. This is an assessment of the performance of the shelter which takes into account the presence of trees around the north and east side of the site. The trees increase the insulation effect of the shelter, mainly on the north-east side. They create shade and

protect the ruins from solar input by acting as lateral covers. The annual solar radiation at this point (NE) would go up to 162000 W/h without them. The NW corner is a peripheral location of the site. It is really close to the edge of the shelter and clearly affected by the outer environment. The annual total solar radiation at this point can reach 276000 W/h.

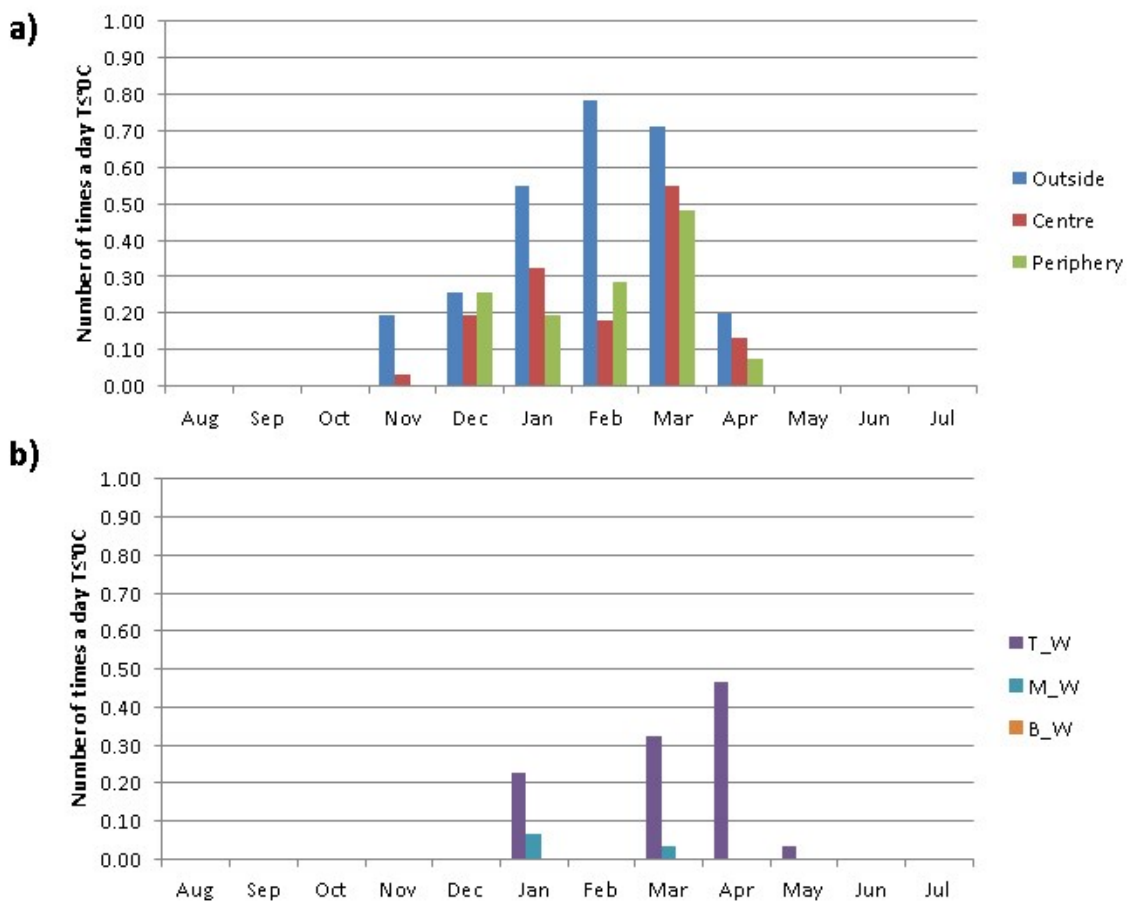


**Figure 5.10:** Theoretical insolation analysis for the Bishop’s Palace site carried out with Autodesk Ecotect® Analysis

### 5.3.3. Freeze-thaw events

Figure 5.11, a) and b) represent the number of times a day temperature dropped below 0°C (as a proxy for freezing events) outside, in the centre and on the NW periphery of the shelter and at the top, middle and bottom parts of the wall

respectively. Figure 5.11, a) shows that the greatest number of freezing events was registered outside the shelter as expected. On the other hand, the periphery tended to experience fewer number of events than the centre of the shelter. Figure 5.11, b) shows that there were no records of freezing temperatures on the bottom part of the wall and just two months registered frost events on the middle part. These results are in line with the daily minimum temperatures in winter shown in Figure 5.3.



**Figure 5.11:** Monthly mean of number of times per day temperature dropped below 0°C (a) outside, centre and periphery of the shelter and (b) outside and at different parts of the wall ( T\_W= top part of the wall; M\_W=middle part of the wall; B\_W= bottom part of the wall)

In order to demonstrate if there were significant differences in the number of freezing events per day between monitoring positions during the year of record, a 2-level Poisson Generalized Linear Model (GLM) was fitted with Day as the second level. There were no significant differences in the number of freezing events between outside and

the centre and periphery of the shelter (Table 5.7). In addition, freezing events were less likely to occur on the middle of the wall than at the top. Daily freezing events at the top part occurred 6 times as often as on the middle part (Table 5.8). As there were no freeze-thaw events recorded on the bottom part of the wall, this location was not considered in the model.

**Table 5.7:** Poisson GLM for mean number of freezing events per day with outside the shelter as reference position. Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-1.077	0.121	-8.895	< 2e-16	***
Centre	-0.201	0.191	-1.051	0.293	
Periphery	-0.057	0.202	-0.284	0.776	

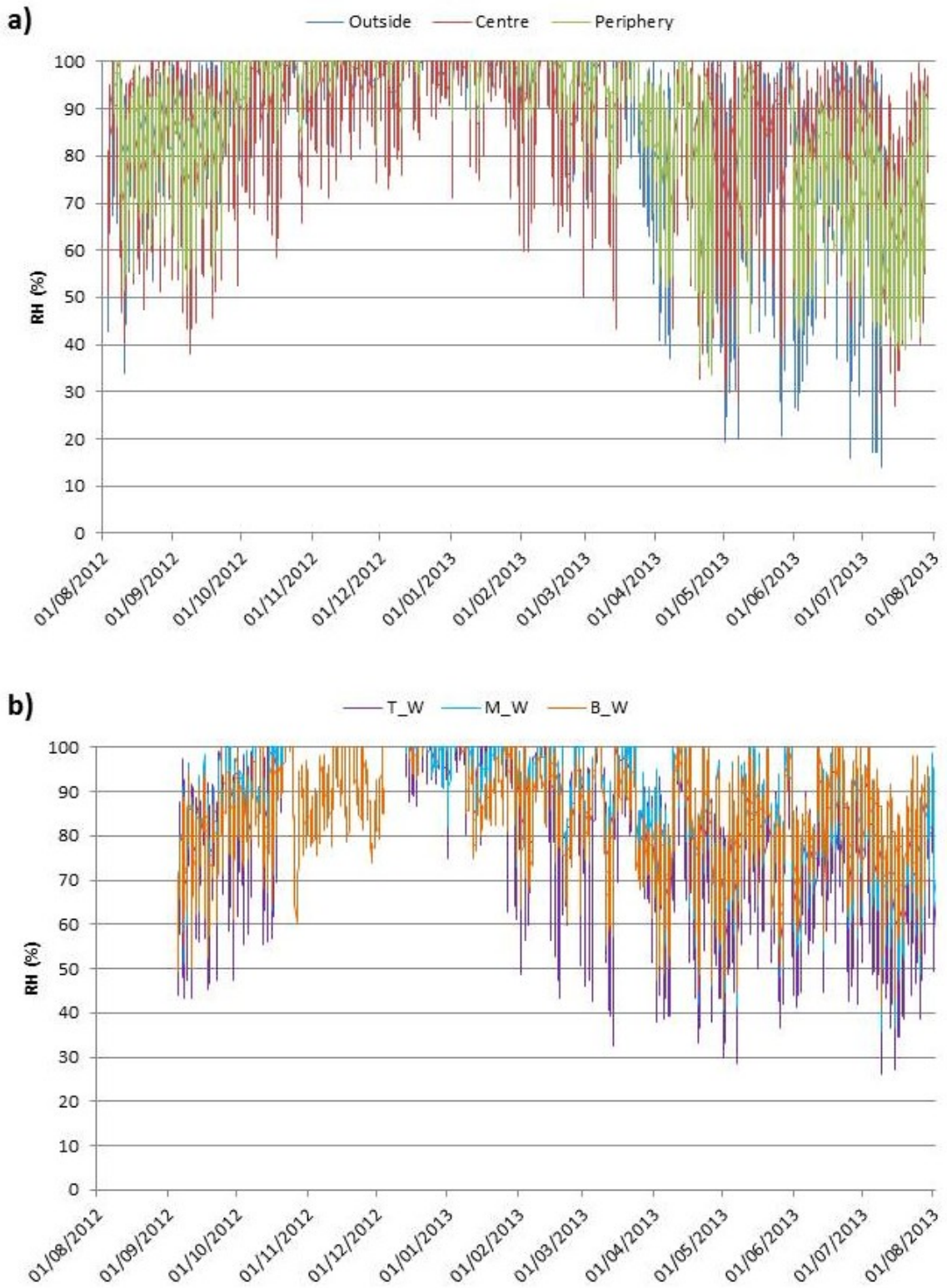
**Table 5.8:** Poisson GLM for mean number of freezing events per day with middle part of the wall as reference position. Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-2.638	0.580	-4.547	5.45e-06	***
Top wall	1.809	0.605	2.990	0.002	**

### 5.3.4. Relative Humidity

Figure 5.12 a) illustrates the RH values recorded outside, in the centre and on the NW periphery of the shelter for a year. The maximum RH was very high in all positions during the whole monitoring time. The minimum RH was higher in winter while in spring and summer the daily range was greater. In general, RH outside was higher and showed greater variability than inside the shelter. Figure 5.12 b) shows the near surface RH values on the site wall (top, middle and bottom) for the 11 months of record, which followed the outside trends. Maximum RH values were very high in all positions on the wall in winter but not as high as outside. In addition, the RH range was smaller not only than outside, but also than in the centre and periphery of the shelter,

as expected, given the differences in temperature ranges between these positions. The bottom part of the wall showed a more stable RH in relation to the top and middle.



**Figure 5.12:** RH readings a) outside the shelter, centre and periphery of the shelter and b) top, (T\_W), middle (M\_W) and bottom (B\_W) parts of the wall

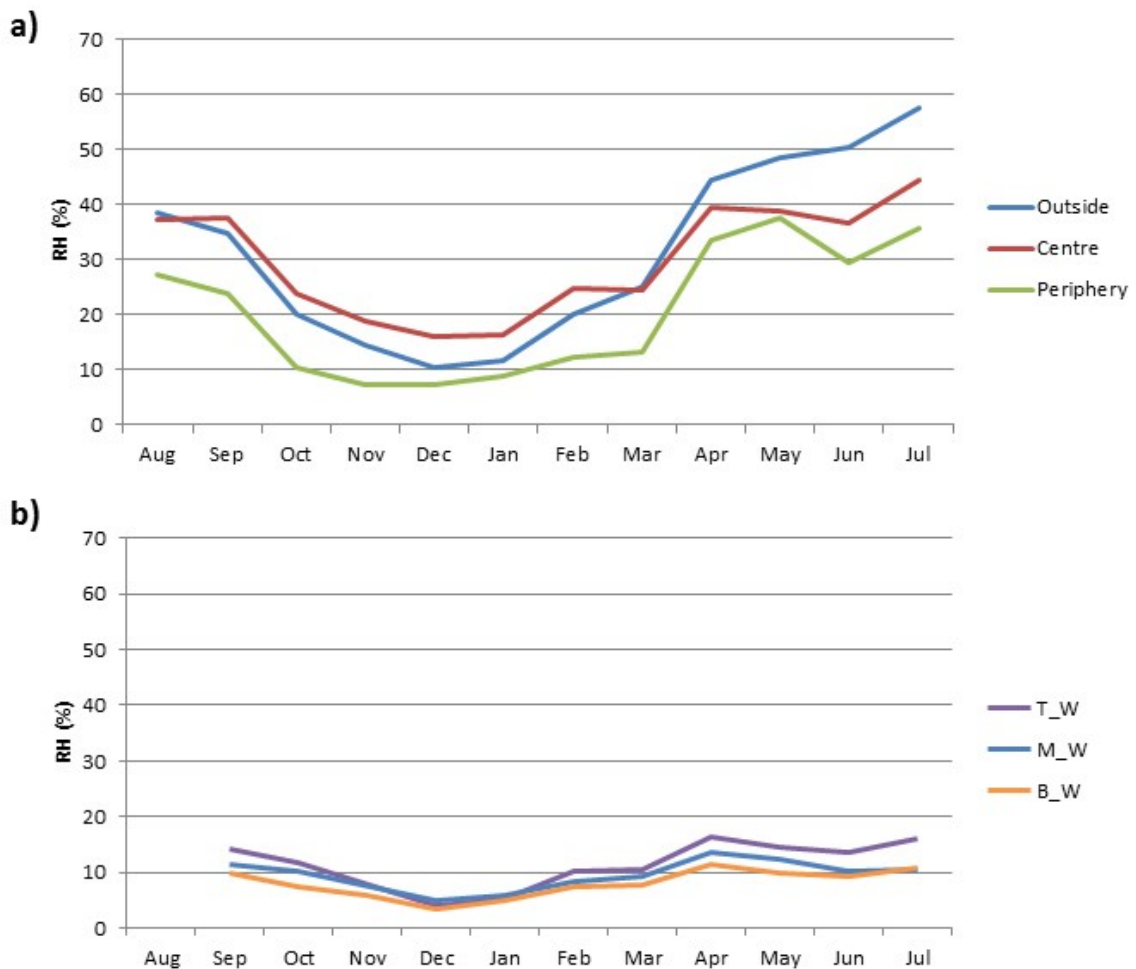
Non-parametric Mann-Whitney-Wilcoxon tests on daily mean RH show that, during the year of record, the peripheral area had higher RH than outside ( $U=6964.5$ ,  $P<2.2e^{-16}$ ) and the RH outside was higher than in the centre ( $U=33150$ ,  $P=3.19e^{-05}$ ). In addition, the middle part of the wall showed higher daily RH mean values than the top ( $U=3080.5$ ,  $P<2.2e^{-16}$ ) and bottom ( $U=24877$ ,  $P=1.409e^{-05}$ ), and the bottom part was more humid than the top ( $U=11440.5$ ,  $P=7.453e^{-09}$ ).

#### ***5.3.4.1. Relative Humidity fluctuations***

Non-parametric Mann-Whitney-Wilcoxon tests on the standard deviations of daily mean RH extracted from the annual raw data in Figure 5.12 show that RH outside the shelter fluctuated more than on the periphery ( $U=47529$ ,  $P<2.2e^{-16}$ ). However, there were no significant differences in RH variability between the centre and outside the shelter ( $U=25144.5$ ,  $P=0.608$ ). If we look at differences in standard deviations of daily RH means between both positions just in summer (from 21<sup>st</sup> June to 20<sup>th</sup> September), and winter (from 21<sup>st</sup> December to 20<sup>th</sup> March), we observe that the outside was more variable than the centre in summer ( $U=1780$ ,  $P=0.004$ ), whereas the central part of the shelter fluctuated more than outside in winter ( $U=693$ ,  $P=8.531e^{-08}$ ). The variability of RH at the top part of the wall was greater than on the middle ( $U=35030.5$ ,  $P<2.2e^{-16}$ ) and the middle part fluctuated more than the bottom ( $U=34439.5$ ,  $P<2.2e^{-16}$ ).

In addition, daily RH fluctuations can be analysed using differences between daily maximum and minimum RH values, which represent diurnal ranges. Figure 5.13 a) shows the monthly means of the diurnal range in RH outside, in the centre and on the periphery of the shelter. The diurnal RH range was greater in spring and summer than autumn and winter, especially outside the shelter. This indicates that the outside could

be more affected by salt weathering than inside the shelter, mainly during the hottest months of the year. Figure 5.13 b) shows the monthly means of the daily RH range at the top, middle and bottom parts of the wall. The site wall is more protected against RH fluctuations than outside and also the centre and periphery of the shelter. The bottom part showed the most stable RH.



**Figure 5.13:** Mean of diurnal RH range per month (a) outside, centre and periphery and (b) at the different parts of the wall (T\_W= top part of the wall; M\_W=middle part of the wall; B\_W= bottom part of the wall)

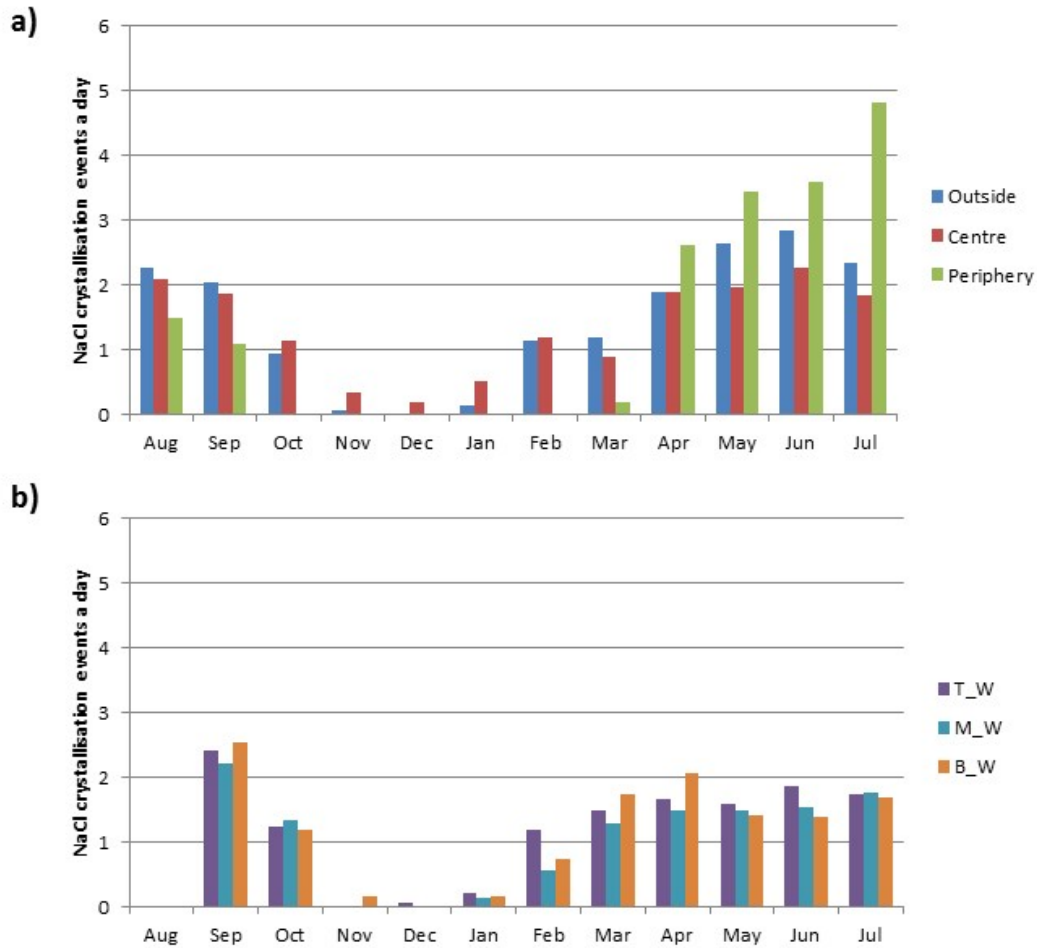
RH outside the shelter fluctuated more than on the periphery during the whole year. However, RH outside was only more variable than the centre of the shelter between March and August, when also all of the positions had a greater daily RH range. RH depends on temperature. Frequent changes in temperature in summer, such as day-

night cycles, made RH fluctuate more, mainly outside the shelter. In winter, the centre of the shelter fluctuated more than outside probably because outside there were constant lower temperatures. Although the periphery was more humid, it showed more constant RH values than outside and the centre of the shelter. Similarly, the bottom part of the wall showed higher RH values but fluctuated less than the top and middle parts.

#### **5.3.4.2. NaCl crystallisation events**

Figure 5.14 shows monthly means of the number of times RH crossed 75% per day (as a proxy for NaCl crystallisation-dissolution events), calculated from the raw RH data shown in Figure 5.12. There were a very small number of events in November, December and January. During this time, RH was over 75% almost all the time, mainly outside and on the periphery (Figure 5.12). The greatest number of salt crystallisation events was recorded in spring and summer, when RH varied over a wider range (Figure 5.13).

Figure 5.14 a) shows the monthly means of daily NaCl crystallisation events outside, in the centre and on the periphery. During winter, the few events recorded took place in the centre of the shelter. On the other hand, the central part of the shelter had the lowest numbers, in comparison with outside and the periphery, in spring and summer. During that time, the periphery showed the greatest numbers of salt crystallisation events. Figure 5.14 b) shows the monthly means of number of daily NaCl crystallisation events on the different parts of the wall. The majority of the events happened in spring and summer but there were no great differences between the top, middle and bottom parts of the wall.



**Figure 5.14:** Monthly means of the number of times RH crossed the NaCl threshold per day a) outside, centre and periphery of the shelter and b) top (T\_W), middle (M\_W) and bottom (B\_W) parts of the wall

The annual mean and the 95% confidence intervals of the number of NaCl crystallisation events per day are shown in Table 5.9.

**Table 5.9:** Means and 95% confidence intervals for daily NaCl crystallisation events in a year

	Lower 95%	Mean	Upper 95%
Outside	0.714	0.846	1.002
Periphery	0.642	0.763	0.908
Centre	0.666	0.790	0.937
Top wall	0.608	0.726	0.867
Middle wall	0.530	0.635	0.761
Bottom wall	0.594	0.708	0.843

The frequency of NaCl crystallisation events was greater outside the shelter than in the central part and on the periphery. The middle part of the wall had slightly fewer NaCl crystallisation events than the top and bottom parts.

A Poisson Generalised Linear Model (GLM) was fitted to determine whether there were significant differences in NaCl crystallisation events in the different positions. The number of times the NaCl threshold was crossed per day during the year of record was fitted as the response in the GLM with Location as an explanatory variable and taking into account correlation for same day. The results indicate the periphery and the central part of the shelter were not significantly different from outside (Table 5.10). GLM analysis also showed that the middle of the wall was not significantly different from the bottom. However, there was evidence of a slight difference between the number of NaCl crystallisation events occurring in the middle and the top part of the wall (Table 5.11).

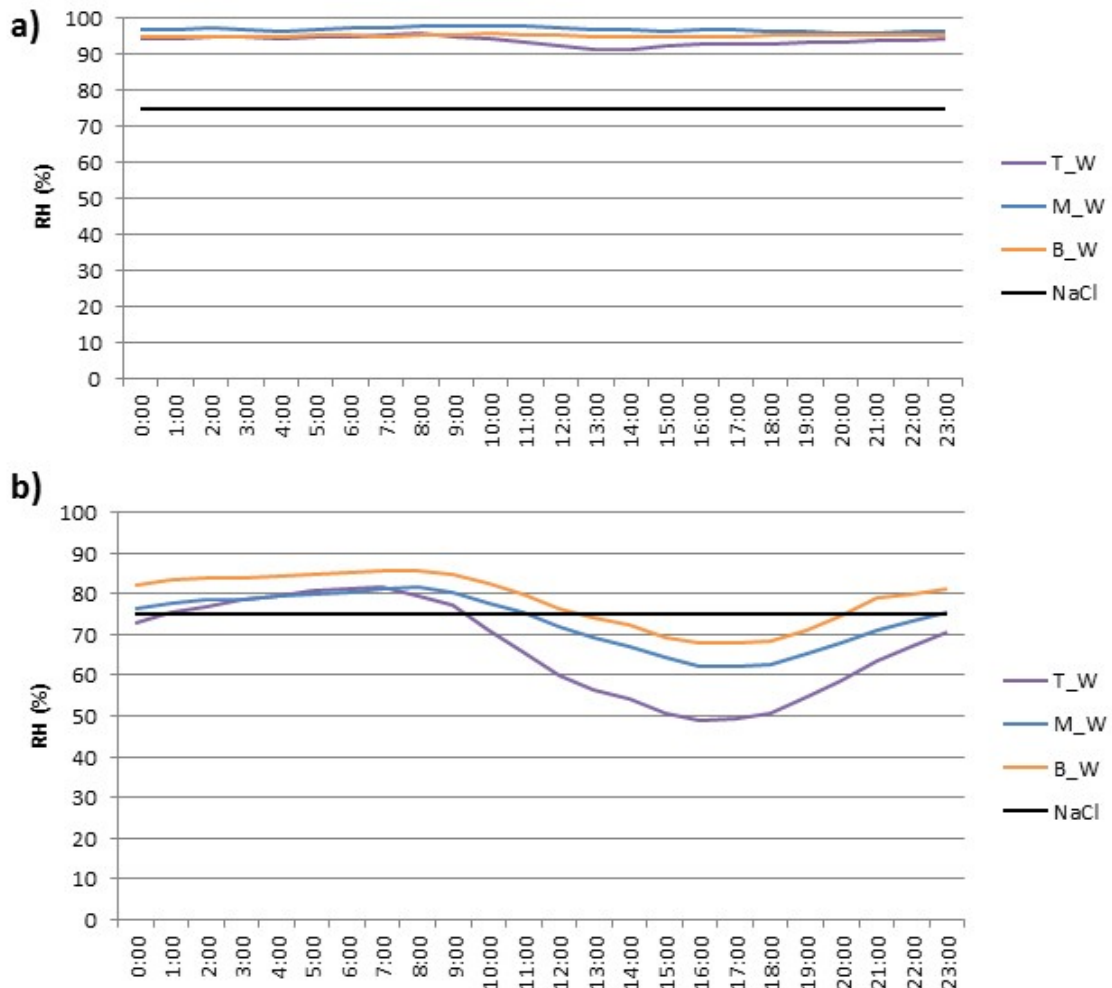
**Table 5.10:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallisation events per day with outside as reference position.

Position	Value	Std.Error	DF	t-value	p-value
(Intercept)	-0.167	0.086	1522	-1.932	0.054
Periphery	-0.103	0.066	1522	-1.567	0.117
Centre	-0.069	0.064	1522	-1.080	0.280

**Table 5.11:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallisation events per day with the middle part of the wall as reference position

Position	Value	Std.Error	DF	t-value	p-value
(Intercept)	-0.454	0.092	1522	-4.924	<0.001
Top wall	0.134	0.073	1522	1.844	0.065
Bottom wall	0.108	0.073	1522	1.488	0.137

A synthetic representative day was calculated per month using hourly RH means for the top, middle and bottom wall in order to find out more about the differences in RH on the site walls at different times of the day and year. There were no phase state transitions for NaCl in winter (Figure 5.15, a). On the other hand, the number of times RH crossed the reference value every day during summer is usually two at the top, middle and bottom parts of the wall. The RH values crossed the 75% threshold in early morning and evening. This means that on an average day during summer there was at least one cycle of crystallisation-dissolution of soluble salts on the walls considering NaCl as a reference (Figure 5.15, b).



**Figure 5.15:** Hourly RH means at the top, middle and bottom parts of the wall as well as outside in a) December 2012 and b) July 2013

### 5.3.5. Surface wetting events

The surface wetness values obtained with the leaf wetness loggers were used as a proxy for wetness occurrence on the surface of the remains and to compare the relative amount of water deposited on the sensors in the central part of the shelter and outside. Figure 5.16 show the monthly means of daily wetness level in the centre of the shelter and outside during the year of record. The graph represents daily means as absolute values on an arbitrary scale from 0-100%. They are related to the voltage output from the electrical grids of the sensors (see Chapter 3 for more information about methodology). The daily wetness mean was greater in winter and decreased in summer, which indicates that both positions were affected by the outer environmental conditions. However, the centre of the shelter was wetter than outside over the majority of the year.



**Figure 5.16:** Monthly means of daily mean wetness occurrence (%) outside and in the centre of the shelter

The results of the non-parametric Mann-Whitney Wilcoxon tests on daily wetness mean and standard deviations between the centre of the shelter and outside showed that the daily wetness occurrence was significantly higher in the centre of the shelter

than outside during the year of record ( $U=23421.5$ ,  $P=1.236e^{-05}$ ). However, there were more wet/dry transitions outside ( $U=45271.5$ ,  $P=8.733e^{-12}$ ). Additionally, a GLM model was fitted to find out if daily mean wetness depended on temperature mean, RH mean and position during the year the site was monitored. The results are shown in Table 5.12.

**Table 5.12:** Results of the Generalized Linear Model for daily wetness mean with outside the shelter as reference position (RH.Mean = Relative Humidity Mean; T.Mean = Temperature Mean); Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-180.953	11.654	-15.528	< 2e-16	***
Position Centre	68.882	25.658	2.685	0.007	**
RH. Mean	2.358	0.114	20.735	< 2e-16	***
T. Mean	1.072	0.306	3.502	0.000	***
Position Centre : T. Mean	-1.154	0.437	-2.642	0.008	**
Position Centre: RH. Mean	-0.332	0.241	-1.379	0.168	

RH mean influenced wetness but there was no significant interaction between RH and positions (in the centre and outside the shelter). Temperature mean also affected wetness and, in this case, there was a significant interaction. The wetness occurrence was significantly higher in the centre of the shelter than outside and the difference between them decreases with the mean temperature.

In order to examine the difference in wetness mean between inside and outside the shelter at different times of the day and months of the year, a synthetic representative day per month was calculated from the hourly wetness mean values.

Figure 5.17 illustrates the hourly means in wetness occurrence outside and inside the shelter in winter and summer (January and June as examples). The wetness output was usually greater in the early mornings and nights than during middays. Probably this is related to condensation events happening when the air is moist and surface

temperatures relatively low (Camuffo and Giorio, 2003). In addition, the wetness value was higher in winter mainly inside the shelter. However, the wetness outside the shelter fluctuated more than that inside during every month.

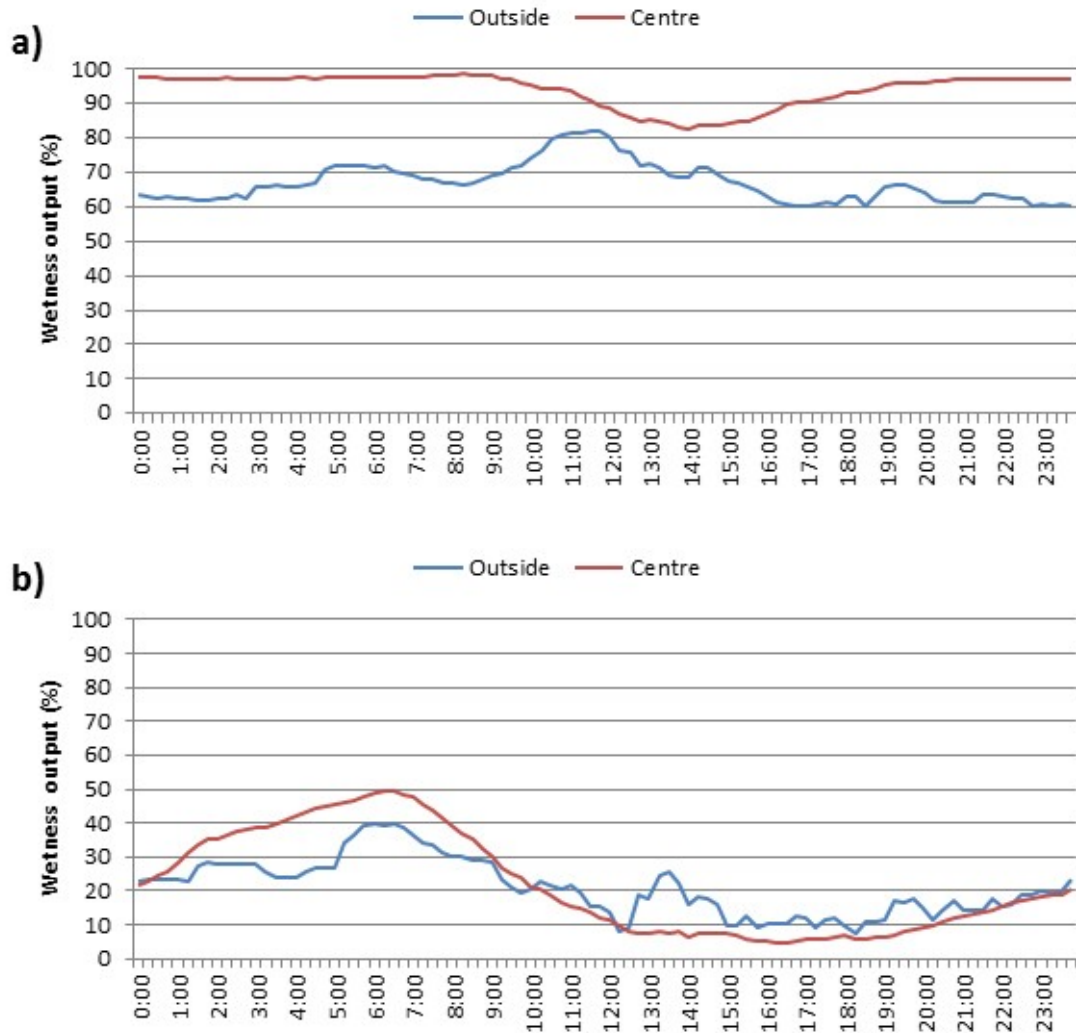


Figure 5.17: Hourly wetness mean (%) outside and centre of the shelter in a) January and b) June 2013

### 5.3.5.1. Dew point temperature

Another way to study surface wetness events is by looking into dew point temperature. It was calculated with surface temperature and RH values obtained from the hygrochron dataloggers, instead of the wetness leaf sensors, following the Magnus

formula (see section 3.2.2 in Chapter 3). Condensation occurs when dew point temperature ( $T_{dp}$ ) is equal to or in excess of surface temperature.

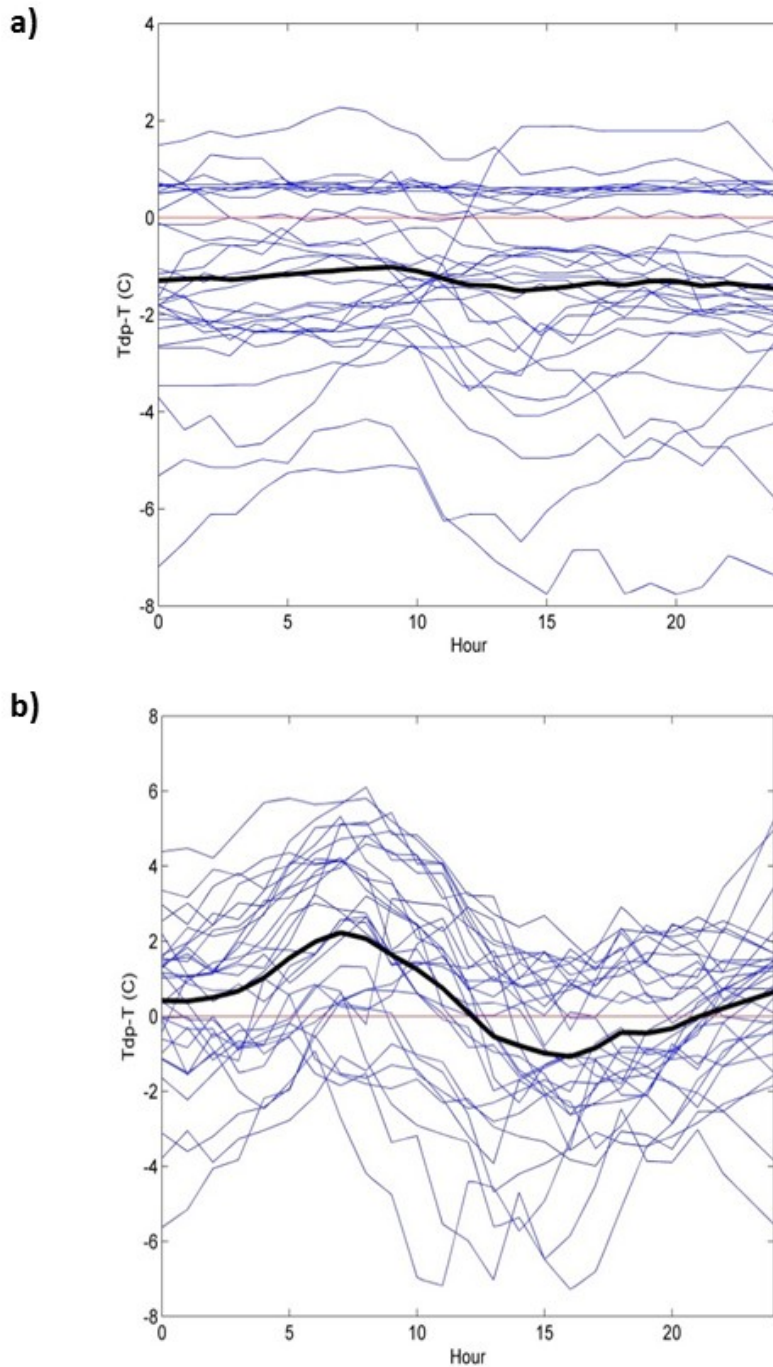
Table 5.13 shows the percentage of the time in a year when dew point temperature in the centre, on the periphery, outside and on the site wall was equal to or in excess of surface temperature. It represents how frequently condensation should take place on surfaces in the different positions. The central part of the shelter registered fewer condensation events than outside and the periphery, which had the highest likelihood of condensation. Condensation is also likely to occur more often on the middle part of the wall than on the bottom or at the top.

**Table 5.13:** Percentage of the total amount of time in a year when the surface temperatures were equal to or lower than the dew point temperature for each position

Outside	Periphery	Centre of the shelter	Top part of the wall	Middle part of the wall	Bottom part of the wall
36.5%	43%	34.2%	27.4%	31.4%	24.2%

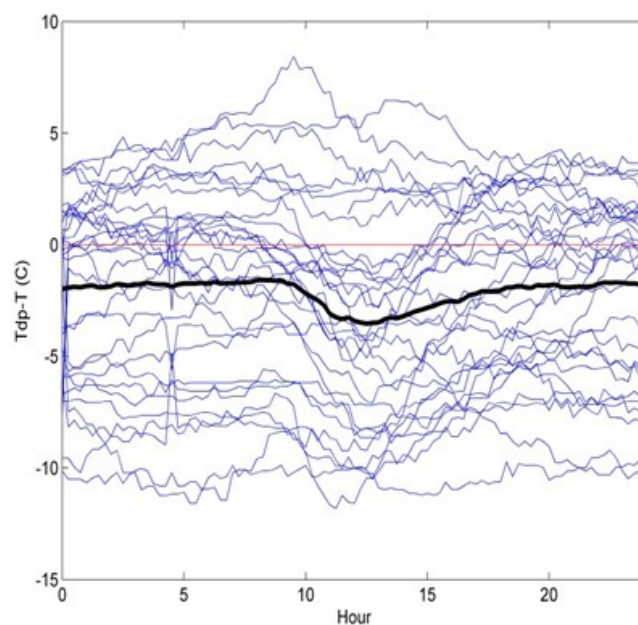
Additionally, the difference between dew point temperature and surface temperature has been plotted against hours of the day to find out at what time of the day condensation would happen at different times of the year. Figure 5.18 a) and b) show the difference between dew point and surface temperature at the bottom part of the wall in January and June respectively. Condensation was more likely to occur in June and in early mornings and evenings. Data from the top and middle parts of the wall follow the same trends. These results are in line with previous research (Camuffo, 1998, Camuffo and Giorio, 2003). Condensation is more likely to take place at night because of the contrast between the moist air and the low temperature of the walls. It is also common in early mornings because the nocturnal temperature inversion is still taking place while the sunshine produces some evaporation, resulting in an increase in

moisture and subsequent rise in dew point temperature. Additionally, during spring, the site walls are still cold and the air temperature is affected by warm and humid winds.



**Figure 5.18:** Differences in dew point temperature (Tdp) and surface temperature (T) in °C at the bottom part of the wall in (a) January and (b) June 2013. The black line shows the hourly mean of the difference between Tdp and surface temperature on all the days of the same month (blue lines). Condensation occurs when the difference between Tdp and surface temperature (y-axis) is over 0

There is a difference in results between the methods used to determine condensation events. The wetness sensors showed that the central part of the shelter remained wetter for longer in comparison with outside while the dew point temperature indicates that there were more condensation events outside the shelter than in the central part. For example, Figure 5.19 shows there was little probability of condensation at the centre of the shelter in January 2013 when the hourly dew point temperature mean was lower than the surface temperature. On the other hand, the wetness leaf sensor at the central part of the shelter recorded an hourly daily wetness mean of around 70% in the same month (Figure 5.17, a).



**Figure 5.19:** Differences in dew point temperature (Tdp) and surface temperature (T) in °C in the central part of the shelter in January 2013. The black line shows the hourly mean of the difference between Tdp and surface temperature on all the days of January (blue lines). Condensation occurs when the difference between Tdp and surface temperature (y-axis) is over 0

## 5.4. Discussion and conclusions

The research has shown some clear trends in microclimatic conditions over a year. Some results were as expected (Table 5.2) and others quite different (Table 5.14 and Table 5.15).

**Table 5.14:** Results and ranges of specific microclimatic conditions outside, on the periphery and in the centre of the shelter\*. When the values were significantly different to the other positions it is marked in red\*

	Outside	Periphery	Centre
Mean daily T in summer	16.1°C (Medium)	18.2°C (Medium)	17.5°C (Medium)
Mean daily T in winter	3.6°C (Medium)	3.7°C (Medium)	4.2°C (Medium)
Mean diurnal T range in summer	12.3°C (High)	10.8°C (Medium)	9.4°C (Medium)
Mean diurnal T range in winter	5.4°C (Medium)	4.4°C (Low)	4.7°C (Low)
Total annual solar radiation	920 kW/h (High)	354 kW/h (Medium)	120 kW/h (Medium)
Freezing events in a year	81 (High)	43 (Medium)	39 (Medium)
Mean daily RH	88.7% (Medium)	91.5% (High)	87.2% (Medium)
Mean diurnal RH range in summer	44% (High)	30.5% (Medium)	41% (High)
Mean diurnal RH range in winter	16.8% (Medium)	10.3% (Low)	20.1% (Medium)
NaCl crystallisation events (mean number per day)	0.84 (Low)	0.76 (Low)	0.79 (Low)
Time in a year (%) with condensation events	36.5% (Medium)	43% (Medium)	34.2% (Medium)

**Table 5.15:** Results and ranges of the specific microclimatic conditions at the top, middle and bottom parts of the representative wall\*. When the values were significantly different to the other positions, it is marked in red\*.

	Top	Middle	Bottom
Mean daily T in summer	18.5°C (Medium)	17.8°C (Medium)	16.9 °C (Medium)
Mean daily T in winter	4.7°C (Medium)	4.8 (Medium)	5.5 °C (High)
Mean diurnal T range in summer	4.6°C (Low)	2.4°C (Low)	2.3°C (Low)
Mean diurnal T range in winter	2.9 (Low)	1.2 (Low)	0.9 (Low)
Freezing events in a year	32 (Medium)	3 (Low)	0 (Low)
Mean daily RH	82.8% (Medium)	86.2% (Medium)	85.8% (Medium)
Mean diurnal RH range in summer	16.1% (Medium)	11.4% (Low)	11% (Low)
Mean diurnal RH range in winter	7.5% (Low)	6.9% (Low)	5.7% (Low)
NaCl crystallisation events (mean number per day)	0.73 (Low)	0.63 (Low)	0.76 (Low)
Time in a year (%) with condensation events	27.4% (Low)	31.4% (Medium)	24.2 (Low)

\* For daily T in summer: HIGH=above 20°C, MEDIUM=20-10°C, LOW= below 10°C. For daily T in winter: above 5 °C, MEDIUM=5 to -5°C, LOW= below -5°C. For diurnal T ranges: HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of freezing events: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For daily RH: HIGH=above 90%, MEDIUM=90-60%, LOW= below 60%. For diurnal RH ranges: HIGH=above 30%, MEDIUM=30-15%, LOW= below 15%. For annual mean NaCl crystallisation events per day: HIGH=above 3, MEDIUM=3-1, LOW= 1. For condensation events (%time): HIGH=above 60%, MEDIUM=60-30%, LOW= below 30%.

Table 5.14 and Table 5.15 summarise the risk of stone decay due to temperature (means and ranges), solar radiation, freezing events, RH (means, ranges and NaCl crystallisation events) and wetting events based on the data collected.

The first objective of this chapter was to evaluate the microclimate inside the shelter (centre and periphery) in comparison with outside. In order to answer this question, results (summarised in Table 5.14) were compared with the predictions in Table 5.2. The results showed that, as expected, the outside had a more extreme environment. Although summer temperature and RH values were lower than expected, diurnal temperature and RH ranges (mainly in summer), solar irradiation and freezing events were higher than in the centre and on the periphery of the shelter during the monitoring year. In the centre of the shelter, mean daily temperature values, diurnal temperature and RH ranges, solar irradiation and frost events were all higher than expected. In addition, mean daily temperature and RH range in the central part under the shelter in winter were significantly higher than the outside and periphery. The microclimate on the periphery was similar to that predicted. However, wetting events, temperature values in summer, and mainly annual RH values were significantly higher than in the other two positions. Although, in general, the outer environment fluctuated more than that inside the shelter (centre and periphery), which could increase the risk for salt crystallisation events, there were no significant differences in NaCl crystallisation events between positions.

The reason for sheltering the site was to exclude frost and extreme temperatures and minimise water entry and movement (see Chapter 4). The shelter reduced the effect of direct solar radiation on the site ruins, but it seems not to have protected the site as

much as expected. The central part of the shelter is able to reduce the severity of temperature fluctuations within the ruins, with a subsequent reduction in the number of freezing events, but freezing did occur occasionally (Figure 5.11). In addition, the peripheral area (NW of the site) showed higher RH values than the centre and outside the shelter (see section 5.3.4). Wetting events were also frequent (Table 5.13). The ruins have moisture stains at this location. The deficiency in cover design in this area, at the edge of the shelter, could affect stone decay. Especially after heavy rain, water puddles are visible on the ground (see Chapter 4). Rainwater could be re-directed onto the periphery by the shelter or a faulty drain. On the other hand, the NW periphery was more stable than outside the shelter in terms of temperature and RH fluctuations probably due to high but constant RH values. This makes this area less vulnerable to frost and salt crystallisation events but at high risk of biocolonisation. In addition, chemical weathering due to pollutant deposition, which could lead to material loss, is more accelerated on wetter (Török, 2002a) and horizontal surfaces (Camuffo and Giorio, 2003), as the NW point. Increased temperatures on the periphery at specific times of the day are related to the faulty covering area of the shelter (see section 5.3.1.2).

The second objective was to determine how the microclimatic conditions within the shelter are experienced by upper, middle and lower portions of the ruined walls. In order to answer this question, results (summarised in Table 5.15) were compared with the predictions in Table 5.3.

The bottom part of the wall behaved as expected with the exception of higher temperatures in summer. In fact, all parts of the wall had higher temperature values

than predicted during that season, but they were significantly higher at the top (see section 5.3.1). The temperature and RH at the top portion of the wall also fluctuated significantly more than at the middle or bottom (Figure 5.8 and Figure 5.13). In addition, the top part experienced more freezing events than predicted and these were higher than in the other two locations (Figure 5.11). The middle part was more humid than the top or bottom. It also experienced more wetting events as measured by dew point temperatures (Table 5.13). However, it had fewer RH fluctuations in summer and NaCl crystallisation events than predicted.

The bottom part of the wall was very stable in terms of microclimatic fluctuations but it was also very humid. This could be due to the access of water to the wall from the ground through capillarity action and no direct sunlight; therefore biocolonisation could be a problem. The risk of frost or salts crystallisation was, however, reduced because this area presented fewer fluctuations than the top part of the wall (see sections 5.3.1.3 and 5.3.4.1). However, the presence of soluble salts in the stone pores might increase the dew point temperature and condensation could occur in relatively dry environments (Camuffo, 1998). On the other hand, the top wall had more variability in RH with a subsequent increase in the probability of salt weathering. Although the frequency of condensation was in line with other parts of the wall (Table 3.10), the amount of water deposited by nocturnal condensation events may be higher because the top part of the wall is a horizontal surface (Camuffo and Giorio, 2003). Therefore, the risk of salt weathering increases. The top section also tracks the outer environment. It had higher temperature values in summer than predicted, probably due to direct solar radiation at specific times of the day, and frequent fluctuations, which makes frost weathering relevant. The middle part of the wall was thought to be

a transition zone between upper and lower sections and also an evaporation zone with risk of salt weathering. This area is close to the limit of moisture rise (just above the moisture stain on the wall). Although NaCl crystallisation events were not significantly more frequent on this section of the wall than on the others (see section 5.3.4.2), the middle part of the wall was very humid and with frequent wetting events. Therefore, crystallisation of soluble salts could be taking place in a slightly different place on the wall, between the middle and the top (Charola, 2000).

Regarding the methods used in this chapter, it has been demonstrated that a wide range of microclimatic conditions can be determined by just monitoring temperature and RH with simple equipment and calculations. In addition, the monitoring can be done simultaneously at different locations allowing comparisons. However, wetness events are especially difficult to monitor. As we have seen in the results obtained with the wetness logger sensors (section 5.3.5), wetness events would take place mainly inside the shelter in winter, when, additionally, the difference between inside and outside the shelter increased. However, there is less probability of condensation in this situation. The dew point calculations show that condensation occurred in mornings and evenings but it was more probable in spring due to the thermal inertia of the monument. Although the wetness leaf sensors reflect the early morning and night condensation events and also high ambient humidity, they could not be able to reproduce the real situation in the ruins. Therefore, the wetness loggers are not an effective method to find out if condensation is happening on the site unless previous calibration is carried out in order to determine the exact equivalence between the voltage output and the moisture content of the stone at a certain ambient temperature and RH.

## **6. EVALUATING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON LIMESTONE DECAY WITH CHALK, COTSWOLD LIMESTONE AND PORTLAND STONE BLOCKS**

### **6.1. Introduction and aims**

The inherent characteristics of carbonate stones influence their weathering (Schaffer, 1932, Rodriguez-Navarro and Doehne, 1999, Siegesmund and Dürrast, 2011) but environment and time also have an influence on the change in their properties (Bell, 1993, Inkpen and May, 2006). Using a greater variety of techniques permits the determination of a wider range of interconnected decay processes (Doehne and Price, 2010, Přikryl, 2013). In addition, it is ensured that the results are independent of the method used (Nicholson, 2002). Surface techniques, such as visual assessments, can determine the nature of stone deterioration, and techniques which quantify change in stone properties provide an insight beneath the surface and also allow a measuring of the degree and rate of deterioration (Siedel et al., 2011). A large number of techniques is available (Stuart, 2007, Török and Přikryl, 2010). However, percentage weight change (Inkpen, 1995, Nicholson, 2001), surface hardness (Aoki and Matsukura, 2007, Viles et al., 2011) , Young's modulus (Goudie and Viles, 2000, Nicholson, 2002, Viles and Goudie, 2007) ultrasonic pulse velocity (Nicholson, 2002, Ahmad, 2011), and colour change (Viles et al., 2002, Viles and Gorbushina, 2003, Cutler et al., 2013) have been extensively used to measure the degree of deterioration.

This chapter aims to quantify and compare the degree and nature of limestone deterioration outside and inside the shelter at the Bishop's Palace at Witney using Chalk, Cotswold limestone and Portland stone blocks (hereafter Chalk, Cotswold and

Portland). The reason for using small blocks was to obtain representative information about decay within a short period of time and without invasive sampling of the remains themselves.

The following research questions have been examined using the stone blocks:

1. To what extent does the shelter affect the degree of deterioration of the stone blocks as quantified by:
  - 1.1. Dry weight change
  - 1.2. Change in elasticity
  - 1.3. Change in surface hardness
  - 1.4. Change in ultrasonic pulse velocity (UPV)
2. How effective is the shelter at reducing environmental causes of deterioration in the stone blocks, such as:
  - 2.1. Moisture content
  - 2.2. Surface temperature (fluctuations and freezing events)
3. How does the shelter influence the nature of deterioration and soiling in the stone blocks assessed by:
  - 3.1. Surface colour
  - 3.2. General appearance (through macroscopic and microscopic pictures)

## **6.2. Materials and methods**

The degree and nature of deterioration and soiling were determined by monitoring change in dry weight, elasticity (EMOD), surface hardness, ultrasonic pulse velocity (UPV), surface colour, macroscopic and microscopic characteristics, moisture content and surface temperature in the stone blocks. A summary is shown in Table 6.1.

**Table 6.1:** Pieces of equipment used to monitor changes in stone blocks properties and environmental factors of decay as well as data handling and statistical analysis methods

	<b>Equipment</b>	<b>Data handling</b>	<b>Statistical analysis</b>
<b>Dry weight</b>	Balance	Percentage of initial dry weight per block after 3, 9 and 12 months	Two-way ANOVA tests per each stone type (variables: location and months). Three-way ANOVA test (variable: stone type, months and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>EMOD</b>	Grindosonic	Means and standard deviations of EMOD (median) after 3, 9 and 12 months	Three-way ANOVA test (variables: stone type, months and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Surface hardness</b>	Equotip	Median HL per block before and after 12 months	Three-way ANOVA test (variables: stone type, months and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>UPV</b>	Pundit	Means and standard deviations of UPV (median) after 3, 9 and 12 months	Three-way ANOVA test (variables: stone type, months and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Surface colour</b>	Spectro-photometer	dE*ab per block (overall colour change) after 3, 9 and 12 months, dE*ab, dL*, da* and db* means and reflectance of selected blocks	Two-way ANOVA tests per each stone type (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Macroscopy</b>	DSRL camera	Pictures (before and after 12 months)	
<b>Microscopy</b>	35x optical microscope	Pictures (before and after 12 months)	
<b>Moisture content</b>	Field balance, FMW meter	Means of percentage of initial dry weight and moisture content per month	A Spearman Rank Order Correlation
<b>Surface temperature</b>	Hygrochrons (i-buttons)	Monthly means of daily surface T ranges and number of times $T \leq 0^{\circ}\text{C}$ a day	Linear model for diurnal T range and Poisson Generalized Linear Model for mean number of frost events per day

Four replicates of Chalk, Cotswold and Portland were located in each of four positions: outside the shelter and under the shelter (centre, north-east and south-west) from 3<sup>rd</sup> August 2012 to 29<sup>th</sup> July 2013. The change in properties was documented periodically (0, 3, 9 and 12 months) with the exception of hardness, which was recorded at 0 and 12 months to avoid excessive surface deterioration. When tests required a series of measurements per sample (hardness and UPV), the median was selected as

representative value to exclude outliers (see section 3.3.2). Pictures were taken to document macroscopic and microscopic changes after a year. Moisture content in the stone blocks was monitored in the field by change in weight (field balance OHAUS Compact Series Scale,  $\pm 0.1\text{g}$  accuracy) and using a hand held moisture content meter (FMW-T, Brookhuis) once per month. In addition, surface temperature (i-button® hydrochron dataloggers, accuracy=  $\pm 0.5\%RH$  and  $\pm 0.5^\circ C$ ) was recorded every 15 minutes simultaneously in all positions. A summary is shown in Table 6.2

**Table 6.2:** Summary of the time when data was recorded for each key factor of stone deterioration

	Dry weight	EMOD	Surface hardness	UPV	Surface colour	Macroscopic-microscopic characteristics	Moisture content	Surface T
0 months	✓	✓	✓	✓	✓	✓		
3 months	✓	✓		✓	✓			
9 months	✓	✓		✓	✓			
12 months	✓	✓	✓	✓	✓	✓		
Every month							✓	
Every 15 min								✓

The positions where the stone blocks were located were selected after the condition survey of the Bishop’s Palace (Chapter 4). The periphery under the shelter (SW and NE) was predicted to track environmental changes outside and could be considered a middle point between completely covered and exposed areas. The NE area seems to be very humid. It is surrounded by trees, and biofilms cover a large amount of the remains. South westerly is the predominant wind direction in South England, so the SW area is likely to be affected by wind driven rain and present condensation-evaporation problems. One sample of Portland limestone located in the NE (PL\_10) was lost after one month so no data could be collected. Table 6.3 summarises the hypothesised changes in stone blocks predicted to occur at the different positions.

**Table 6.3:** Predictions of changes (decrease for dry weight, EMOD, hardness and UPV) in key indicators of deterioration after a year of exposure\*

		<b>Outside</b>	<b>SW</b>	<b>NE</b>	<b>Centre</b>
<b>Chalk</b>	Dry weight	High	Medium	Medium	Low
	EMOD	Medium	Low	Low	-
	Hardness	Medium	Low	Low	-
	UPV	Medium	Low	Low	-
	dE*ab	High	Medium	Medium	Low
	Macroscopy	Medium	Low	Low	Low
	Microscopy	Medium	Low	Medium	Low
	Moisture	High	Medium	High	Low
	T fluctuation	Medium	Medium	Medium	Low
	Frost	Medium	Low	Low	Low
<b>Cotswold</b>	Dry weight	Medium	Low	Low	Low
	EMOD	Low	Low	Low	-
	Hardness	Low	Low	Low	-
	UPV	Low	Low	Low	-
	dE*ab	Medium	Low	Low	Low
	Macroscopy	Low	Low	Low	-
	Microscopy	Low	Low	Low	-
	Moisture	Medium	Low	Medium	-
	T fluctuation	Medium	Medium	Medium	Low
	Frost	Medium	Low	Low	Low
<b>Portland</b>	Dry weight	Low	Low	Low	-
	EMOD	Low	Low	Low	-
	Hardness	Low	Low	Low	-
	UPV	Low	Low	Low	-
	dE*ab	Low	Low	Low	-
	Macroscopy	Low	Low	Low	-
	Microscopy	Medium	Low	Low	-
	Moisture	Low	Low	Low	-
	T fluctuation	Medium	Medium	Medium	Low
	Frost	Medium	Low	Low	Low

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change: HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=no noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For T fluctuations (mean diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For all measurements “-“ means that no change is predicted.

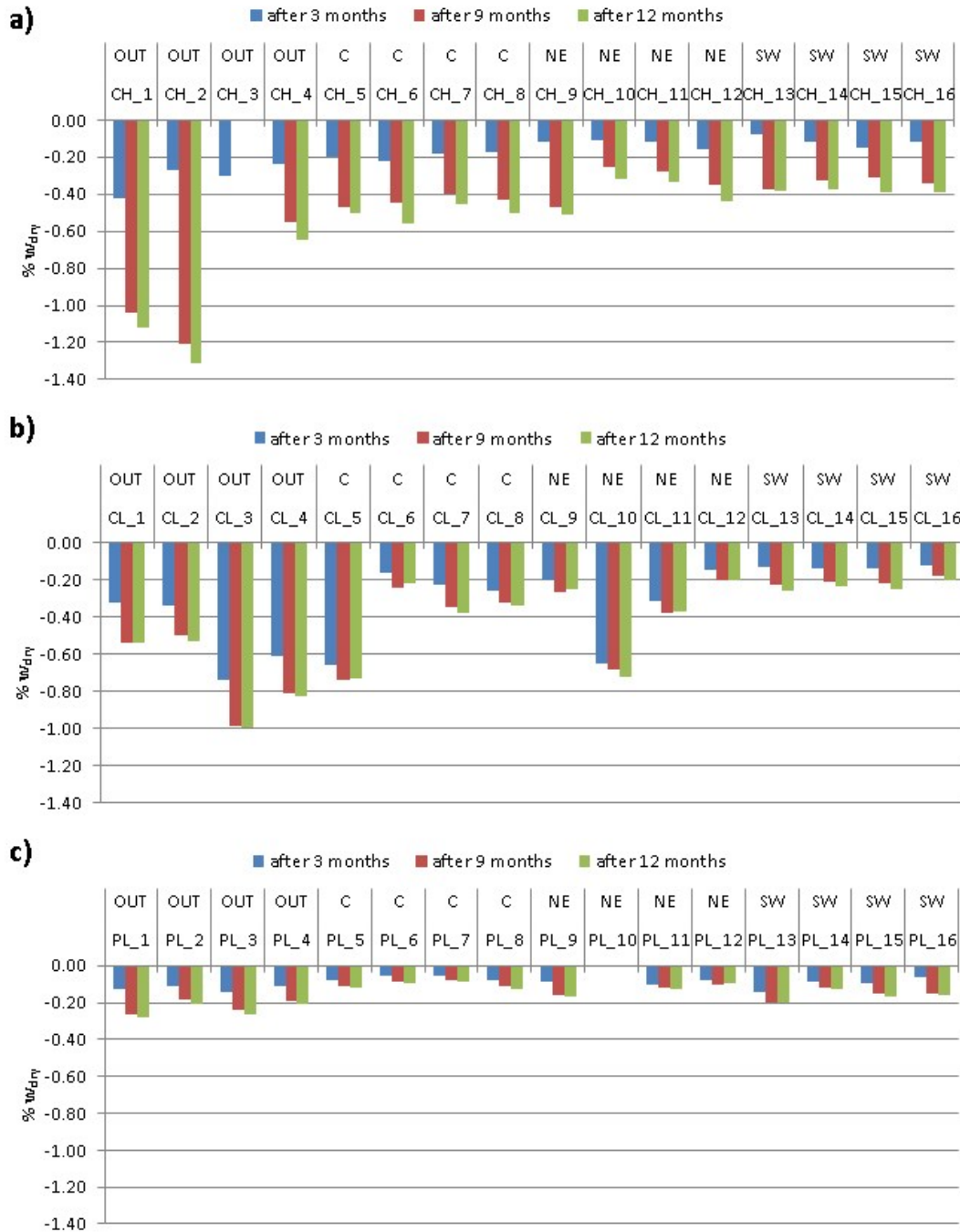
The samples (9x3x3 cm) were cut from three limestones of different vulnerability to decay. Cotswold limestone (Cotswold cream) is a local heterogeneous oolitic limestone very similar to the one used for the construction of the Bishop's Palace. Portland limestone is a widely researched bioclastic limestone denser and probably more resilient to stone decay than Cotswold. A particularly vulnerable Chalk from the South of England was also used (see section 3.3.1). Previous studies (Nicholson, 2001) have demonstrated that chalk and oolitic limestones with a similar elasticity, ultrasonic pulse velocity and porosity characteristics to the ones used in this project are very vulnerable to frost weathering; and chalk also to the effect of salts. These are two of the main possible problems at the Bishop's Palace (Chapter 4).

## **6.3. Results**

### **6.3.1. Dry weight change**

Changes in sample weights were recorded after each exposure interval and calculated as percentages of initial dry weights. Figure 6.1 illustrates the weight changes in Chalk, Cotswold and Portland blocks located outside and under the shelter, in the central part, NE and SW side after 3, 9 and 12 months of exposure. All of the blocks decreased in weight. Although some blocks could have increased in weight because of soiling or crust growth, loss of material was predominant, probably due to an increase in the number of microcracks and size of the pores.

The samples located outside the shelter were the most affected of all types of stone. In addition, the weight loss increased over time, but it is especially evident in the outside samples between 3 and 9 months of exposure (from November to April).



**Figure 6.1:** Weight lost by a) Chalk, b) Cotswold and c) Portland samples placed outside (OUT), central part of the shelter (C) and under the shelter in the north-east (NE) and south-west (SW) side of the site after 3, 9 and 12 months of exposure

The effect of winter temperatures and freeze-thaw cycles could have been the reason for the decrease in weight. Chalk samples outside the shelter lost more weight than the other stone types after a year (-1.03 %W<sub>dry</sub> mean). In addition, one Chalk sample cracked (CH\_02) and another broke (CH\_03) in November, which led to a considerable

loss of material from both samples. This could be the result of initial inner cracks or faults in the samples, but also due to the effect of the harsh outside environmental conditions affecting Chalk more than the other types of stone.

The Portland stone data can be compared with data from a number of other studies in the UK using stone tablets in exposure trials (Table 6.4). Although the size and shape of stone used in this study is different, the data from Witney is most similar to that collected from rural and relatively unpolluted sites, such as Wells and Lough Navar.

**Table 6.4:** Mean of the dry weight changes (as percentage of initial dry weight) in exposed and sheltered Portland limestone samples

%Wdry	Exposed: -1.80 Sheltered: +0.07	Exposed: -0.50 Sheltered: +0.08	Exposed: -0.19 Sheltered: +0.13	Exposed: -0.35 Sheltered: - 0.01	Exposed: -0.40 Sheltered: (N/A)	Exposed: -0.24 Sheltered: - 0.13
Duration	2 years	1 year	1 year	1 year	1 year	1 year
Place	London	London	Wells	Lough Navar	Lough Navar	Witney
Shape and size	Tablets (4x4x1 cm)	Tablets (5x5x0.8cm)	Tablets (5x5x0.8cm)	Tablets (5x5x0.8cm)	Tablets (5x5x1cm)	Blocks (9x3x3cm)
Reference	(Inkpen, 1995)	(Butlin et al., 1992)	(Butlin et al., 1992)	(Butlin et al., 1992)	(Moses, 1996)	This study

In order to find out if the weight loss differences were statistically significant, a three-way ANOVA test on the mean weight loss (as percentage of initial dry weight) of Chalk, Cotswold and Portland samples in the different positions after 3, 9 and 12 months was carried out. The results showed significant differences in weight loss between locations ( $F=63.4$ ,  $DF=3$ ,  $P<0.001$ ), type of stones ( $F=103.57$ ,  $DF=2$ ,  $P<0.001$ ), and months of exposure ( $F=42.48$ ,  $DF=2$ ,  $P<0.001$ ). Chalk samples lost significantly more weight than Cotswold and Portland, and Portland was the least affected by weight loss. On the other hand, the amount of weight loss increased over time for all stone types.

Additionally, two-way ANOVA tests were undertaken for the weight lost (%Wdry) by Chalk, Cotswold and Portland samples to obtain more information about the

differences between positions and months of exposure within the same stone type. Results showed that positions were significantly relevant for the weight loss in Chalk ( $F=29.38$ ,  $DF=3$ ,  $P<0.001$ ), Cotswold ( $F=11.09$ ,  $DF=3$ ,  $P<0.001$ ) and Portland samples ( $F=30.67$ ,  $DF=3$ ,  $P<0.001$ ). Table 6.5 shows the results of the post-hoc pairwise multiple comparison tests (Holm-Sidak method) on the difference in weight change between positions within the same stone type. In all cases, samples located outside the shelter lost significantly more weight than the ones under the shelter. In addition, Portland samples located in the SW lost significantly more weight than the ones at the centre.

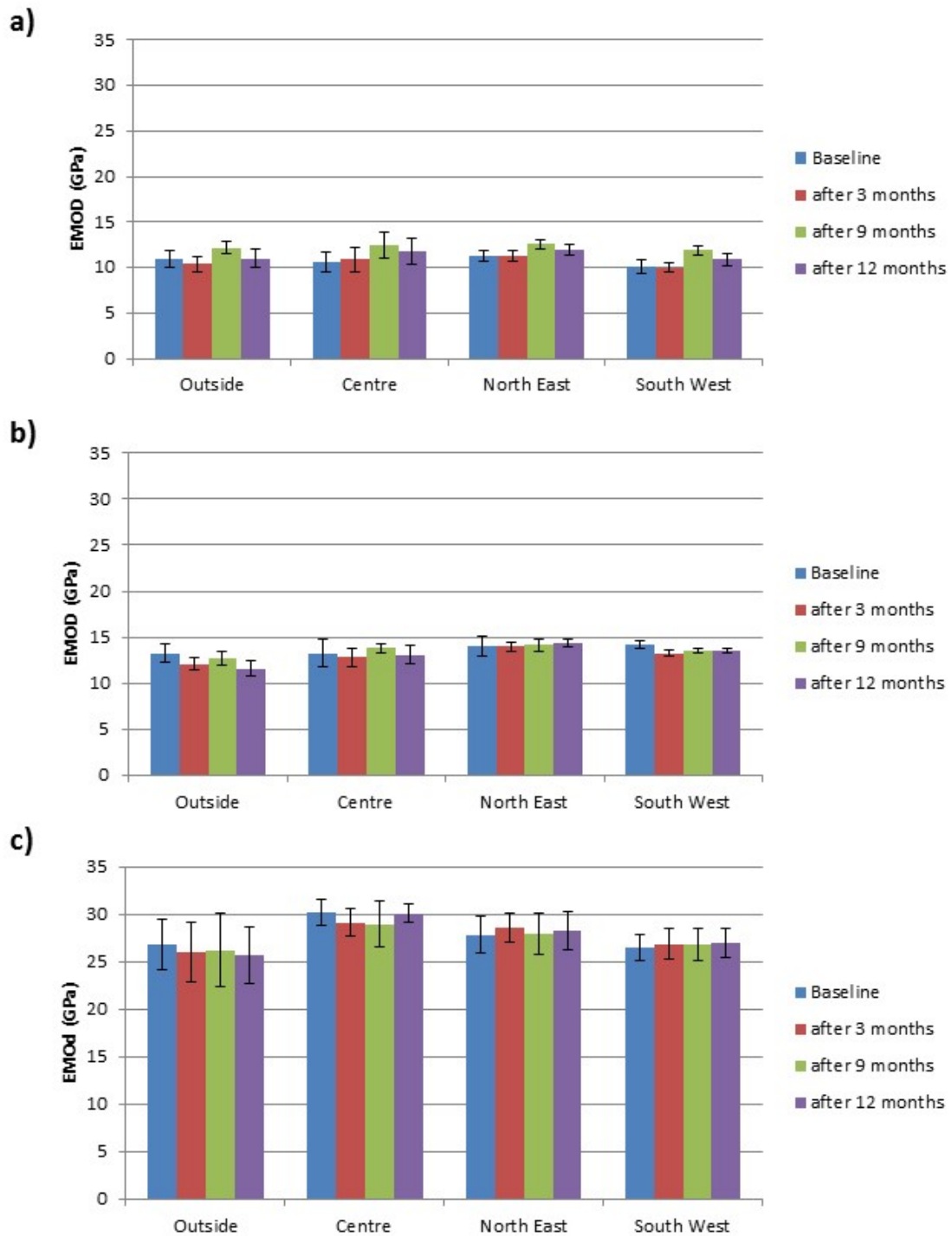
**Table 6.5:** Results of the pairwise multiple comparison tests (Holm-Sidak method) on % $W_{dry}$  lost for Position within Stone type. Overall significance level = 0.05

Stone type	Comparison	Diff of Means	t	P	P<0.05
Chalk	Outside vs. SW	0.479	8.365	<0.001	Yes
	Outside vs. NE	0.470	8.219	<0.001	Yes
	Outside vs. Centre	0.379	6.631	<0.001	Yes
	Centre vs. SW	0.099	1.872	0.196	No
	Centre vs. NE	0.090	1.715	0.182	No
	NE vs. SW	0.008	0.157	0.876	No
Cotswold	Outside vs. SW	0.450	5.711	<0.001	Yes
	Outside vs. NE	0.278	3.522	0.006	Yes
	Outside vs. Centre	0.260	3.300	0.009	Yes
	Centre vs. SW	0.190	2.411	0.062	No
	NE vs. SW	0.172	2.189	0.069	No
	C vs. NE	0.0175	0.222	0.825	No
Portland	Outside vs. Centre	0.102	9.254	<0.001	Yes
	Outside vs. NE	0.077	6.501	<0.001	Yes
	Outside vs. SW	0.055	4.966	<0.001	Yes
	SW vs. Centre	0.047	4.288	<0.001	Yes
	NE vs. Centre	0.024	2.066	0.091	No
	SW vs. NE	0.022	1.904	0.066	No

Two-way ANOVA statistical tests showed that months of exposure were also significant for weight change but only in Chalk ( $F=38.23$ ,  $DF=2$ ,  $P<0.001$ ) and Portland samples ( $F=24.67$ ,  $DF=2$ ,  $P<0.001$ ). In addition, the interaction between position and months of exposure was statistically significant for weight change in Chalk samples ( $F=2.74$ ,  $DF=6$ ,  $P=0.029$ ). Pairwise multiple comparison tests (Holm-Sidak method) on weight change between months of exposure within each stone type show that the difference between Chalk samples placed outside and inside the shelter is only significant at 9 ( $t=5.003$ ,  $P<0.001$ ) and 12 months ( $t=5.289$ ,  $P<0.001$ ). In addition, there was a statistically significant difference in weight lost between 3 and 9 months ( $t=5.571$ ,  $P<0.001$ ) and 3 and 12 months ( $t=6.49$ ,  $P<0.001$ ) in Portland samples. As 3 months corresponds to October and 9 months to April, it is probable that the greatest change in weight is related to the effect of winter.

### **6.3.2. Elasticity changes**

Figure 6.2 depicts the EMOD means and standard deviations of the four replicates per stone type located in each position after 0, 3, 9 and 12 months of exposure. EMOD values depend on the material characteristics. Stiffer materials have higher EMOD. The mean of the initial EMOD values was 28 GPa for Portland, 14 GPa for Cotswold and 11 GPa for Chalk. These results are in line with previous research (Bell, 1993, Nicholson, 2001). However, the influence of positions and time are not so clear.



**Figure 6.2:** Means and standard deviations of elastic modulus (EMOD) in a) Chalk, b) Cotswold and c) Portland samples placed outside and under the shelter (centre, NE and SW) after 0, 3, 9 and 12 months of exposure (n=4 in each position)

A three-way ANOVA statistical test on the EMOD means of Chalk, Cotswold and Portland samples at different locations at 0, 3, 9 and 12 months of exposure indicated that differences in EMOD means were significantly different depending on stone type

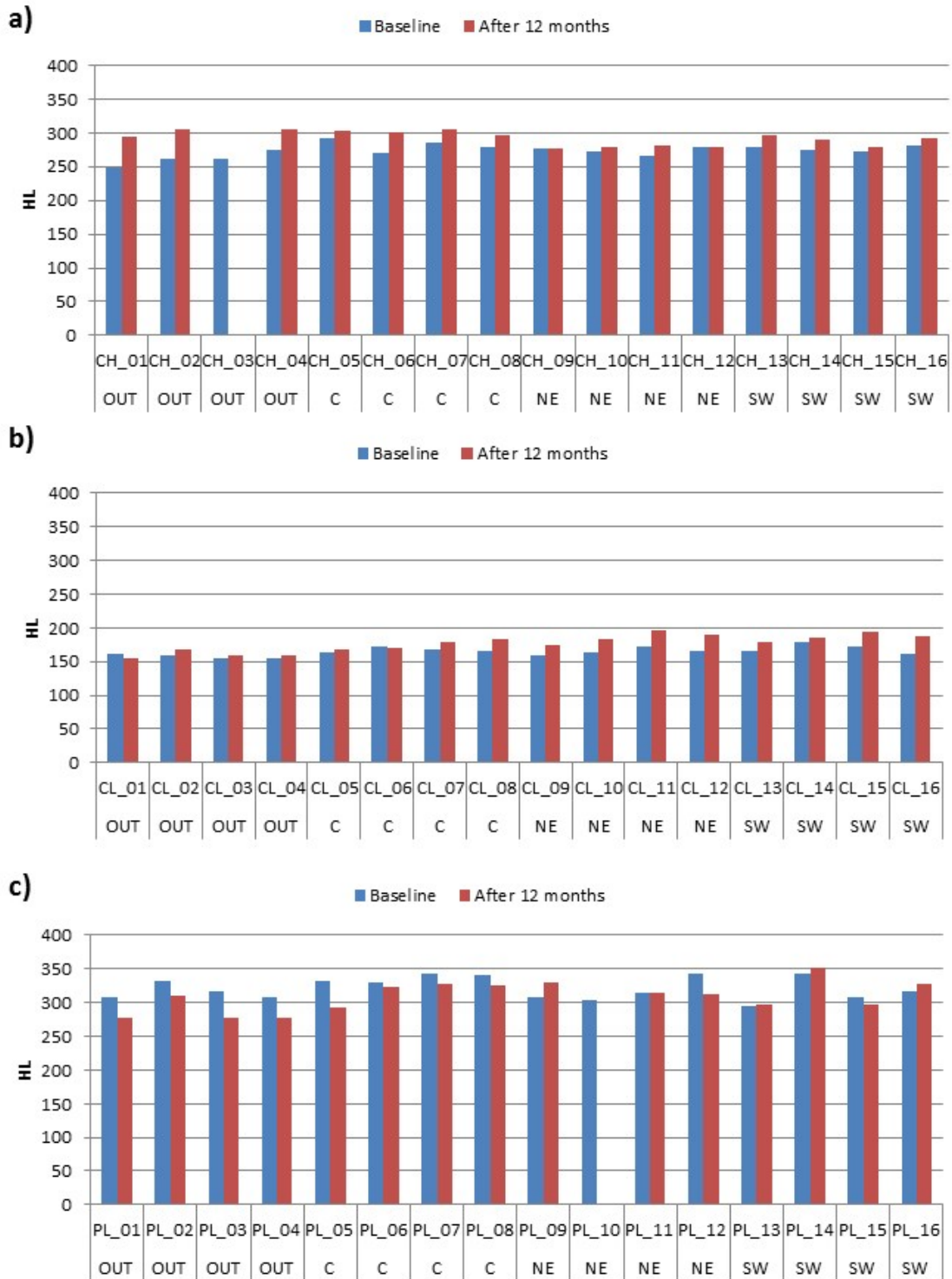
( $F=12931.74$ ,  $DF=2$ ,  $P<0.001$ ), position within the site ( $F= 66.553$ ,  $DF=3$ ,  $P<0.001$ ), and time of exposure ( $F= 8.496$ ,  $DF=3$ ,  $P<0.001$ ). However, post-hoc pairwise multiple comparison tests (Holm-Sidak method) showed that the EMOD values were not significantly different between the start and end of the experiment (Table 6.6). Although some trends could be seen in the EMOD changes, the differences between locations and time are not conclusive

**Table 6.6:** Results of the pairwise multiple comparison tests (Holm-Sidak method) on EMOD means for Positions and Months. OUT= outside, C= central part of the shelter, NE= north-east part of the site under the shelter; SW= south-west part of the site under the shelter. Overall significance level = 0.05

<b>Comparisons for factor: Position</b>				
Comparison	Diff of Means	t	P	P<0.050
C vs. OUT	1.514	11.725	<0.001	Yes
NE vs. OUT	1.45	11.227	<0.001	Yes
C vs. SW	1.041	8.06	<0.001	Yes
NE vs. SW	0.977	7.561	<0.001	Yes
SW vs. OUT	0.473	3.665	0.004	Yes
C vs. NE	0.0643	0.498	0.624	No
<b>Comparisons for factor: Months</b>				
Comparison	Diff of Means	t	P	P<0.050
9 vs. 3 months	0.652	5.046	<0.001	Yes
9 vs. 0 months	0.338	2.615	0.085	No
12 vs. 3 months	0.334	2.585	0.073	No
9 vs. 12 months	0.318	2.461	0.071	No
0 vs. 3 months	0.314	2.432	0.051	No
12 vs. 0 months	0.0198	0.154	0.88	No

### 6.3.3. Surface hardness changes

Portland is the hardest limestone of the three types used in this study. It had a mean of 318 HL at the start of the exposure, whereas Cotswold had 170 HL and Chalk, 273 HL. Figure 6.3 shows the initial and final surface hardness values for Chalk, Cotswold and Portland samples located outside and under the shelter.



**Figure 6.3:** Surface hardness values (HL) in a) Chalk, b) Cotswold and c) Portland replicates placed outside, under the shelter, north-east and south-west side of the site before and after 12 months of exposure

Figure 6.3, a) shows that all Chalk samples increased in hardness after a year. However, the replicates placed outside changed more. Figure 6.3, b) depicts that Cotswold

limestone blocks also tended to increase in hardness, but mainly inside the shelter. Portland limestone blocks outside and under the central part of the shelter decreased in hardness, although the change was greater in the outside blocks (Figure 6.3, c).

Statistical tests were undertaken to determine if the HL values in Chalk, Cotswold and Portland samples after 12 months of exposure were significantly different from those taken initially and if the locations of the samples at the site influenced the change. A three-way ANOVA test, with log transformation to meet the assumption of normality, was carried out on hardness values of Chalk, Cotswold and Portland for 0 and 12 months. The results indicated that there was a significant interaction between positions, type of stone and time of exposure ( $F=4.441$ ,  $DF=6$ ,  $P<0.001$ ). In addition, multiple comparison tests (Holm-Sidak method) on surface hardness of Chalk, Cotswold and Portland samples were carried out. The results of the differences in hardness values between 0 and 12 months within same location and stone type are shown in Table 6.7.

**Table 6.7:** Results of the pairwise multiple comparison tests (Holm-Sidak method) on surface hardness (HL) for Months within Positions. Overall significance level = 0.05

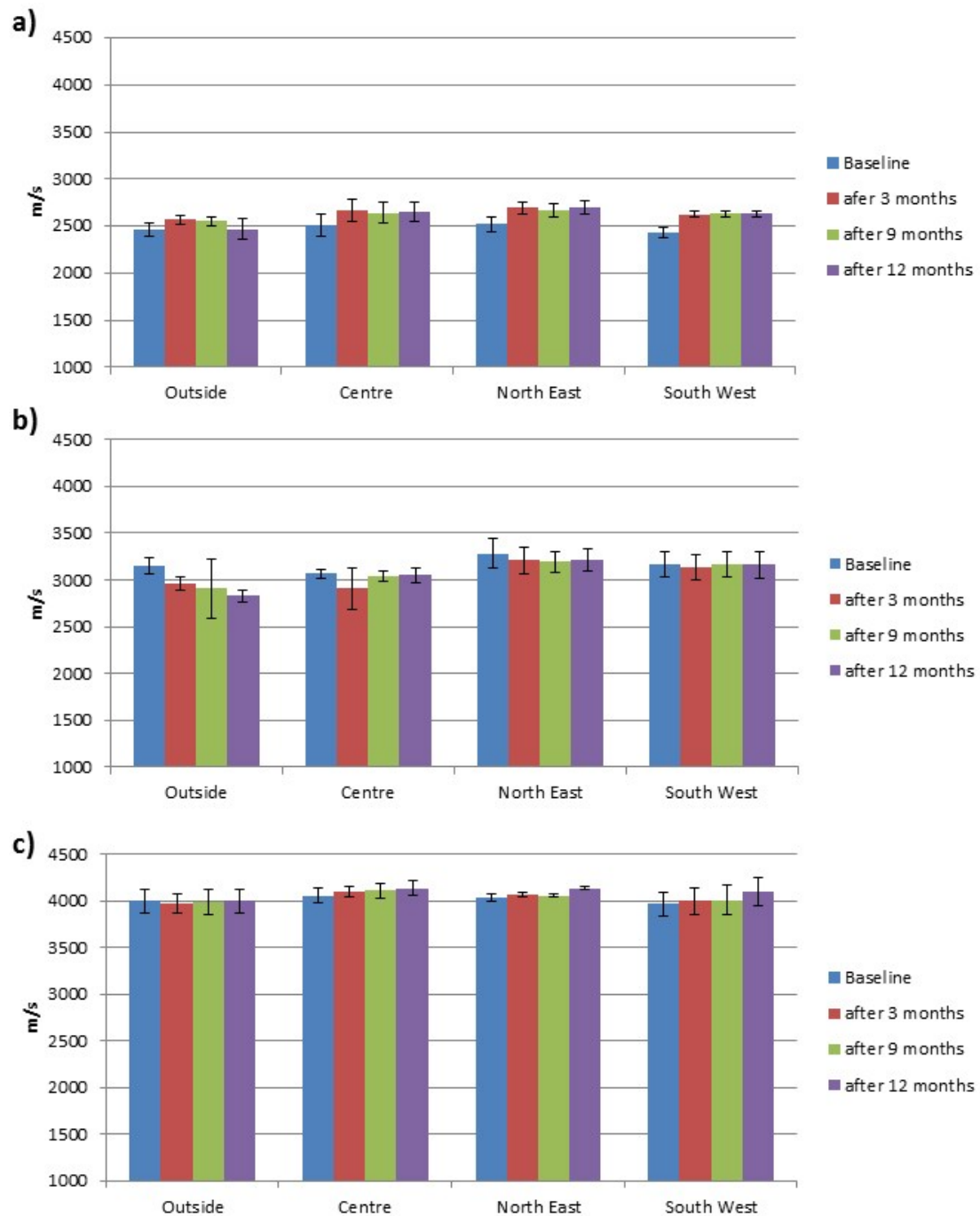
Stone type	Comparison	Diff of Means	t	P	P<0.05
Chalk	0 vs. 12 months within OUTSIDE	40.583	7.880	<0.001	Yes
	0 vs. 12 months within CENTRE	20.250	4.247	<0.001	Yes
	0 vs. 12 months within NE	5.750	1.206	0.240	No
	0 vs. 12 months within SW	12.500	2.621	0.015	Yes
Cotswold	0 vs. 12 months within OUTSIDE	2.875	0.623	0.539	No
	0 vs. 12 months within CENTRE	7.375	1.597	0.123	No
	0 vs. 12 months within NE	21.625	4.683	<0.001	Yes
	0 vs. 12 months within SW	17.250	3.735	0.001	Yes
Portland	0 vs. 12 months within OUTSIDE	29.750	2.472	0.021	Yes
	0 vs. 12 months within CENTRE	18.750	1.558	0.133	No
	0 vs. 12 months within NE	1.750	0.135	0.894	No
	0 vs. 12 months within SW	2.000	0.166	0.869	No

All Chalk samples showed significant increases in surface hardness between 0 and 12 months, apart from those placed at the NE. Cotswold samples located at the NE and SW showed significant increases in hardness whereas those outside and in the centre did not. For Portland limestone, the only significant changes in 12 months were a decrease in hardness experienced by those outside the shelter.

#### **6.3.4. Changes in ultrasonic pulse velocity (UPV)**

Figure 6.4 shows the UPV means and standard deviations of the four replicates per stone type located in each position after 0, 3, 9 and 12 months of exposure.

Portland limestone is a denser stone type and presents higher UPV values than Cotswold and Chalk. The baseline mean of the UPV values was 4022.38 m/s for Portland, 3134 m/s for Cotswold and 2486.75 m/s for Chalk. The differences in UPV between stone types are in line with previous research (Leary, 1983, Bell, 1993, Nicholson, 2001, Nicholson, 2002). Studies on marble decay (Ahmad, 2011) established that a decrease in ultrasonic longitudinal velocity of around 3000 m/s correlates to an extremely weathered state and a decrease of around 1000 m/s relates to an increase in porosity. In this case, the differences over time are in the order of 100 m/s. The stone types studied here are not as dense as marble but the UPV changes are still very minor. In addition, the data do not show a clear trend apart from a decrease in UPV in the Cotswold samples placed outside the shelter.



**Figure 6.4:** Means and standard deviations of UPV (m/s) for a) Chalk, b) Cotswold and c) Portland samples placed outside, under the central part of the shelter, north-east and south-west side of the site after 3, 9 and 12 months of exposure (n=4 in each position)

Statistical analysis was carried out to examine significant differences between stone types, locations and months of exposure. A three-way ANOVA test on the UPV means of Chalk, Cotswold and Portland samples showed that there were significant

differences between stone types ( $F=9266.621$ ,  $DF=2$ ,  $P<0.001$ ) and positions ( $F=55.257$ ,  $DF=3$ ,  $P<0.001$ ) but not between months ( $F=3.139$ ,  $DF=3$ ,  $P=0.051$ ).

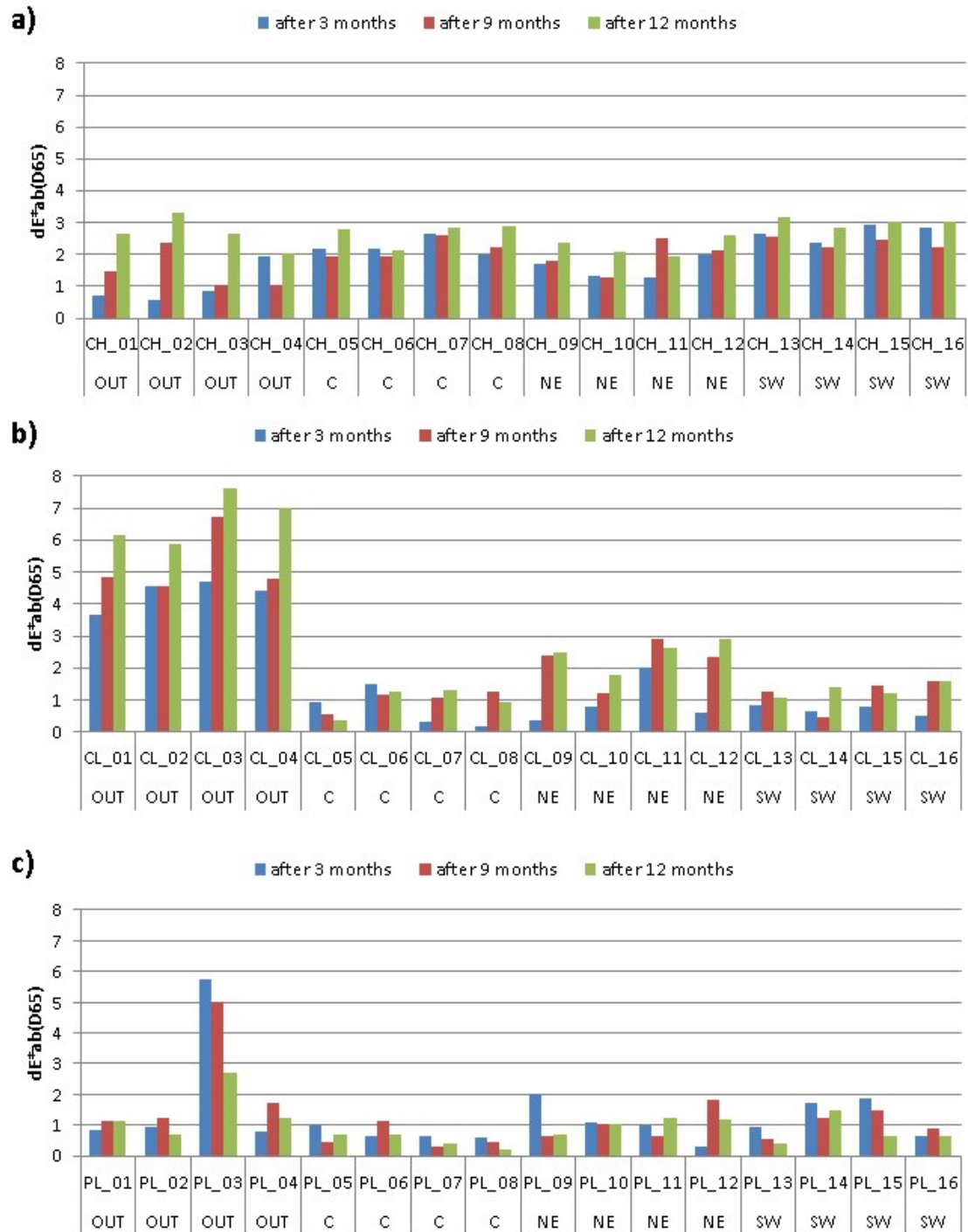
Table 6.8 depicts the results of the post-hoc pairwise multiple comparison tests on UPV means between positions. However, it is not possible to determine any conclusive result.

**Table 6.8:** Results of the pairwise multiple comparison tests (Holm-Sidak method) on UPV means. OUT= outside, C= central part of the shelter, NE= north-east part of the site under the shelter; SW= south-west part of the site under the shelter. Overall significance level = 0.05

Comparisons for factor: Position				
Comparison	Diff of Means	t	P	P<0.050
NE vs. OUT	160.413	12.779	<0.001	Yes
SW vs. OUT	96.326	7.674	<0.001	Yes
C vs. OUT	90.899	7.241	<0.001	Yes
NE vs. C	69.514	5.538	<0.001	Yes
NE vs. SW	64.087	5.105	<0.001	Yes
SW vs. C	5.427	0.432	0.671	No

### 6.3.5. Surface colour changes

Figure 6.5 shows the overall colour difference of Chalk, Cotswold and Portland stone samples after 3, 9 and 12 months. Colour difference was measured using  $dE^*ab$ , which quantifies the overall colour change in relation to initial values. A CIELAB overall colour difference over 3.8  $dE^*ab$  is distinctively perceptible to the naked eye while a difference of 1.8 is just noticeable (Bieske and Vandahl, 2008). All Chalk samples had a change in colour over 2  $dE^*ab$  after a year. The mean colour difference in Cotswold samples outside the shelter reached more than 6  $dE^*ab$  after 12 months, much higher than those inside. In addition, Portland blocks outside the shelter, with an overall colour mean change of 1.45  $dE^*ab$  after a year, tended to change more than those inside, especially those in the centre.



**Figure 6.5:** Overall colour difference ( $dE^*ab$ ) on a) Chalk, b) Cotswold and c) Portland samples placed outside, under the central part of the shelter and under the shelter in the north-east and south-west side of the site after 3, 9 and 12 months of exposure

In order to determine the influence of the position and months for each stone type, two-way ANOVA tests on the overall colour difference in Chalk, Cotswold and Portland samples were undertaken. There is a statistically significant interaction between

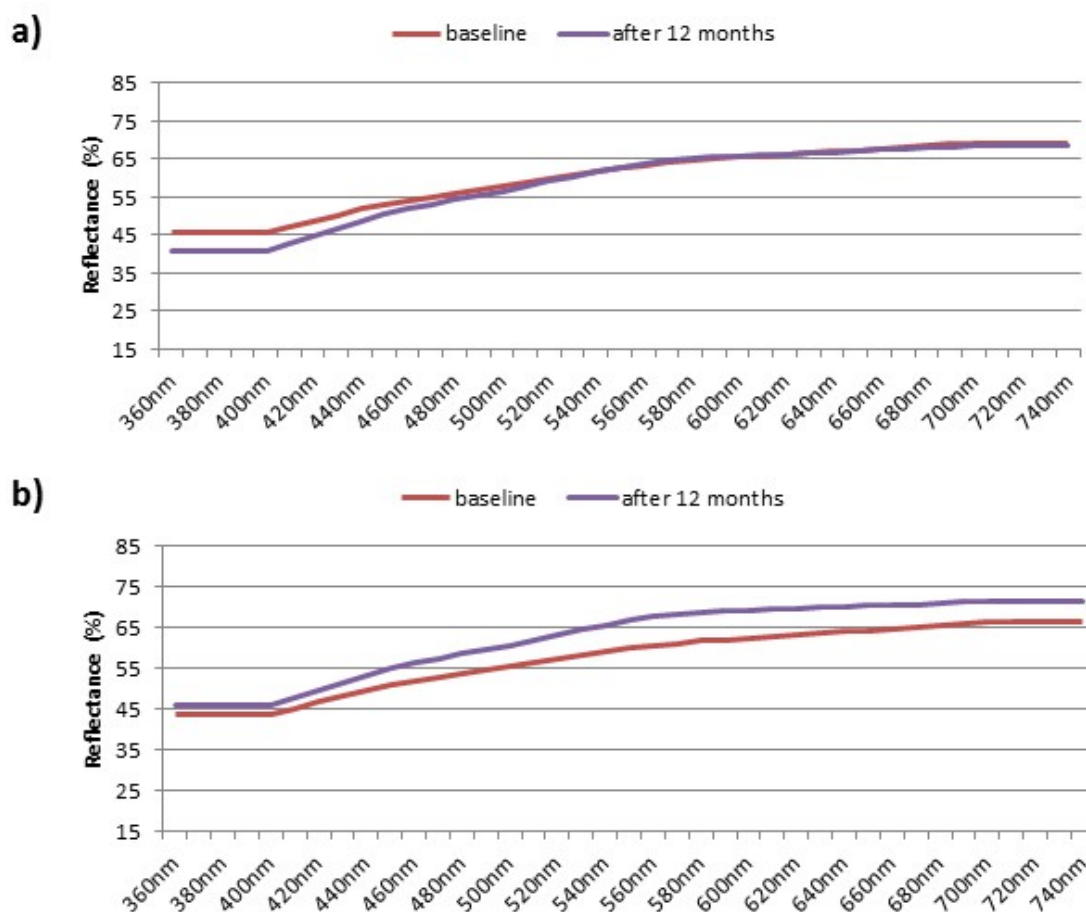
positions and months for colour change in Chalk ( $DF=6$ ,  $F=2.632$ ,  $P=0.032$ ) and Cotswold samples ( $DF=6$ ,  $F=3.018$ ,  $P=0.017$ ) but not for Portland ( $DF=6$ ,  $F=0.137$ ,  $P=0.998$ ) where only position was significant ( $DF=3$ ,  $F=8.930$ ,  $P<0.001$ ). Post-hoc pairwise multiple comparison tests (Holm-Sidak method) showed there is no significant difference in colour change in Chalk samples between any of the positions after 12 months of exposure. However, the greater change in colour took place after 3 months in samples located in the SW and centre of the shelter, when the difference in relation to outside was significantly different ( $P<0.001$ ). On the other hand, colour in Chalk samples placed outside the shelter was only significantly different than the initial measurement after 12 months ( $t=5.794$ ,  $P<0.001$ ). For Cotswold limestone, the colour difference in the samples located outside the shelter was greater than in any other position just after 3 months ( $P<0.001$ ). In addition, the colour difference in samples located at NE was greater than in the centre ( $t=2.92$ ,  $P=0.018$ ) and SW ( $t=2.462$ ,  $P=0.037$ ) after 9 months of exposure. In general, Portland limestone samples located under the central part of the shelter changed less in colour than the samples outside ( $t=3.122$ ,  $P=0.022$ ), but there is no other significant interaction.

Additionally, CIELAB differences in  $dL^*$  (lightness/darkness),  $da^*$  (red/green) and  $db^*$  (yellow/blue) were examined to determine the characteristics of the colour change. Table 6.9 summarises the mean differences in  $dE^*ab$ ,  $dL^*$ ,  $da^*$  and  $db^*$  in Chalk, Cotswold and Portland samples after a year. Blocks located outside, and some in NE, became darker or less light than the others. This could be related to a greater rate of soiling or biological colonisation in these areas.

**Table 6.9:** Colour difference as mean  $dE^*ab$ ,  $dL^*$ ,  $da^*$  and  $db^*$  in Chalk, Cotswold and Portland samples after 12 months (n=4 in each position). The results exclude the spectral component (SCE measurements)

	Position	$dE^*ab$ (D65)	$dL^*$ (D65)	$da^*$ (D65)	$db^*$ (D65)
<b>Chalk</b>	Outside	2.66	-0.22 darker	0.29 greener	2.63 yellower
	Centre	2.67	2.53 lighter	0.63 greener	0.50 yellower
	North-east	2.26	1.37 lighter	0.43 greener	1.43 yellower
	South-west	3.02	2.62 lighter	0.60 greener	1.34 yellower
<b>Cotswold</b>	Outside	6.68	-4.92 darker	-1.32 Less green	4.23 yellower
	Centre	0.98	-0.77 darker	0.11 greener	-0.45 Less yellow
	North-east	2.45	-2.33 darker	-0.06 Less green	-0.12 Less yellow
	South-west	1.31	-1.27 darker	-0.10 Less green	-0.03 Less yellow
<b>Portland</b>	Outside	1.94	-0.45 darker	0.21 greener	-0.58 Less yellow
	Centre	0.54	0.21 lighter	0.30 greener	-0.24 Less yellow
	North-east	1.30	-1.11 darker	0.34 greener	0.19 yellower
	South-west	1.00	0.30 lighter	0.28 greener	-0.37 Less yellow

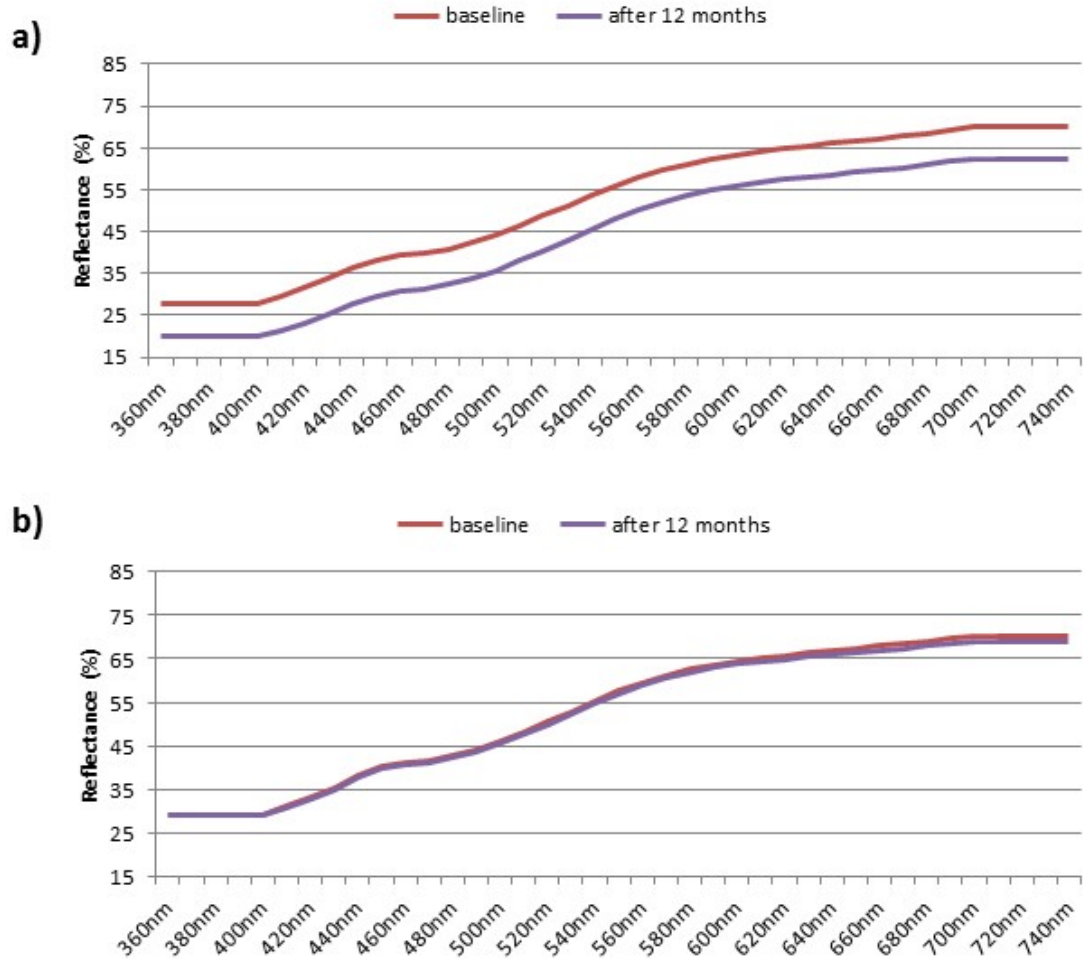
Another way to estimate colour change is by studying the stone samples' reflectance. Figure 6.6 shows the reflectance of Chalk samples located outside and inside the shelter. Samples outside the shelter decreased in the percentage of reflectance in the short-length waves. On the other hand, the reflectance of the samples placed under the shelter increased in all length waves but mainly in the long ones. Therefore, all Chalk samples turned yellow. However, the samples placed outside show a greater amount of yellowing. In addition, the samples located outside the shelter became slightly darker whereas the samples placed inside became lighter. These results confirmed the data from Table 6.9.



**Figure 6.6:** Reflectance of representative Chalk samples placed a) outside the shelter (CH\_01), and b) under the central part of the shelter (CH\_05). SCE measurements

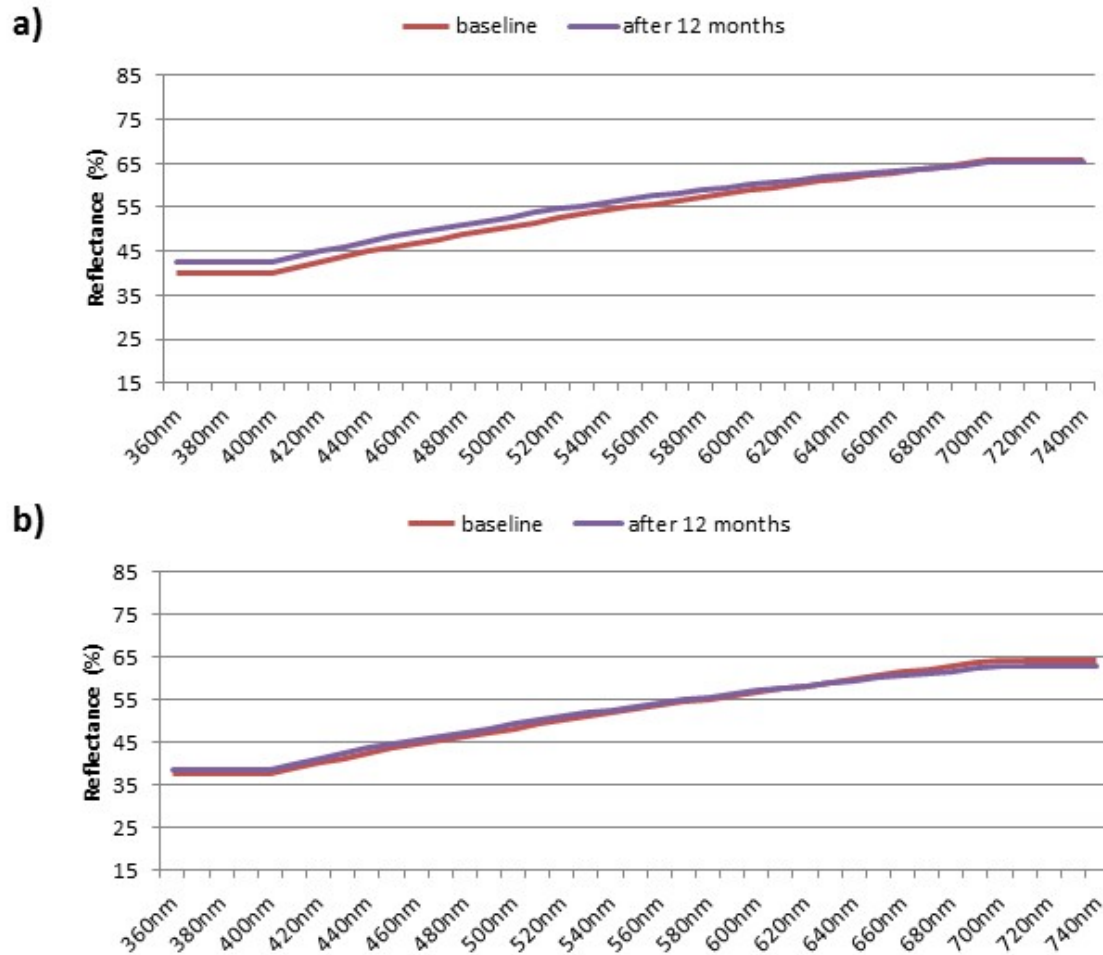
As we have seen in Table 6.9, the Cotswold samples outside the shelter became much darker than the ones inside. In addition, they became yellower. Figure 6.7 illustrates the reflectance of the Cotswold samples located outside and under the central part of the shelter across the visible light wavelengths.

The darkening of the surface in the Cotswold samples placed outside the shelter is seen as an overall decrease in the percentage of reflectance. On the other hand, the samples placed inside the shelter do not show any differences in colour after 12 months.



**Figure 6.7:** Reflectance of representative Cotswold samples placed a) outside the shelter (CL\_01), and b) under the central part of the shelter (CL\_05). SCE measurements

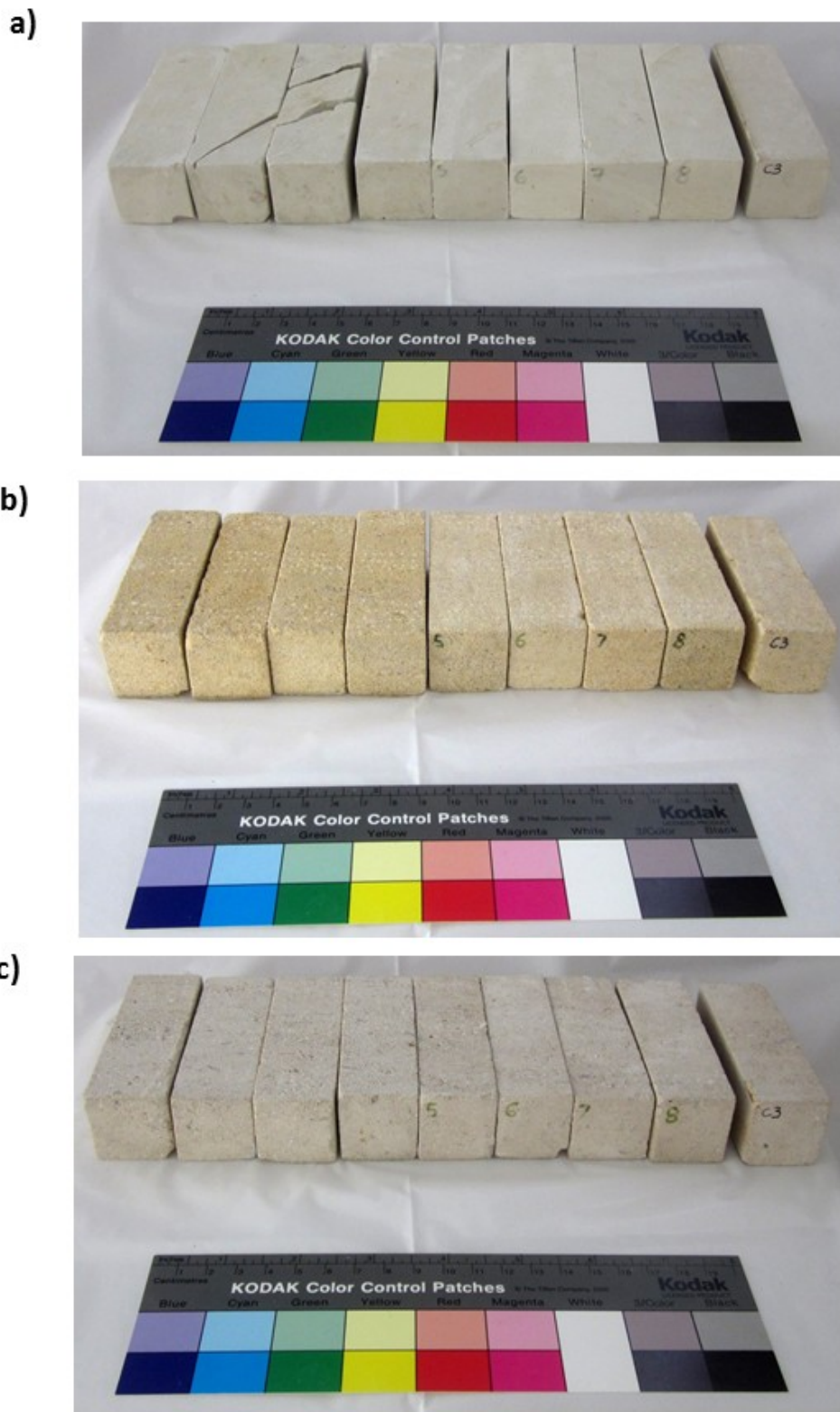
Portland samples do not show any remarkable differences in lightness or hue when  $dL^*$ ,  $da^*$ , and  $db^*$  are studied (Table 6.9). However, Figure 6.8 shows that samples placed outside the shelter had a slight increase in reflectance in the short-length waves after a year of exposure, which is perceived as a slightly blue hue of the stone surface.



**Figure 6.8:** Reflectance of representative Portland samples placed a) outside the shelter (PL\_01), and b) under the central part of the shelter (PL\_05). SCE measurements

### 6.3.6. Macroscopic and microscopic surface changes

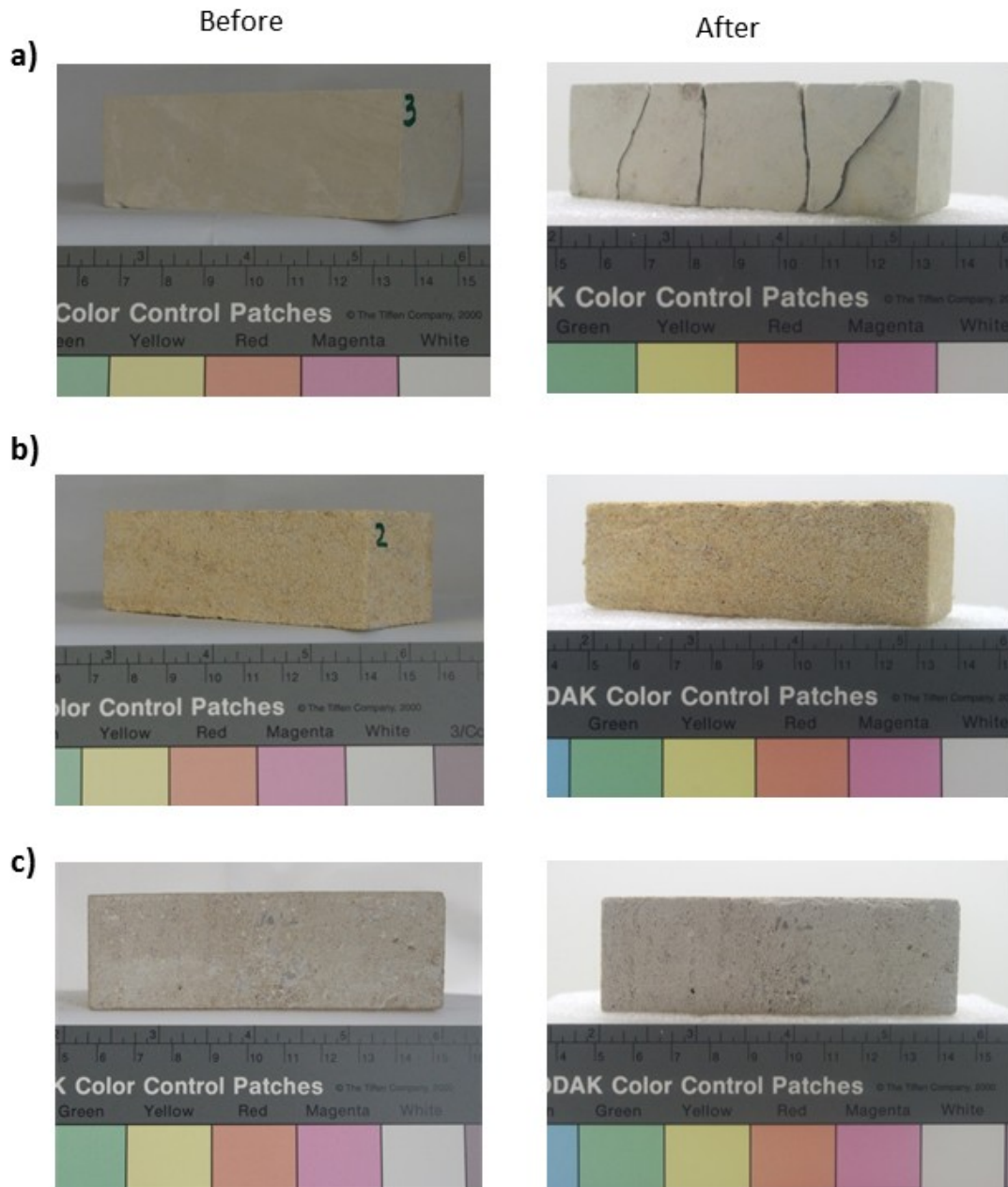
A general picture of all samples was taken at the end of the exposure trial to determine visual colour differences. Figure 6.9 depicts macroscopic pictures of Chalk, Cotswold and Portland samples located outside and under the central part of the shelter after a year of exposure. Chalk samples inside the shelter (centre, NE and SW) became lighter in colour. All Cotswold samples became darker, although this is more noticeable in those located outside. Portland stone does not show any perceptible changes. These results were also detected by comparing initial and final  $dL^*$  values on the top horizontal surface (Table 6.9).



**Figure 6.9:** Macroscopic pictures of a) Chalk, b) Cotswold and c) Portland blocks placed outside the shelter (the first four samples starting from the left), under the central part (numbers 5 to 8) and a control block (C3)

Individual pictures of each sample were taken initially and after 12 months in order to monitor change in their general appearance. The samples placed inside the shelter did

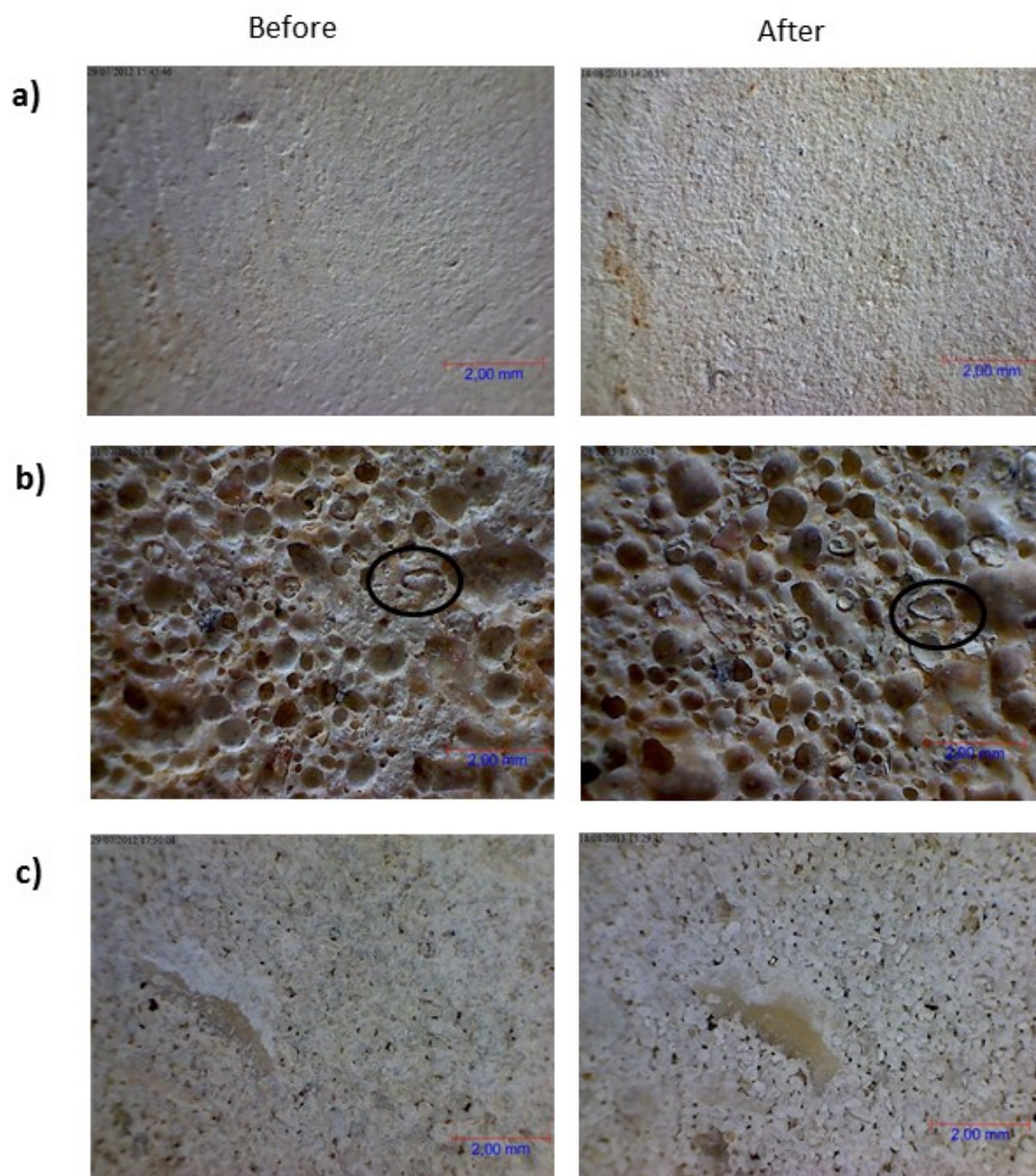
not show any substantial macroscopic change in terms of erosion or cracks. However, there is some evidence of loss of material in samples located outside the shelter. These external changes are also detected in dry weight measurements (Figure 6.1). Figure 6.10 shows macroscopic pictures of representative Chalk, Cotswold and Portland samples placed outside the shelter before and after a year of exposure.



**Figure 6.10:** Macroscopic pictures of samples placed outside the shelter before and after a year of exposure. a) Chalk (CH\_03); b) Cotswold limestone (CL\_02); and c) Portland limestone (PL\_01)

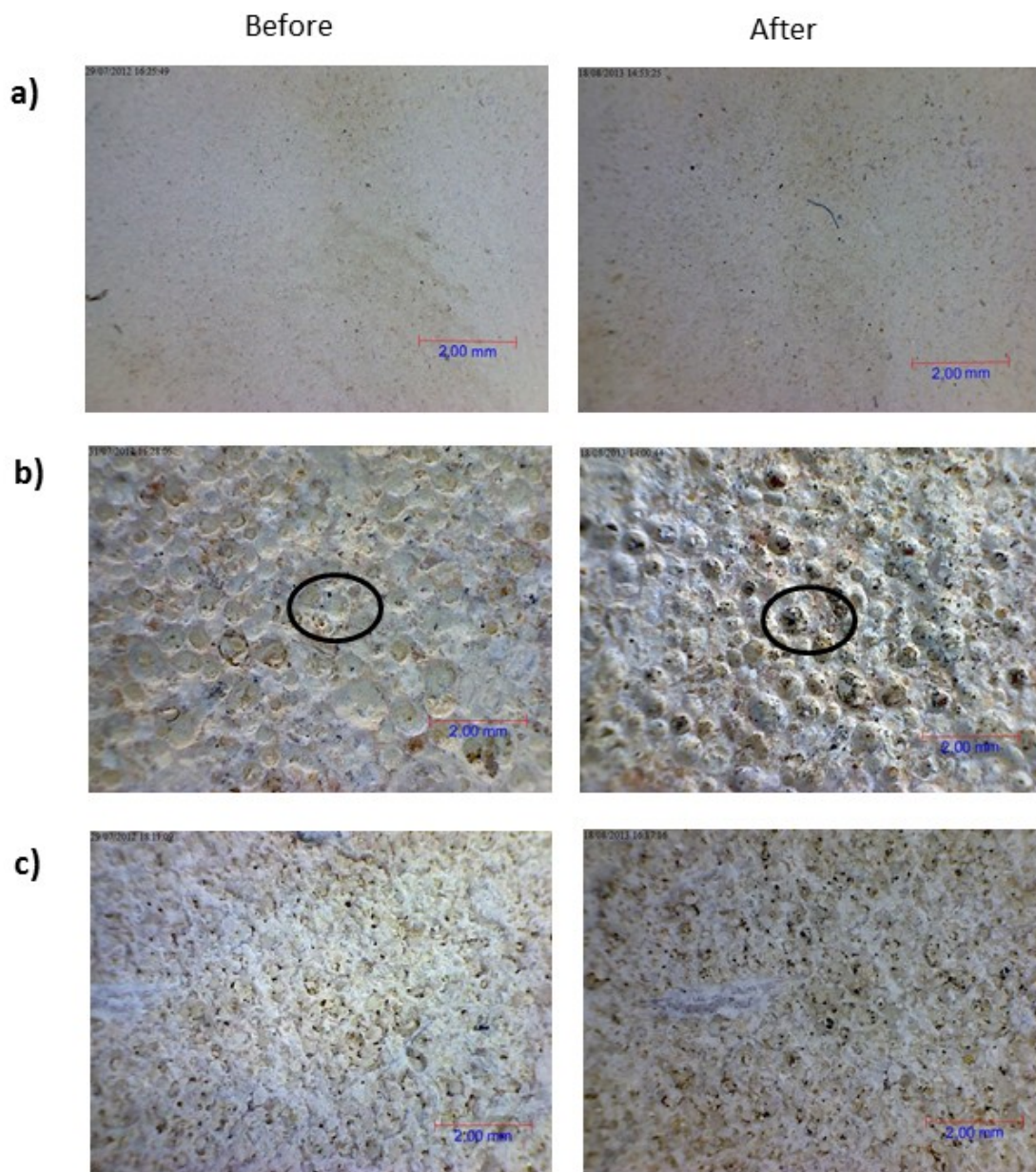
Two Chalk blocks cracked after a few months of exposure (as an example see Figure 6.10, a). Cotswold and Portland samples outside the shelter show erosion of the edges and corners (Figure 6.10, b) and Figure 6.10, c) respectively), although in the case of Portland to a lower degree.

In addition, detailed pictures of the surface of Chalk, Cotswold and Portland samples were taken with a 35x optical microscope initially and after a year.



**Figure 6.11:** Microscopic pictures of samples placed outside the shelter before and after a year of exposure. (a) Chalk (CH\_01); b) Cotswold (CL\_01); and c) Portland (PL\_01)

Figure 6.11 shows the pictures of the samples outside the shelter at the start and after 12 months. Chalk samples present an increase in surface roughness (Figure 6.11, a). There was a loss of ooliths in Cotswold samples after 12 months (Figure 6.11, b) and erosion of carbonate cement between stone grains in Portland samples, creating more small circular pores on the surface (Figure 6.11, c).



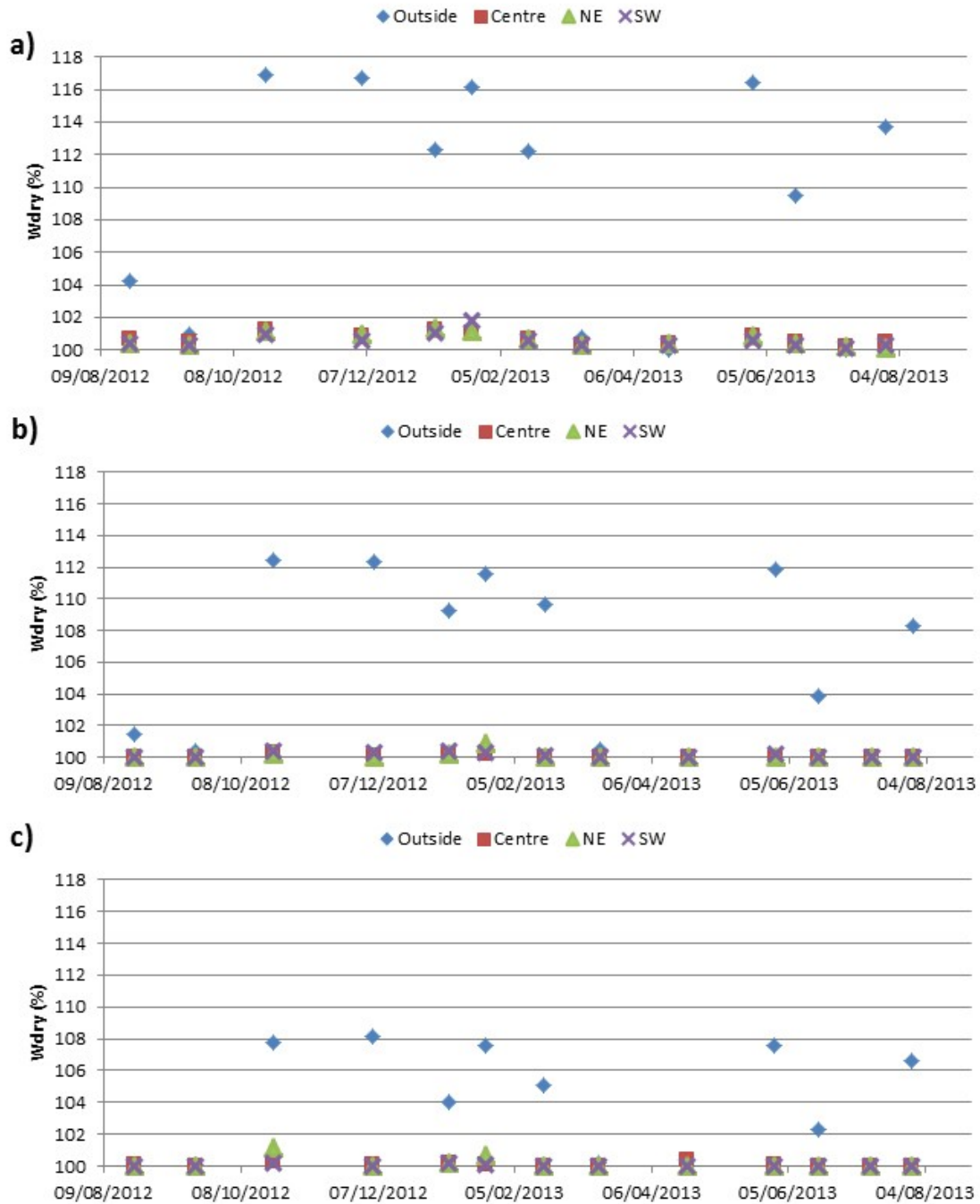
**Figure 6.12:** Microscopic pictures of samples placed under the central part of the shelter before and after a year of exposure. (a) Chalk (CH\_09); b) Cotswold (CL\_09); and c) Portland (PL\_09)

On the other hand, Figure 6.12 shows the microscopic pictures of the samples placed under the central part of the shelter before and after a year. Chalk samples depict a slight increase in surface roughness and soiling (Figure 6.12, a), although soiling is more noticeable in Cotswold (Figure 6.12, b) and Portland samples (Figure 6.12, c). However, it is not possible to appreciate any substantial difference between samples located at the different positions under the shelter.

### **6.3.7. Moisture content changes**

The change in weight was used as a proxy for changes in moisture content in the samples. The measurements were taken once per month during the year of monitoring in order to find out how moisture content differed between samples located at different positions outside and inside the shelter. Figure 6.13 illustrates weight changes as mean percentage of initial dry weight in Chalk, Cotswold and Portland blocks located outside, centre, NE and SW of the shelter.

The moisture content of the samples placed outside the shelter fluctuated more than the ones inside for all types of stone, decreasing in drier months and increasing in the wetter ones. Chalk blocks increased more in weight than Cotswold samples, and these more than Portland. The weight was more stable in the samples placed inside the shelter and it did not change remarkably with seasons. In addition, there was no difference in weight change between the different locations inside the shelter.



**Figure 6.13:** Means of the difference between weight and initial dry weight expressed as percentage of initial dry weight (%) for a) Chalk, b) Cotswold and c) Portland blocks between August 2012 and July 2013 (n=4 in each position)

A FMW moisture meter was used to corroborate the results obtained by measuring weight changes and to find out which method is more efficient. The FMW measurements were taken at the same time as the weight. Figure 6.14 shows the

mean FMW values of Chalk, Cotswold and Portland blocks located at the same position between August 2012 and July 2013.

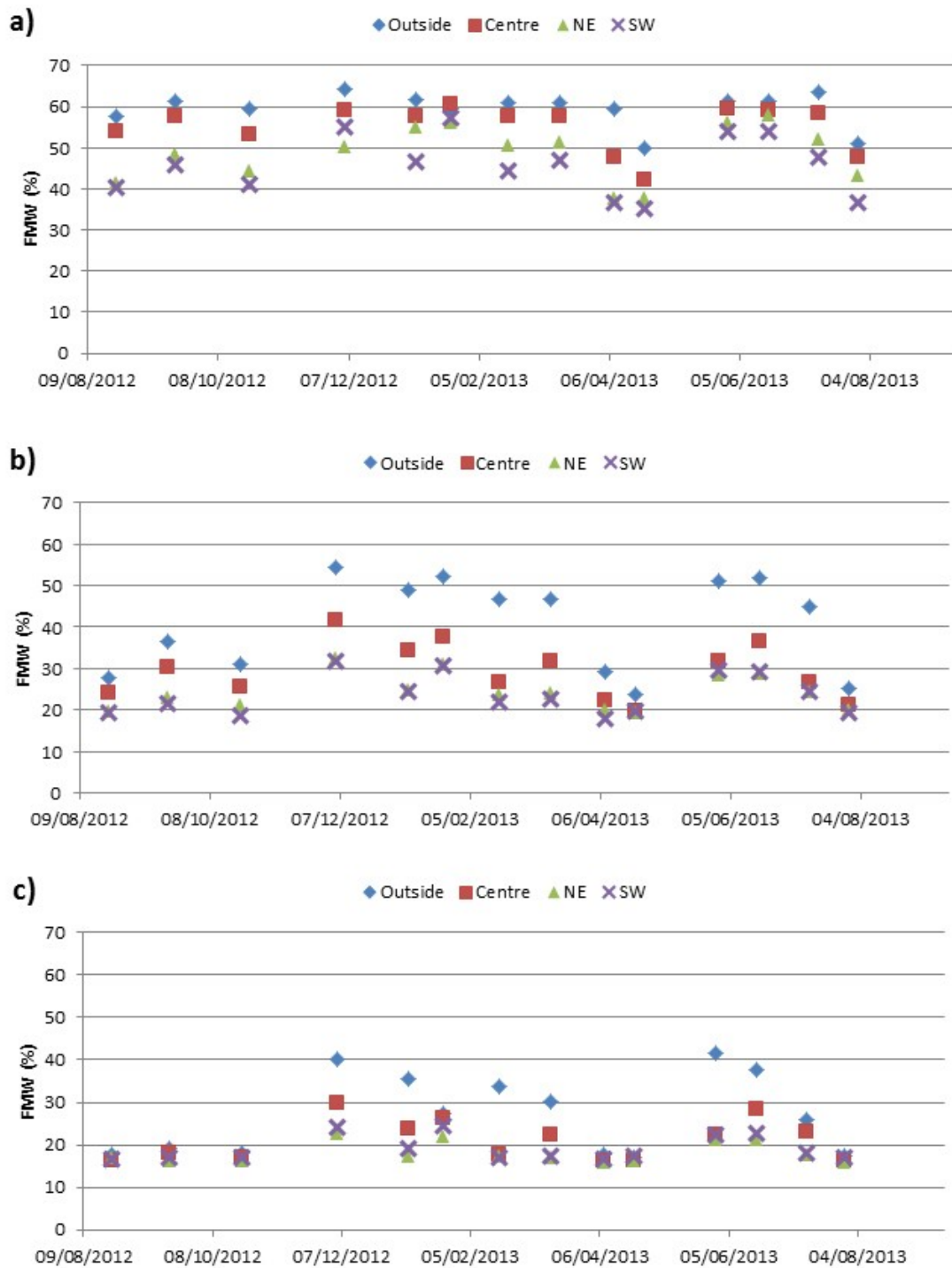


Figure 6.14: Mean moisture content (FMW %) of a) Chalk, b) Cotswold and c) Portland blocks between August 2012 and July 2013 (n=4 in each position)

Figure 6.14, a) demonstrates that Chalk samples had higher moisture content than Cotswold and these were higher than Portland samples. The moisture content in Chalk samples placed outside was only slightly higher than the ones placed inside the shelter, and seasonal differences were very narrow. The Chalk values could be misleading as the moisture contents might be higher than the maximum which can be detected by the FMW. On the other hand, the moisture content in Cotswold and Portland samples outside the shelter were higher than the ones inside mainly during the wetter months, as it shown in Figure 6.14, b) and c) respectively. The influence of the environment on FMW moisture content readings is more than that observed with the weight change data.

FMW and weight data indicate that samples placed outside the shelter showed higher and more fluctuating moisture contents, which decreased drastically in the drier months, when there was no difference between samples inside and outside the shelter. During autumn and winter, the blocks might have dried more slowly as the accumulation of surface moisture could have penetrated to depth, wetting the interior of the samples. In addition, there was no considerable difference between positions inside the shelter for any stone type. All the blocks located inside the shelter, including the ones in the peripheral area, show a more stable behaviour than outside. Their weights and moisture content remained relatively constant all year. Reasons that the moisture content in the samples was different inside and outside the shelter could be that RH levels were also different (see Chapter 5). The relation between moisture content (%Wdry) and RH has been studied by Eshøj and Padfield (1993), who established that water absorption of limestone increase with RH over 80%. A Spearman Rank Order Correlation test corroborates that there is a positive correlation

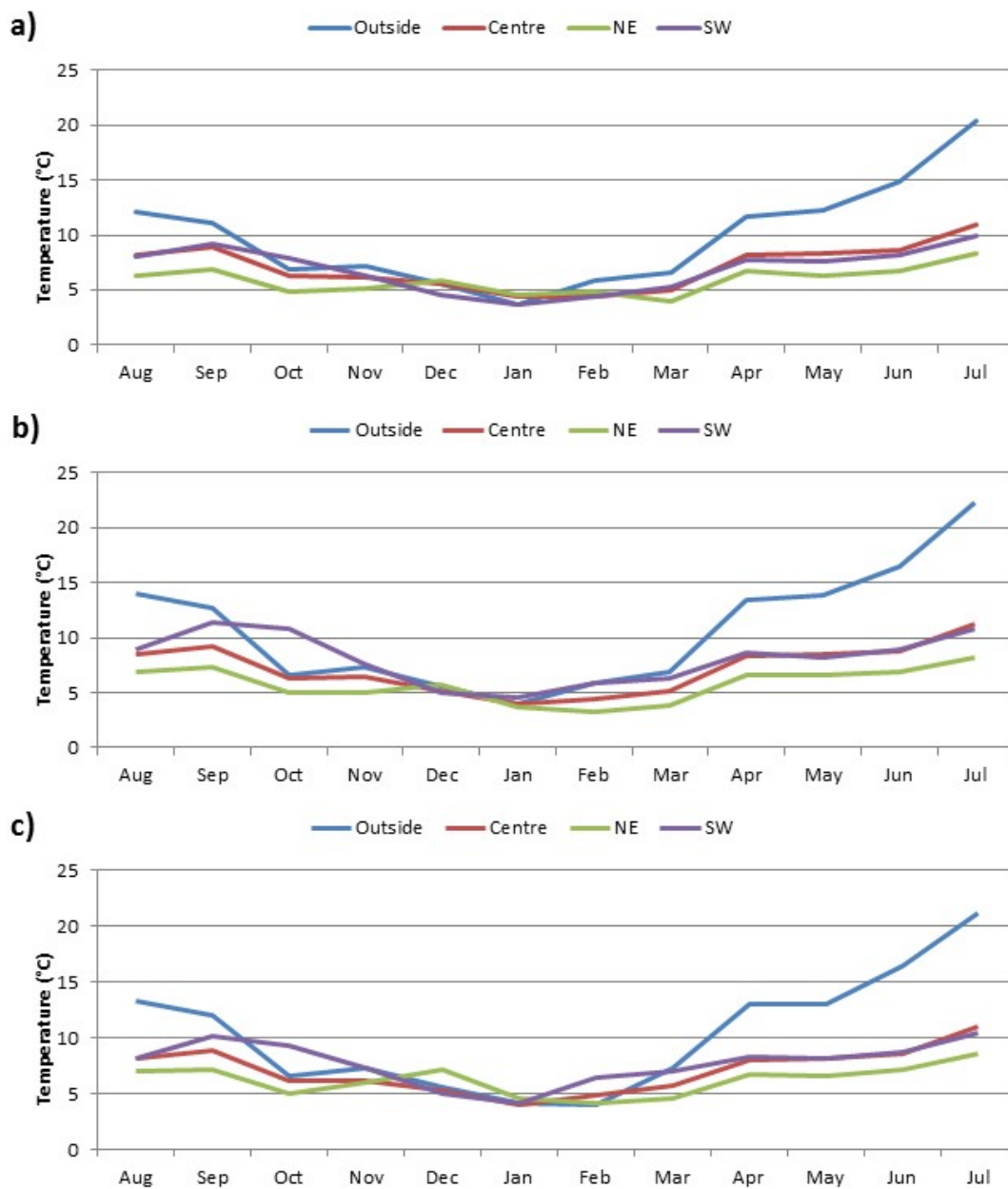
between the daily RH mean and moisture content (%Wdry) inside ( $r=0.703$ ,  $P=0.006$ ,  $n=13$ ) and outside the shelter ( $r=0.764$ ,  $P=0.001$ ,  $n=13$ ).

A Spearman Rank Order Correlation test was undertaken in order to find out if the changes in moisture content measured by the FMW moisture meter were correlated to the ones obtained with the weight. The pair of variables, weight change (as percentage of initial dry weight) and moisture content readings (FMW %), show a positive correlation ( $r =0.752$ ,  $P=2e^{-7}$ ,  $n=150$ ). This means that there is a significant relationship between them and weight and FMW moisture content values tend to increase together. The Brookhuis FMW-T moisture meter is a non-destructive and easy to carry piece of equipment which has been frequently used in other stone weathering studies (Eklund et al., 2013, Mol and Viles, 2013, McCabe et al., 2013). This study has showed that it could be good indicator of moisture content in stone samples when weight cannot be used. There are, however, two limitations. It is not totally reliable when the type of stone has as high a moisture content as Chalk; it can only be applied to flat surfaces; and only detects moisture up to a certain depth, which makes it more suitable for small samples.

#### **6.3.8. Surface temperature**

As we have seen before in Chapter 3, temperature changes may induce stress in the stone. The difference between maximum and minimum temperatures per day was used to determine the range of the daily surface temperature fluctuations in Chalk, Cotswold and Portland samples located inside and outside the shelter. Figure 6.15 depicts the monthly means in daily surface temperature ranges on Chalk, Cotswold and Portland samples located outside and inside the shelter (centre, NE and SW)

during a year. In winter and autumn, all the samples showed similar surface temperature fluctuations. In spring and summer, however, samples placed outside the shelter showed greater daily ranges than the samples inside for all stone types. This means that the shelter was most probably able to reduce solar radiation and, therefore, reduce the range of the daily fluctuations.



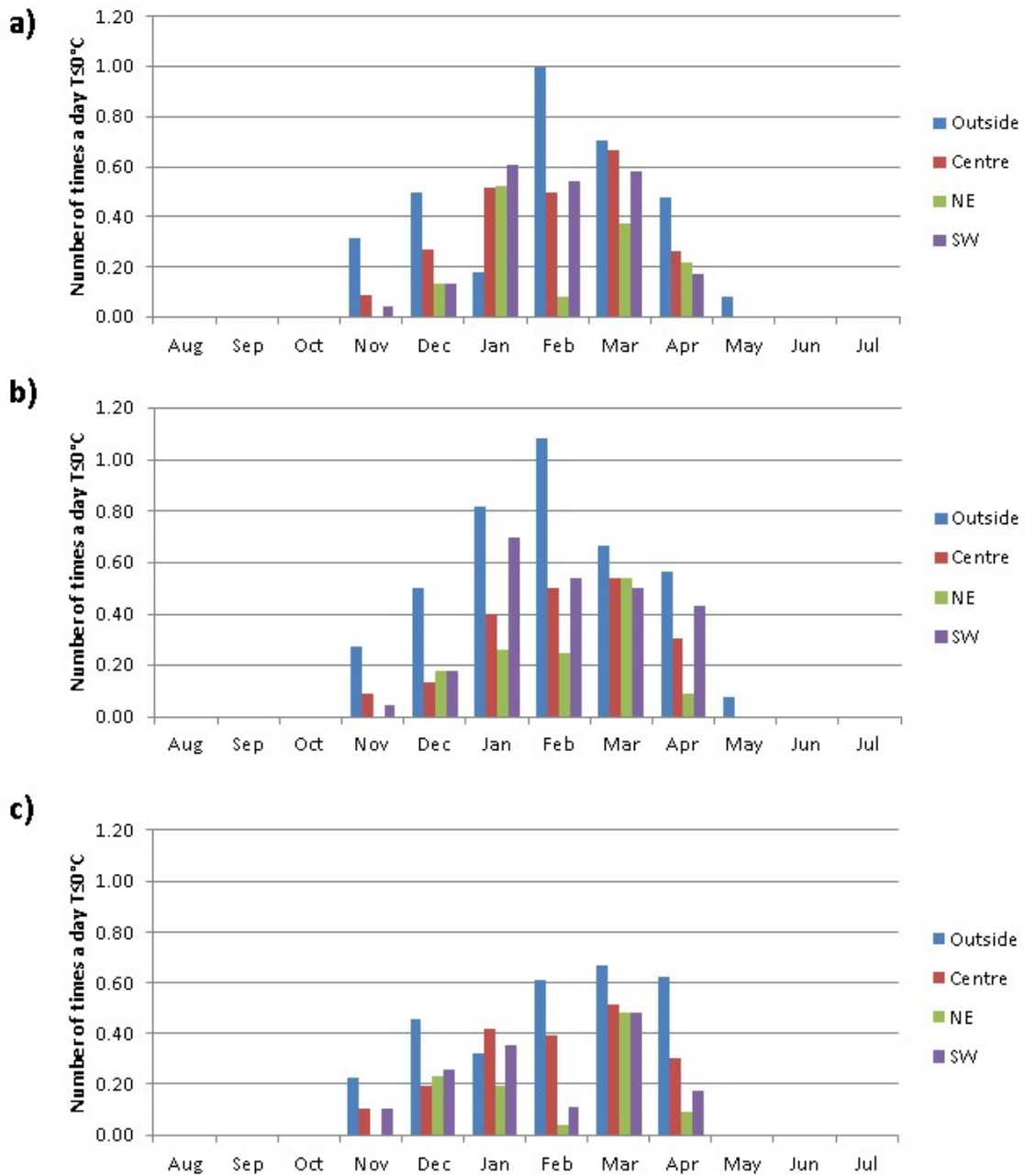
**Figure 6.15:** Monthly mean of the difference between maximum and minimum surface temperature per day in a) Chalk , b) Cotswold and c) Portland blocks placed outside, centre, NE and SW of the shelter

There was no difference in daily surface temperature fluctuations between the samples located in the centre and SW but the temperature range was slightly smaller in the samples located at the NE. To quantify the differences between positions and stone types and find out if they are statistically significant, a multilevel linear model with day as random effect for the diurnal stone surface temperature ranges was fitted. The results are shown in Table 6.10. The daily temperature range in the centre of the shelter was statistically lower than outside but greater than in the NE for all stone types. In addition, there were no significant differences in diurnal surface temperature range between stone types.

**Table 6.10:** Results of the multilevel linear model with day as random effect for the diurnal stone surface temperature range

Reference: Centre of the shelter and Chalk	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.590	0.014	3183	111.727	<0.001
Position NE	-0.075	0.010	3183	-7.204	<0.001
Position Outside	0.131	0.010	3183	12.503	<0.001
Position SW	-0.018	0.010	3183	-1.697	0.089
Stone type Cotswold	0.003	0.010	3183	0.318	0.750
Stone type Portland	-0.0002	0.010	3183	-0.023	0.981
Reference: Centre of the shelter and Cotswold	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.593	0.014	3183	111.961	<0.001
Position NE	-0.090	0.010	3183	-8.571	<0.001
Position Outside	0.147	0.010	3183	13.721	<0.001
Position SW	0.031	0.010	3183	2.951	0.003
Stone type Portland	-0.003	0.010	3183	-0.351	0.725
Reference: Centre of the shelter and Portland	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.590	0.013	3183	114.943	<0.001
Position NE	-0.050	0.009	3183	-5.248	<0.001
Position Outside	0.106	0.010	3183	10.306	<0.001
Position SW	0.02	0.009	3183	2.675	0.008

Additionally, the number of times surface temperature dropped below 0°C per day was taken as a proxy for the number of freezing events.



**Figure 6.16:** Monthly mean of the number of times per day surface temperature dropped below 0°C in a) Chalk, b) Cotswold, and c) Portland samples located outside, centre, NE and SW of the shelter

Figure 6.16 shows the monthly mean of the number of freezing events per day in Chalk, Cotswold and Portland samples located outside and inside the shelter (centre, north-east and south-west). In general, the samples placed outside the shelter show a

greater number of freezing events than the ones inside the shelter for all stone types, with the exception of Chalk and Portland blocks in January, probably because the outside blocks were under freezing temperatures for longer. There is no clear difference between positions inside the shelter and between Chalk and Cotswold; although Portland stones showed a slightly fewer number of freezing events than the other two stone types.

In order to determine if there were statistically significant differences in the number of freezing events per day between positions and stone types, the number of times the surface temperature went below 0°C per day was fitted as the response of a 2-level Poisson Generalised Linear Model (GLM). Results showed that freezing events were less likely to occur in the NE periphery. In the other locations inside the shelter, there was more probability of having fewer freezing events than outside but the difference is not significant. In addition, there were no differences between stone types. Results are shown in Table 6.11.

**Table 6.11:** Results of the Poisson Generalized Linear Model for the number of freezing events per day. Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Reference: Outside and Chalk	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-0.076	0.121	-0.634	0.526	
Position NE	-0.699	0.208	-3.369	0.000	***
Position Centre	-0.160	0.161	-0.995	0.320	
Position SW	-0.215	0.164	-1.310	0.190	
Stone type Cotswold	0.129	0.098	1.314	0.189	
Stone type Portland	0.015	0.102	0.152	0.879	
Reference: Outside and Cotswold	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-0.052	0.116	0.447	0.654	
Position NE	-0.699	0.207	-3.369	0.000	***
Position Centre	-0.160	0.161	-0.995	0.319	
Position SW	-0.215	0.164	-1.310	0.190	

Stone type Portland	-0.113	0.101	-1.123	0.261	
Stone type Chalk	-0.129	0.098	-1.314	0.188	
Reference: Outside and Portland	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	-0.061	0.119	-0.516	0.605	
Position NE	-0.699	0.208	-3.369	0.000	***
Position Centre	-0.160	0.161	-0.995	0.320	
Position SW	-0.215	0.164	-1.310	0.190	
Stone type Cotswold	0.113	0.101	1.123	0.261	
Stone type Chalk	-0.015	0.102	-0.152	0.879	

Both surface temperature and freezing events are in line with the results obtained in Chapter 5. Blocks located outside and in the centre of the shelter showed similar surface temperature ranges and number of freezing events than ambient conditions.

#### **6.4. Discussion and Conclusions**

The stone blocks presented changes in their physical properties after a year of exposure outside, at the periphery and under the central part of the shelter. Some changes confirmed the predictions in Table 6.3 and others were unexpected.

Table 6.12 summarises the results obtained from the analysis of dry weight, elasticity, hardness, UPV, colour change, macroscopic and microscopic pictures, moisture content and daily temperature fluctuations and number of frost events in Chalk, Cotswold and Portland samples. The trend of the change is indicated by an arrow in the case of dry weight, EMOD, hardness and UPV change.

**Table 6.12:** Results of the changes in key indicators of decay after a year. The degree of change refers to mean values of the samples (n=4). It is marked in red when significantly different to the other positions

		Outside	SW	NE	Centre
<b>Chalk</b>	Dry weight	High ↓	Low ↓	Low ↓	Low ↓
	EMOD	- ↑	- ↑	- ↓	High ↑
	Hardness	High ↑	Low ↑	- ↑	Medium ↑
	UPV	- ↑	Medium ↑	Medium ↑	Medium ↑
	dE*ab	Medium	Medium	Medium	Medium
	Macroscopy	High	Medium	Medium	Medium
	Microscopy	Medium	Low	Low	Low
	Moisture	High	Low	Low	Low
	T fluctuation	Medium	Medium	Low	Low
	Frost	Medium	Medium	Medium	Medium
<b>Cotswold</b>	Dry weight	Medium ↓	Low ↓	Low ↓	Low ↓
	EMOD	High ↓	- ↓	- ↑	- ↓
	Hardness	- ↑	Medium ↑	Medium ↑	- ↑
	UPV	Medium ↓	- ↓	- ↓	- ↓
	dE*ab	High	Low	Medium	Low
	Macroscopy	High	Low	Low	Low
	Microscopy	Medium	Medium	Medium	Medium
	Moisture	Medium	Low	Low	Low
	T fluctuation	Medium	Medium	Low	Low
	Frost	High	Medium	Medium	Medium
<b>Portland</b>	Dry weight	Low ↓	Low ↓	Low ↓	- ↓
	EMOD	Medium ↓	- ↑	- ↑	- ↓
	Hardness	Medium ↓	- ↑	- ↑	- ↓
	UPV	- ↑	Low ↑	Low ↑	- ↓
	dE*ab	Low	Low	Low	Low
	Macroscopy	Medium	Low	Low	Low
	Microscopy	Medium	Low	Low	Low
	Moisture	Medium	Low	Low	Low
	T fluctuation	Medium	Medium	Low	Low
	Frost	Medium	Medium	Medium	Medium

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change: HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=no noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For T fluctuations (mean diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For all measurements “-” means that change is close the change in controls (Table 3.9).

The first objective of this chapter was to examine to what extent the shelter affected the degree of deterioration of the stone blocks as quantified by dry weight, elasticity, surface hardness and UPV change. The results are analysed together with the moisture content and surface temperature, which refers to objective number 2.

All of the stone samples lost weight after 12 months but the difference was more noticeable in the replicates placed outside (see Figure 6.1). In addition, the greater change in weight took place between 3 and 9 months. This could be connected with the effect of winter months, when the number of times the temperature went below 0°C increased and the surface temperature reached minimum values in the samples placed outside the shelter in all stone types. Although the diurnal temperature difference was higher in summer (Figure 6.15), probably it did not affect stone decay as much as the effect of the winter, especially frost events. Samples placed outside the shelter reached freezing temperatures more frequently and they were wetter for longer (Figure 6.16 and Figure 6.13, respectively). Chalk and Cotswold were the types of stone more affected by weight loss, mainly in the samples located outside the shelter. Lower HL values have been correlated to weathered surfaces (Aoki and Matsukura, 2007); therefore, the samples exposed outside the shelter were expected to show greater decrease in hardness than those inside. All Chalk blocks increased in hardness after a year, perhaps related to short-term, natural ageing process. Cotswold limestone samples also increased in surface hardness but significantly more inside than outside the shelter. Portland samples decreased in hardness mainly outside the shelter when the weight lost was also greater. However, this data must be analysed with caution as statistical tests (section 3.3 in Chapter 3) showed that there were no significant differences in hardness values between exposed and control samples in the

laboratory. This could be related to the great variability of the data obtained from heterogeneous stone surfaces. In addition, although it was expected that the microenvironmental conditions as well as the time of exposure would reduce EMOD and UPV values (Cooks, 1983, Goudie et al., 1992), the results were not conclusive. Probably a greater length of exposure time would be needed to obtain clear trends for these parameters.

The objective number 3 of this chapter was to determine how the shelter influences the nature of deterioration and soiling in the stone blocks assessed by surface colour and macroscopic and microscopic pictures. The results are analysed together with the moisture content and surface temperature (objective number 2). The stone samples placed inside the shelter changed less in their general appearance than ones located outside. They present some evidence of weathering such as a slight erosion of the edges, increase in surface roughness, loss of carbonate cement between grains and, in the case of Chalk samples, visible cracks (see section 6.3.6). In addition, they show lower levels of particulate deposition probably related to the washing effect of the rain. Samples at the NE edge of the shelter and mainly outside became darker or less light than the ones in the SW and centre of the shelter (Table 6.9). Additionally, Chalk and Cotswold samples outside the shelter became yellower. Samples outside the shelter were very wet most of the year and the environment at the NE edge probably had a high but constant RH with small temperature fluctuations (due to fewer number of freezing events and lower surface temperature ranges than other positions inside the shelter). This, together with the fact that the site is relatively unpolluted (see Chapter 7) and the degree of change is related to the time of the year, could indicate

the presence of biofilms. This result is also in line with those found after the survey (see Chapter 4).

The main decay mechanisms affecting the stone blocks seem to be biocolonisation, loss of material (probably caused by physical weathering processes, mainly freeze-thaw cycles), and soiling. These were also identified as main active decay processes in the ruins of the Bishop's Palace after undertaking a condition survey (see Chapter 4).

Objective number 4 of this chapter was to find out if there were differences in the deterioration of the stone samples depending on the position they were placed. There were fewer significant differences in the stone properties' changes and key environmental parameters for stone decay between NE, SW and centre of the shelter as outside. The exception is the possible biological growth at the NE edge explained above. Although the shelter did not stop decay completely, stone samples under the shelter were less affected than those outside.

The degree of change depended on the type of stone, Chalk being the most vulnerable. A Spearman Rank Order Correlation test for EMOD, UPV, dry weight and hardness values of Chalk, Cotswold and Portland samples before and after a year indicated that there is a significant relationship between them ( $P < 0.05$  all pairs of variables). In addition, they have positive correlation coefficients; therefore the stone properties tended to increase together. Chalk has the lowest UPV values and EMOD. Chalk samples also have the lowest weight. Although it is harder than Cotswold stone at the surface level, Chalk is not as hard as Portland. On the other hand, Portland limestone is the hardest and with higher EMOD. It also shows higher UPV values, which indicates higher density. The samples of this stone type are heavier than the others. This,

alongside the study of water absorption, open porosity and apparent density properties (see section 3.3.1 in Chapter 3), indicates that Chalk is very porous and soft and has demonstrated that is the most effective indicator of decay for physical weathering, mainly for dry weight. Cotswold samples could be a good option for monitoring change in appearance (colour and macroscopic and microscopic changes) as changes could be noticeable after just 3 months (see Figure 6.5). In addition, they could be used as a proxy for change in site ruins which have been built with this stone type.

In relation to the methodology, weight change is a useful and simple method to monitor weathering in stone blocks. It is suitable for sites with low budgets and significant results might be obtained in short exposure times. Elasticity, hardness and ultrasonic pulse velocity are good indicators of change in physical properties of stone blocks, as it has been proven by other studies (Moses et al., 2014). However, longer exposure times might be needed for this specific case study. Colour changes have also been very useful to obtain information about biological growth or soiling, although they are more useful in stones with a homogeneous surface colour.

## **7. EXAMINING THE EFFECTS OF THE OPEN SHELTER AT THE BISHOP'S PALACE (WITNEY) ON DISSOLUTION, SOILING AND MICROBIAL GROWTH ON PORTLAND LIMESTONE TABLETS**

### **7.1. Introduction and aims**

An exposure trial based on Portland limestone tablets was used to investigate variations in weathering processes (dissolution, soiling and microbial growth) inside and outside the shelter at the Bishop's Palace. In addition, decay rates were compared with results obtained from a large-scale UK programme (Butlin et al., 1995).

Soiling has been defined by ICOMOS International Scientific Committee for Stone (2008) as a deposit of a very thin layer of exogenous particles giving a dirty appearance to the stone (see Chapter 4). Soiling is most often associated with a darkening of the surface related to the deposition of airborne particulate matter (Cutler et al., 2013). However, it can also be the result of green algae or pigmented biofilms or the combination of both. For example, extracellular polymeric substances (EPS) can contribute to the accumulation of pollutants (Viles and Gorbushina, 2003). Therefore, a darkening of the surface could be a result of organic or inorganic soiling, while greening is likely to be associated with algal growth. Biological communities can damage stone by mechanical weathering due to, for example, pore pressures exerted by growing cells and the expansion and contraction of cells (and their EPS matrix) via wetting/drying, and/or chemical weathering related to the action of metabolic substances. However, microbes can also have a protective role, by consolidating the surface of stone and shielding from rain and pollution to varying degrees (Viles, 2012). On the other hand, deposition of atmospheric pollutants directly on the stone surface

can lead to chemical weathering (Camuffo, 1986, Grossi and Brimblecombe, 2002). Gaseous and particulate pollutants (including carbon soot, fly ash, dust and associated salts) can be deposited directly on the stone surface (dry deposition) or dissolved in rainwater (wet deposition). Sheltered areas are subjected only to dry deposition. Pollutants can accumulate on the stone surface and be 'activated' by water droplets from condensation or rising damp leading to the formation of salt crusts (Steiger, 2003, Brimblecombe, 2011). In addition, airborne organic pollutants on the surface of stone can enrich the substratum for microbial colonisation (Saiz Jimenez, 2003). Specific processes associated with rainfall also affect unsheltered stone. The dissolution of limestone, for example, depends on rainfall amount, its temperature and CO<sub>2</sub> content (Viles, 2003). Importantly, the solubility rate of calcium carbonate increases with rain acidity and pollution (Webb et al., 1992). In addition, resultant soluble salt crusts such as calcium nitrates and sulphates (i.e. gypsum crusts) are more soluble than carbonates, meaning precipitation can make unsheltered stones more prone to mass loss (Lipfert, 1989). They may also produce mechanical stresses in the substrate due to different molecular volume (Brimblecombe, 2011). Sulphate crusts on stone can be formed by the action of sulphur oxides from industrial emissions, while nitrogen oxides are mainly associated with pollution from traffic.

The rate of decay of calcareous stones in relation to pollution and climate has been studied by numerous projects (Lipfert, 1989, Webb et al., 1992, Inkpen et al., 1994). Among them, the National Materials Exposure Programme (NMEP), established in 1986, aimed to assess the impact of acid deposition on building materials in the United Kingdom (Butlin et al., 1992, Butlin et al., 1993). As part of the first phase of this programme, Whit Bed Portland limestone tablets (50x50x8 mm) were mounted on

freely rotating carousels in exposed and sheltered positions at 29 sites with different climatic conditions for four years (Butlin et al., 1993). After this time, sheltered tablets were found to contain higher levels of soluble salts in comparison to rain washed tablets. In addition, sheltered tablets tended to gain weight whereas exposed tablets lost weight and increased in surface roughness. The attributed causes were soiling and dissolution, respectively. In addition, the study established damage functions to predict the change in weight in relation to air concentrations of NO<sub>2</sub> and SO<sub>2</sub>, and rainfall acidity and amount. Biological growth on NMEP tablets from Wells, Bolsover and Lough Navar was researched by Viles et al. (2002) who found that pollution was an important factor on the nature and degree of soiling (either biological or inorganic).

After a visual assessment of the decay patterns at the Bishop's Palace site, biological films and crusts were reported as one of the main problems (see Chapter 4). Biological growth is predominant in areas with high water content such as bottom walls and those facing north. In addition, crusts of possible biological origin were spread over the ruins without any clear pattern.

In order to understand the impact of the open shelter at the Bishop's Palace on limestone deterioration due to dissolution, soiling and biological growth, the following objectives have been proposed:

1. to identify how dissolution, soiling and microbial colonisation on limestone under the shelter differ from outside
2. to establish how these processes could affect limestone decay

## 7.2. Materials and methods

Following the UK NMEP methodology, two sets of twelve Whit Bed Portland stone tablets (50x50x20 mm) were placed inside (centre) and outside the shelter at the Bishop's Palace on freely-rotating carousels from the 23<sup>rd</sup> January 2013 to 23<sup>rd</sup> July 2014. Three tablets per set were exposed for 6 months, another three for 12 months and the remaining six, 18 months. Portland stone is a Jurassic oolitic limestone with relatively low water absorption and open porosity coefficients and high apparent density and it is considered to be relatively durable (see section 3.3.1 in Chapter 3 for more information).

This study focused on determining and quantifying the following:

1. biological growth through colour change and microscopy observations
2. soiling by darkening and salt content of the stone tablets
3. decay rates in terms of weight change and in relation to the main environmental conditions that cause chemical weathering: atmospheric pollutants, acidity of rainwater and amount of rainfall

Air pollution, salt content and weight data for the Bishop's Palace have been compared with the results obtained from four NMEP sites with low rainfall acidity and air pollution: Wells (South West England), Bovington Camp (South East England), Lough Navar (Northern Ireland) and Strath Vaich Dam (Scotland). The reason was to determine how the nature and rate of decay processes at the Bishop's Palace compare to these already published sites.

Table 7.1 summarises the methods used to produce the different sets of information (for more information see section 3.4 in Chapter 3).

**Table 7.1:** Data collection, handling and analysis methods used for this study

	<b>Equipment</b>	<b>Data handling</b>	<b>Statistical analysis</b>
<b>Surface colour</b>	Spectrophotometer	dE*ab, dL* and da* per tablet after 6, 12 and 18 months (means and standard deviations)	Two-way ANOVA test (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Microscopy</b>	SEM	Pictures after 18 months	
<b>Salt content</b>	Dionex ion chromatograph	Amount (in ppm) of sulphates, nitrates and chlorides per tablet after 6, 12 and 18 months (means and standard deviations)	Two-way ANOVA test (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Air pollution</b>	Diffusion tubes, Dionex ion chromatograph	Amount (in ppm) of SO <sub>2</sub> and NO <sub>2</sub> in the air (means and standard deviations)	Student's t-test
<b>Dry weight change</b>	Balance	Percentage of initial dry weight per tablet after 6, 12 and 18 months (means and standard deviations)	Two-way ANOVA test (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)

Surface colour changes, including darkening, were measured with a spectrophotometer (CM- 700d, Konica Minolta). In addition, a detailed examination of the stone surface was undertaken by optical microscope and scanning electron microscope. Salt content in the Portland tablets was assessed using a Dionex ion chromatograph. The major anions and cations were extracted using deionised water and their concentrations measured in ppm. The concentrations of salts were compared with the average salt content recorded from the control tablets. The pH of a representative sample of rain falling at the study site was measured in April 2014 (pH meter Orion Model 410A). Combined NO<sub>2</sub> and SO<sub>2</sub> diffusion tubes (Gradko

International Ltd) were also used for 4 weeks in October/November 2013. After exposure, analysis was carried out using ion chromatography.

Table 7.2 summarises the hypothesized changes in stone tablets predicted to occur in the centre and outside the shelter, together with the predictions of the amount of SO<sub>2</sub> and NO<sub>2</sub> in the air. An increase in soiling is expected inside the shelter. Sheltered areas are protected from the washing effect of rain, so pollutants can accumulate on the stone surface increasing surface colour change (especially darkening) and salt content. On the other hand, tablets located outside are at risk of dissolution, and higher weight loss is predicted. Pollutants on the surface of stone inside the shelter can enhance microbial colonisation but biofilms tend to be more abundant in locations with higher water content, which could make outside tablets become greener. In addition, lower levels of pollution are predicted inside and outside shelter at the Bishop's Palace.

**Table 7.2:** Predictions of changes in key indicators of deterioration after a 18 months of exposure and amount of airborne pollutants \*

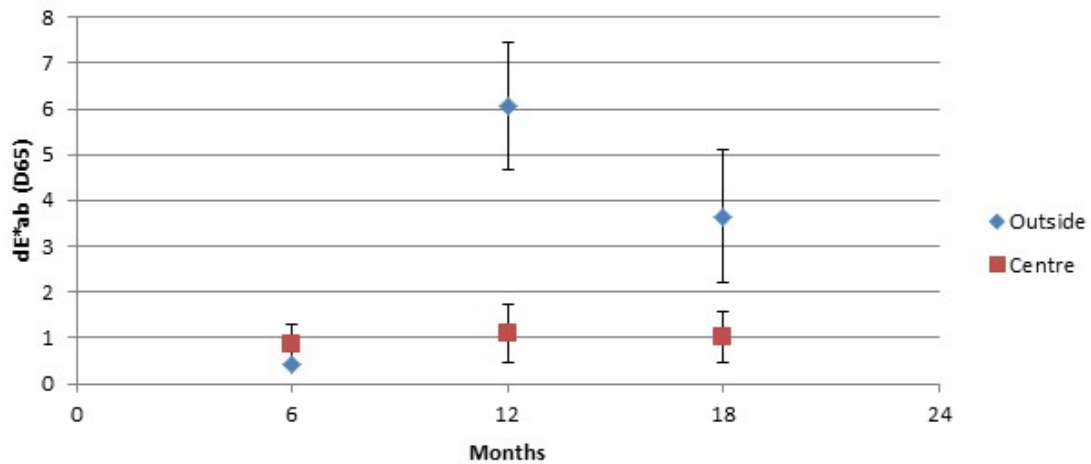
	Outside	Centre
<b>dE*ab</b>	Low	Low
<b>da*</b>	Medium	Low
<b>dL*</b>	Low	Medium
<b>Microscopy</b>	Medium	Low
<b>Sulphate content</b>	-	Low
<b>Nitrate content</b>	-	Low
<b>Chloride content</b>	-	Low
<b>Air pollution: SO<sub>2</sub> concentration</b>	Low	-
<b>Air pollution: NO<sub>2</sub> concentration</b>	Medium	Low
<b>Dry weight change</b>	Low	-

\* For overall colour change (dE\*ab): HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For greening/darkening (da\* and dL\*): HIGH= below -1, MEDIUM= 0 to -1, LOW= above 0. For microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=no noticeable. For salt content: HIGH= more than 20 ppm difference from controls, MEDIUM=20-10 ppm, LOW=less than 10 ppm. For air pollution (µg/m<sup>3</sup>): HIGH=above 10, MEDIUM= 10-5, LOW= below 5. . For dry weight change: HIGH=above 0.5%, MEDIUM=0.5-0.1%, LOW= below 0.1%. For all measurements “-“ means that no change is predicted.

## 7.3. Results

### 7.3.1. Colour change

The overall colour change of sheltered and unsheltered tablets after 6, 12 and 18 months (relative to the baseline) is shown in Figure 7.1. Tablets placed outside the shelter experienced greater overall colour change than those inside the shelter. This difference was more pronounced after 12 months of exposure, when CIELAB colour differences were over 3.8 dE\*ab, the indicative threshold for changes to be distinctively perceptible to the naked eye (Bieske and Vandahl, 2008).



**Figure 7.1:** Overall colour change expressed as dE\*ab (D65) means and standard deviations for tablets placed outside and under the central part of the shelter after 6 (n=3), 12 (n=3) and 18 months (n=6)

A two-way ANOVA statistical test using factors of position (control, inside and outside the shelter) and time (3, 6, 12 months) showed a significant interaction between them, indicating that the effect of position on colour change varied between the different periods of exposure ( $F=6.650$ ,  $DF=4$ ,  $P=0.002$ ). Post-hoc multiple comparison tests (Holm-Sidak method) indicated that there was no difference in colour change after 6 months for sheltered and unsheltered tablets ( $t=0.539$ ,  $P=0.934$ ), but significant differences were observed after 12 months ( $t=6.235$ ,  $P<0.001$ ) and 18 months

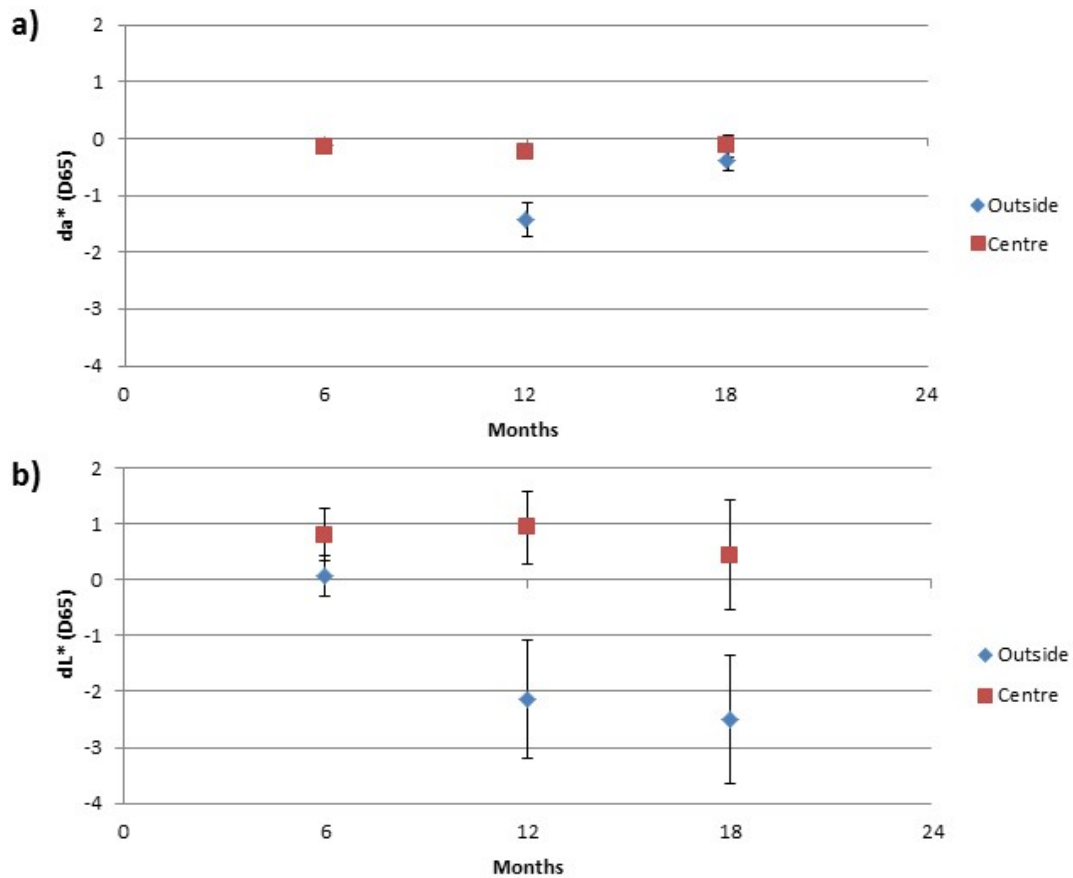
( $t=4.669$ ,  $P<0.001$ ). In addition, there were no significant differences between sheltered and control tablets after 6, 12 or 18 months ( $P<0.050$ ) but unsheltered tablets varied significantly from the controls after 12 ( $t=4.947$ ,  $<0.001$ ) and 18 months ( $t=0.657$ ,  $P=0.011$ ).

Additionally to overall colour change, deviations on the red-green scale ( $da^*$ ) are inferred to be connected with the presence of microorganisms on stone surfaces, such as green algae or cyanobacteria (Cutler et al., 2013). Negative values indicate that the stone surface is greener than the baseline measurement, that is, the same stone tablet before being exposed in the field. When  $da^*$  is below -1, the greening of the surface is considered noticeable (Cutler et al., 2013).

Figure 7.2, a) shows  $da^*$  changes for sheltered and unsheltered tablets after 6, 12 and 18 months. The unsheltered tablets were greener after 12 months compared to after 6 and 18 months. As with data for overall colour change (Figure 7.1), a two-way ANOVA test showed that there was a statistically significant interaction between position and time factors ( $F= 12.87$ ,  $DF=4$ ,  $P <0.001$ ). Subsequent post-hoc multiple comparisons (Holm-Sidak method) showed that the change in  $da^*$  values was statistically different between sheltered and unsheltered tablets after 12 months ( $t=8.591$ ,  $P<0.001$ ) and 18 months ( $t=2.798$ ,  $P=0.035$ ), but no different at 6 ( $t=0.819$ ,  $P=0.808$ ). This means that the tablets placed outside the shelter became greener than the ones inside after a year, as is also reflected in the overall colour change data (Figure 7.1).

In contrast to  $da^*$  data,  $dL^*$  changes reflect darkening (negative values) or lightening (positive values) of the surface. When darker particles are deposited on the stone, the amount of reflected light is reduced (Pesava et al., 1999). Black deposits can relate to

air pollution, dust or pigmented microbial biofilms such as black fungi (Zanardini et al., 2000, Cutler et al., 2013). Conversely, the formation of white efflorescences like gypsum and halite can make the surface lighter (Pio et al., 1997).



**Figure 7.2:** a) Greening of the surface expressed as  $da^*$  (D65), and b) darkening/lightening of the surface expressed as  $dL^*$  (D65). Means and standard deviations for tablets in the centre and outside after 6 (n=3), 12 (n=3) and 18 months (n=6)

Figure 7.2, b) shows  $dL^*$  changes for the tablets at the Bishop's Palace. Darkening of the surface of the limestone tablets positioned outside the shelter was noticeable after 12 months of exposure, when  $dL^*$  values are less than -1 (Cutler et al., 2013). A two-way ANOVA test shows that the interaction between positions and months is not statistically significant ( $F=2.042$ ,  $DF=4$ ,  $P=1.31$ ), indicating that the effect of positions on  $dL^*$  did not vary between the different periods of exposure. However, the positions had a significant effect on  $dL^*$  values ( $F= 15.043$ ,  $DF=2$ ,  $P<0.001$ ). Post-hoc multiple

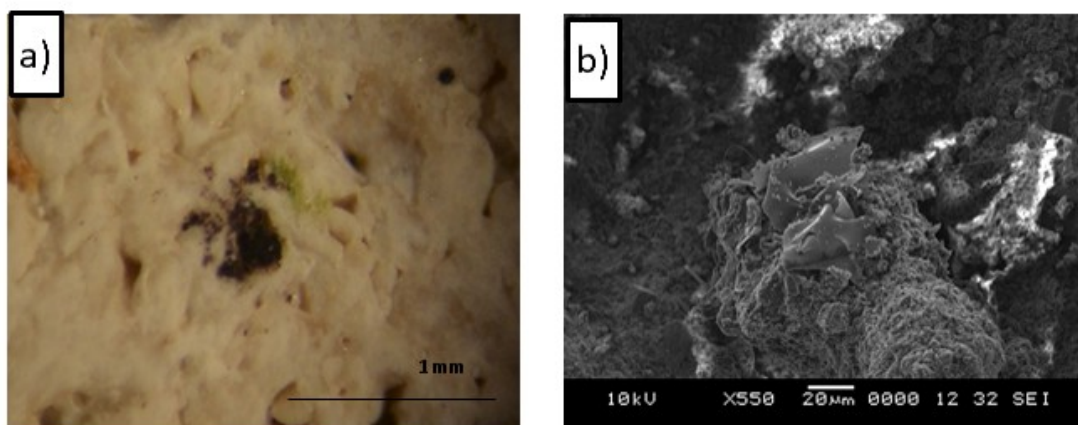
comparisons (Holm-Sidak method) showed that unsheltered samples had become significantly darker than controls ( $t=3.058$ ,  $P=0.013$ ) and sheltered tablets ( $t=5.307$ ,  $P<0.001$ ) but there was no difference between controls and sheltered tablets ( $t=0.441$ ,  $P=0.664$ ). Theoretically, tablets placed inside the shelter may be expected to become darker more quickly than those exposed to the washing effect of direct rainfall outside the shelter. However, the results indicate a decrease in surface reflectance (darkening) for tablets not covered by the shelter. This darkening is therefore probably related to microbial colonisation rather than dry particulate deposition, as has been suggested by previous studies on soiling in Oxford (Viles et al., 2002, Viles and Gorbushina, 2003).

### **7.3.2. Microscopy**

Optical and Scanning Electron Microscopy (SEM) were used on samples exposed for 18 months to confirm the presence and spatial pattern of microorganisms on the stone surfaces, and to evaluate any possible microbial contributions to decay processes. Optical microscopy showed that microbiological colonies were much less well-developed on tablets positioned under the shelter compared to those positioned outside. Microorganisms appeared predominantly at the corners of the samples, probably where water run-off and retention were greater.

Figure 7.3, a) shows an optical microscope image of black and green biological communities that were typical for tablets positioned outside the shelter. In addition, SEM observations showed much clearer evidence of biological colonisation of unsheltered tablets than that in the shelter. Figure 7.3, b) shows that microbial communities were likely developing on the surface of the unsheltered stone, and that

these may be associated with mineral precipitation. Biological communities were common in pores, which are presumably the wettest parts of the stone.

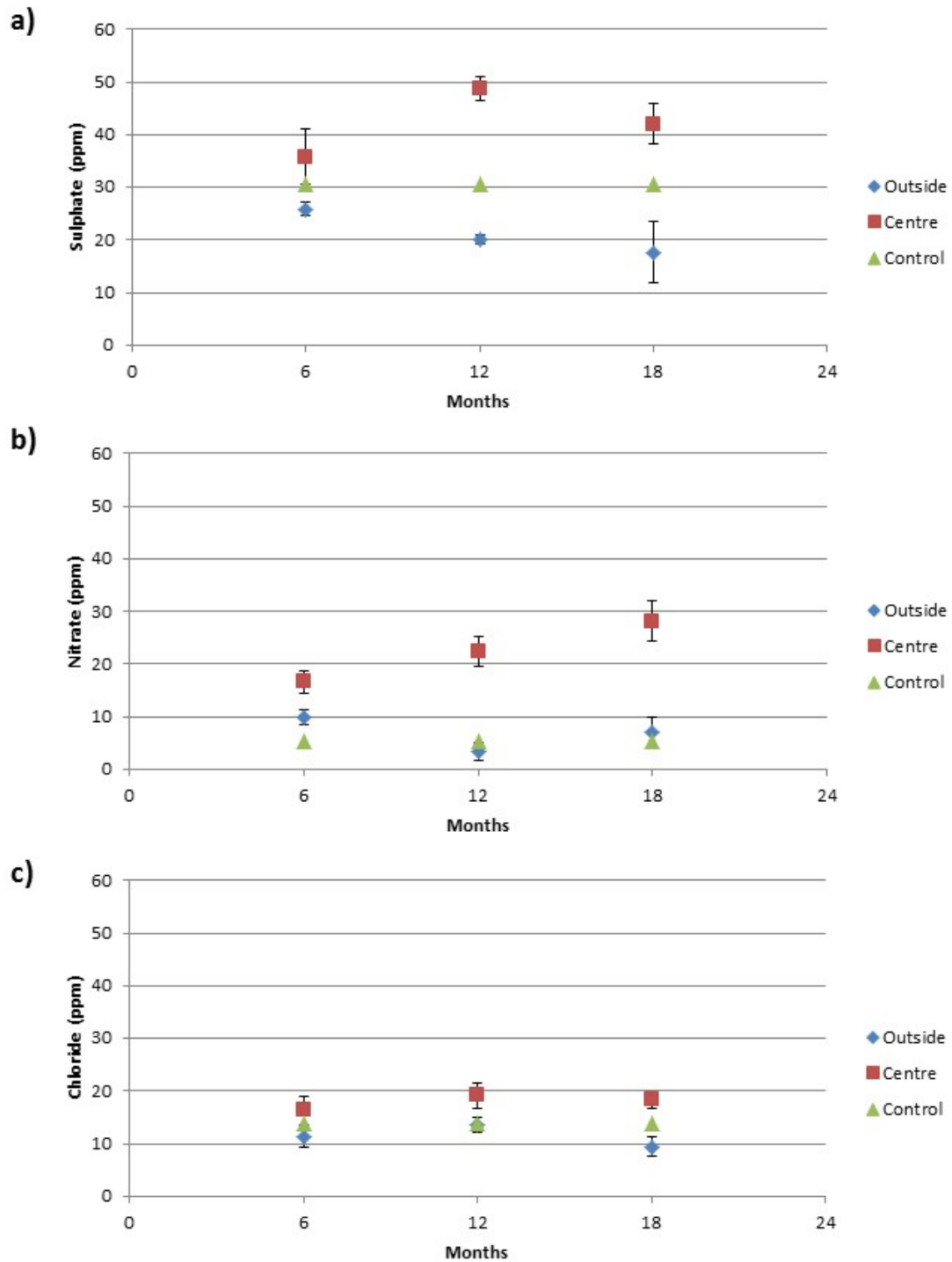


**Figure 7.3:** a) Optical microscope image of biological growth on a tablet placed outside the shelter (18 months of exposure); b) SEM image of an unsheltered sample showing a biological community with filamentous cells covered with calcareous deposits, suggesting precipitation of solubilised calcium (18 months of exposure)

### 7.3.3. Salt content

Detailed analysis of salt content in tablets exposed for 6, 12 and 18 months showed that only the amount of chlorides, nitrates and sulphates varied considerably in relation to position.

Figure 7.4 shows the amount (means and standard deviations) of sulphates, nitrates and chlorides in tablets exposed inside and outside of the shelter, as well as in controls, after 6, 12 and 18 months of exposure. Whereas unsheltered tablets did not show great differences compared to the control tablets, sheltered tablets had greater amounts of salt than both controls and unsheltered tablets, particularly for sulphates. This could be the result of the sheltered tablets being protected from the washing effect of rain.



**Figure 7.4:** Amount of a) sulphates, b) nitrates and c) chlorides in ppm outside and inside the shelter in relation to the mean amount in control blocks after 6, 12 and 18 months of exposure

A two-way ANOVA test showed that the amount of sulphates, nitrates and chlorides in sheltered and unsheltered tablets depended on the position in which they were placed ( $P < 0.001$ ). In addition, there is a statistically significant interaction between position

and time factors for sulphates ( $F= 5.372$ ,  $DF=4$ ,  $F=0.006$ ), nitrates ( $F= 9.881$ ,  $DF=4$ ,  $P<0.001$ ) and chlorides ( $F=4.138$ ,  $DF=4$ ,  $P=0.017$ ), indicating the magnitude of these differences varied with time. Post hoc multiple comparison tests (Holm-Sidak method) showed that concentrations of sulphates were significantly different between sheltered and unsheltered tablets after 12 months ( $t=8.639$ ,  $P<0.001$ ), and after only 6 months for nitrates ( $t=3.662$ ,  $P=0.004$ ) and chlorides ( $t=30336$ ,  $P=0.013$ ).

As salt concentration can change with depth (Watt and Colston, 2000), an analysis of sulphates and nitrates in the upper 2 mm of stone after a year of exposure was also carried out, as summarised in Table 7.3. This analysis showed that proportionally more sulphates and nitrates had accumulated in the surface layers of the stone tablets positioned inside the shelter than in those positioned outside, almost three times the amount in both cases (Table 7.3). A Student's t-test showed this difference was significant for both sulphate ( $t=8.571$ ,  $P=0.001$ ) and nitrate ( $t=-3.225$ ,  $P=0.032$ ).

**Table 7.3:** Means and standard deviations of sulphate and nitrate concentration (ppm) in the first 2 mm of stone after a year of exposure

		Outside	Centre	Control
<b>Sulphate</b>	Mean	31.07	86.77	30.46
	Stdev	5.45	9.84	5.01
<b>Nitrate</b>	Mean	11.88	32.83	5.48
	Stdev	1.76	4.84	1.74

A public report regarding the annual mean concentrations of  $NO_2$  at Witney in 2013 (West Oxfordshire District Council, 2014) shows high concentrations in roadside locations (Table 7.4). Although the Bishop's Palace is not close to a main road, there is a busy car park nearby. Data collected using diffusion tubes positioned at the Bishop's

Palace indicate that SO<sub>2</sub> concentrations here are below the limit of detection, and the values of NO<sub>2</sub> are well below those published by the Council (Table 7.5). Therefore, the site does not appear to be affected by high levels of pollution. In addition, a Student's t-test showed no significant difference in NO<sub>2</sub> levels inside and outside the shelter (t=0.972, P=0.386).

**Table 7.4:** 2013 Witney annual mean NO<sub>2</sub> concentration (µg/m<sup>3</sup>) - Bias Adjustment factor = (National) 0.80

	Site type	Annual Mean NO <sub>2</sub> concentration (µg/m <sup>3</sup> )
<b>Bridge Street, Witney</b>	Roadside	51.3
<b>Mill Street, Witney</b>	Roadside	37.9
<b>Early Rd., Witney</b>	Urban background	14.4
<b>Abbey Rd., Witney</b>	Urban background	15.5

**Table 7.5:** Mean and standard deviations of the amount of sulphur dioxide and nitrogen dioxide (µg/m<sup>3</sup>) in the diffusion tubes located outside and under the shelter. The black tubes were kept covered in a cold and dark room during the same amount of time as the tubes exposed. Limit of detection = 0.05 µg/m<sup>3</sup>

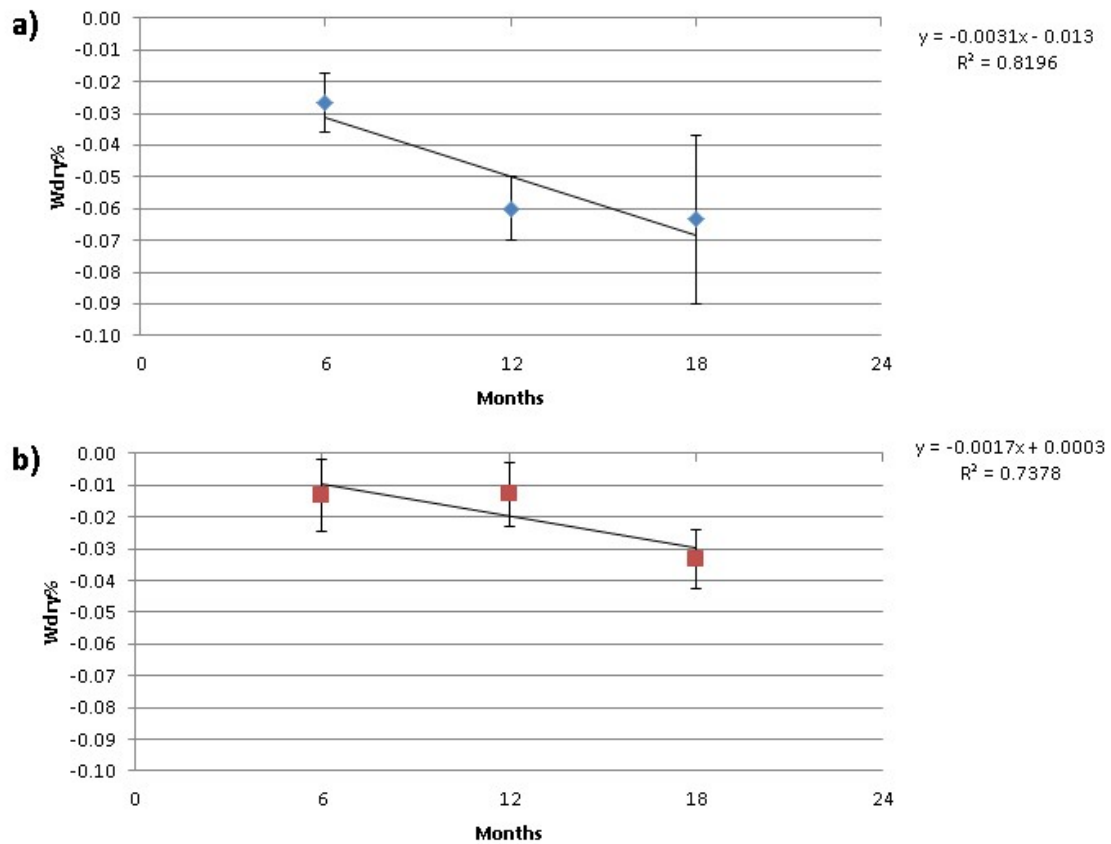
		Outside	Centre	Blank
<b>SO<sub>2</sub></b>	Mean	LOD	LOD	0.01
<b>NO<sub>2</sub></b>	Mean	6.030	6.746	0.004
	Stdev	0.904	0.901	

#### 7.3.4. Weight change

Tablets protected from rainwater might gain weight during exposure due to the formation of crusts whereas unsheltered samples may lose weight due to dissolution of soluble salts and calcite, as was observed by Butlin et al. (1993).

In this study, both sheltered and unsheltered tablets lost weight. Figure 7.5, a) and b) show weight loss as percentage of initial dry weight of tablets after 6, 12 and 18 months of exposure both outside and inside the shelter at the Bishop's Palace. Those placed outside the shelter lost twice as much weight as those positioned inside, a loss

of  $0.06 \pm 0.03\%$  and  $0.03 \pm 0.01\%$ , respectively. A previous study of Portland limestone tablets has suggested that the weight loss during the first 6 months is probably due to removal of superficial calcite dust (Moses, 1996).



**Figure 7.5:** Means and standard deviations of weight change (%Wdry) in a) unsheltered a) and b) sheltered tablets after 6, 12 and 18 months of exposure

A two-way ANOVA test on weight loss of sheltered, unsheltered and control tablets showed that the difference is statistically significant allowing for the influence of exposure time ( $F=7.654$ ,  $DF=2$ ,  $P=0.005$ ). In addition, a post-hoc multiple comparison test (Holm-Sidak method) showed that the weight lost by the unsheltered tablets was significantly greater than both sheltered ( $t=3.486$ ,  $P=0.009$ ) and control tablets ( $t=2.929$ ,  $P=0.02$ ), whilst the difference between sheltered and control tablets was not significant ( $t=0.557$ ,  $P=0.585$ ). There were interesting differences in the rates of mass loss between periods of exposure. For example, the unsheltered tablets lost most of

their weight between 6 and 12 months, whereas the sheltered tablets remained relatively stable up until 12 months, after which the majority of their loss occurred (Figure 7.5). However, the effect of position on weight change did not vary significantly between the different periods of exposure ( $F=0.481$ ,  $DF=4$ ,  $P=0.749$ ).

### **7.3.5. Rates of decay**

The change in weight of the tablets located at the Bishop's Palace (Figure 7.5) is very low in comparison to previously reported rates for the NMEP sites in the 1980s. The NMEP unsheltered tablets lost between -0.29 to -0.94% of initial dry weight in 1987-88 compared to weight changes of -0.21 to and +0.32% for sheltered samples (Butlin et al., 1992). The NMEP study confirmed that weight loss due to chemical weathering occurs through a combination of the dissolution of stone by unpolluted rainwater, dissolution by acid species in rainwater and dry deposition of acid gases and aerosols. The weight gain observed for sheltered tablets was further attributed to soiling and the presence of gypsum crusts on the surface. Table 7.6 shows data from the NMEP study for  $SO_2$  and  $NO_2$ , annual rainfall and acidity, and mean weight loss after a year for unsheltered tablets at four sites (Butlin et al., 1992, Butlin et al., 1993) and at the Bishop's Palace. Wells, Bovington Camp, Lough Navar and Strath Vaich Dam were relatively unpolluted in 1987 in comparison with the other NMEP sites. Lough Navar and Strath Vaich Dam are rural sites and showed the lowest  $SO_2$  and  $NO_2$  levels of the NMEP study. Bovington Camp and Wells showed low levels of rainfall acidity ( $<0.01 \text{ gm}^{-2}$ ) with low  $SO_2$  levels ( $<8 \text{ } \mu\text{gm}^{-3}$ ). Although annual rainfall levels at Witney were similar to Wells and Bovington Camp,  $SO_2$  and rain acidity at the Bishop's Palace were much lower than at any of the NMEP sites, which probably explains the marked differences in annual weight change (Table 7.6).

**Table 7.6:** At the four selected NMEP sites, annual mean SO<sub>2</sub> and NO<sub>2</sub>, total annual rainfall, total annual acidity and mean weight lost after a year of exposure in the unsheltered tablets. At the Bishop's Palace, SO<sub>2</sub> and NO<sub>2</sub> levels in October, total annual rain, rain H<sup>+</sup> levels in April, and mean weight lost after a year in the unsheltered tablets

	Year	SO <sub>2</sub> (µgm <sup>-3</sup> )	NO <sub>2</sub> (µgm <sup>-3</sup> )	Rain (mm)	H <sup>+</sup> (gm <sup>-2</sup> )	Weight lost (%Wdry)
<b>Wells Cathedral</b>	1987-88	7.8	22.9	319	0.002	-0.29
<b>Bovington Camp</b>	1987-88	5.1	12.8	496	0.008	-0.56
<b>Lough Navar</b>	1987-88	2.7	2.5	1482	0.013	-0.35
<b>Strath Vaich Dam</b>	1987-88	2.1	2.3	1197	0.018	-0.52
<b>The Bishop's Palace, Witney</b>	2013-14	LOD	6.0	485.9	0.001	-0.06

Table 7.7 depicts data from the NMEP study for the amount of sulphates and nitrates on the surface of sheltered and unsheltered limestone tablets (Butlin et al., 1993) and the data from the Bishop's Palace. Despite the difference in depths, data indicates that the concentration of sulphates in both sheltered and unsheltered tablets was much lower at Witney than at the NMEP sites. On the other hand, the amount of nitrates found in tablets located outside the shelter at Witney is much higher than at the other sites.

**Table 7.7:** Mean concentration of sulphates, nitrates and chlorides (ppm) in Portland limestone sheltered and unsheltered tablets at the NMEP sites and Bishop's Palace after a year of exposure

	Year	Outside		Centre		Depth (mm)
		SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	
<b>Wells Cathedral</b>	1987-88	153	<0.05	2183	61	0-1
<b>Bovington Camp</b>	1987-88			2868	109	0-0.5
<b>Lough Navar</b>	1987-88	53	<1	172	20	0-1
<b>Strath Vaich Dam</b>	1987-88			144	15	0-1
<b>Bishop's Palace, Witney</b>	2013-14	31	12	87	33	0-2

Butlin et al. (1992) found a significant relationship between weight change, mean annual SO<sub>2</sub> and NO<sub>2</sub> concentrations, and rainfall volume and acidity, accounting for more than 60% of the variation in weight change for unsheltered Portland tablets, thus:

$$\text{Wt loss (Wdry\%)} = 0.08 + 0.010 \text{ SO}_2 - 0.00012 \text{ NO}_2 + 0.00016 \text{ Rain} + 0.0026 \text{ H}^+$$

(r<sup>2</sup>=0.604)

where annual average atmospheric SO<sub>2</sub> and NO<sub>2</sub> is in µg.m<sup>-3</sup>, rainfall in mm and rainfall hydrogen ion loading in mg H<sup>+</sup>m<sup>-2</sup>.

In addition, damage functions for SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> (µg.g<sup>-1</sup>) content in the upper 1mm of sheltered tablets (after two years of exposure) were also found to follow the following relationships (Butlin et al., 1993):

$$\text{SO}_4^{2-} = 2079 + 191(\text{SO}_2) \quad r^2=0.75$$

$$\text{NO}_3^- = 55 + 3 (\text{NO}_2) \quad r^2=0.61$$

Using this model, the predicted weight loss for unsheltered tablets at the Bishop's Palace is 0.16%W<sub>dry</sub> per year. This rate is much higher than the rates observed at Witney, an average of 0.06%. Additionally, the concentration of sulphates and nitrates in sheltered tablets at Witney were much lower than expected if the above formulae are applied. These differences may be related to a general reduction in air pollution between the 1980s and 2010s. However, differences between the four NMEP sites selected and the Bishop's Palace in terms of air quality (Table 7.6) and salt content (Table 7.7) could indicate that salt weathering may not be the main cause of weight loss for unsheltered tablets at the Bishop's Palace.

## 7.4. Discussion and Conclusions

After 18 months of exposure outside and under the central part of the shelter at the Bishop's Palace, Portland limestone tablets presented some changes which confirmed the predictions in Table 7.2 but others were unexpected. Table 7.8 summarises the results obtained from the analysis of colour change, microscopic pictures, salt content and dry weight.

**Table 7.8:** Results of changes in key indicators of deterioration after 18 months of exposure. The degree of change refers to the mean values of the samples (n=6) and when it is significantly different to the other position it is marked in red. The trend of the change is indicated by an arrow in the case of dry weight and salt content

	Outside	Centre
<b>dE*ab (overall colour change)</b>	High	Low
<b>da* (greening)</b>	Medium	Low
<b>dL* (darkening)</b>	High	Low
<b>Microscopy</b>	Medium	Low
<b>Sulphate content</b>	Medium ↓	Medium ↑
<b>Nitrate content</b>	-	High ↑
<b>Chloride content</b>	- ↓	Low ↑
<b>Air pollution: SO<sub>2</sub> concentration</b>	-	-
<b>Air pollution: NO<sub>2</sub> concentration</b>	Medium	Medium
<b>Dry weight change</b>	Low ↓	- ↓

\* For overall colour change (dE\*ab): HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For greening/darkening (da\* and dL\*): HIGH= below -1, MEDIUM= 0 to -1, LOW= above 0. For microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=no noticeable. For salt content: HIGH= more than 20 ppm of difference from controls, MEDIUM=20-10 ppm, LOW=less than 10 ppm. For air pollution (µg/m<sup>3</sup>): HIGH=above 10, MEDIUM= 10-5, LOW= below 5. For dry weight change: HIGH=above 0.5%, MEDIUM=0.5-0.1%, LOW= below 0.1%. For all measurements “-“ means that change is close the change in controls (Table 3.13).

Unsheltered tablets changed more in overall surface colour than expected. In addition, they not only became greener but also became significantly darker than tablets located inside the shelter. The sheltered tablets showed larger amounts of sulphates and nitrates than predicted; and sulphates, nitrates and chlorides content in tablets inside the shelter were significantly higher than in the unsheltered ones. It was

confirmed that the site is a relatively unpolluted area and the amount of nitrates inside the shelter was not very different from outside. As expected, the amount of dry weight loss was greater outside the shelter.

This chapter aims to identify how dissolution, soiling and microbial colonisation on limestone under the shelter differ from outside and to establish how these processes could affect limestone decay.

Different rates of deterioration processes might be affecting the tablets exposed inside and outside of the shelter at the Bishop's Palace. Unsheltered tablets experienced significantly greater colour changes ( $dE^*_{ab}$  and  $d_a^*$ ) than sheltered samples especially after 12 months. These measurements were taken in January, when water availability outside the shelter was higher and presumably, time of wetness longer. A high moisture level on stone surfaces is a dominant factor for biological colonisation (Crispim et al., 2003). Therefore, seasonal colour changes, especially greening, could be related to algal growth. On the other hand, measurements of  $dL^*$  variations indicate that darkening of stone is more relevant for unsheltered tablets over an 18 month period. Low levels of air pollutants (such as  $SO_2$ ) could also indicate that darkening is due to presence of microorganisms rather than accumulation of pollutants, as corroborated by microscope observations. The fact that the darkening of the surface increased after 12 months could indicate that primary colonisers, such as algae, conditioned the stone surfaces for the growth of other organisms. Microorganisms can produce a variety of inorganic and organic acids and chelating agents which can result in mineral dissolution, recrystallisation and re-deposition (Pinna and Salvadori, 2008). In addition, biofilms might decrease stone surface porosity

and permeability and influence evaporation rates (Smith et al., 2011). This eventually could lead to physical weathering due to differences between surface and subsurface moisture content.

The shelter at the Bishop's Palace might be reducing the effect of biological growth underneath it by modifying habitat conditions, mainly water availability. However, the shelter does not exclude the possibility of biofilms, especially photosynthetic biological colonies, developing in the long-term (see Chapter 4). The shelter at the Bishop's Palace is constructed from a lightweight membrane that allows light transmission. In addition, moisture may still have access to the site remains from the ground, in contrast to the tablets, which are attached to carousels.

Unsheltered tablets lost more weight than the sheltered ones. A combination of three different factors could be the reason: physical weathering due to different microenvironmental conditions (see Chapter 4), differential biological growth and/or chemical weathering in tablets located outside the shelter because of dissolution of calcium carbonate. Although it is difficult to assess the exact role of these factors in the decay process, the weight change results suggest that unsheltered stones would be more affected than the sheltered ones in the long term.

Measurements at Witney indicate that concentrations of pollutants in the air inside and outside the shelter at the Bishop's Palace were very similar as open shelters allow air exchange with the outside environment. However, a higher level of salt content in the tablets positioned under the shelter suggests a difference in deposition processes in relation to outside. The shelter prevented direct rainfall, which may otherwise wash particulate deposits away. The shelter might have also modified wind turbulence and

affected dust deposition rates. The Ministero per i Beni e le Attività Culturali (2006) studied marble and calcite tablets at four sheltered archaeological sites in Italy and found accumulation of particles on their surfaces after just four months of exposure, which was attributed to a reduction in air circulation under shelters. This is a possible area of future study. Soluble salts may affect stone as they can dissolve and crystallize within the pores. However, no significant weight or colour changes (associated with the formation of crusts) were detected on sheltered tablets. In general, the weight change of the tablets at the Bishop's Palace is very low in comparison with relatively unpolluted NMEP sites. The main reason seems to be the lower SO<sub>2</sub> concentrations in the air, which could be related to a change in pollution regime since the 1980s. Relatively high NO<sub>2</sub> levels may also be due to the specific location of the Bishop's Palace next to a car park. This is important as nitrogen oxides might enhance biological colonisation (Smith et al., 2011) as well as accelerating limestone dissolution. Portland limestone tablets based on the NMEP method has been found to be a good alternative to monitor the effect of shelters on soiling and microbial growth at archaeological sites instead of a direct analysis on stone remains. Stone tablets can be analysed using destructive methods and results compared with other sites.

## **8. COMPARATIVE STUDY ON THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP'S PALACE (WITNEY) ON MICROCLIMATIC CONDITIONS**

### **8.1. Introduction and aims**

The microclimatic conditions inside and outside two comparable lightweight, open shelters in Malta and at Witney (England) were monitored simultaneously over the same period. The effect of the shelter on the main environmental causes of stone decay at each location was analysed. In addition, a geographical comparison was undertaken to determine if open shelters are a good alternative for preservation of archaeological sites in Mediterranean and temperate maritime climates, and to establish arguments for and against this type of shelters.

Before sheltering Hagar Qim, the (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006) carried out a study on the microclimate and stones of the site, which determined that the main decay mechanism at Hagar Qim was salt weathering from marine aerosols. This agrees with the results obtained after the condition survey (Chapter 4). High solar radiation, wind erosion and RH fluctuations over the 75% threshold were thought to enhance salt dissolution and recrystallisation. In addition, the high diurnal temperature ranges and solar radiation, with a mean annual solar radiation of 5 kW per day, were expected to produce mechanical stresses on the ruins. The Bishop's Palace presented different decay mechanisms. (Historic Buildings and Monuments Commission for England, 1988) suggested frost weathering and high moisture content being the most relevant causes of decay. These are in line with the conditions found outside the shelter (Chapter 5).

This chapter aims to provide a comparative assessment of the effect of the lightweight, open shelters at Hagar Qim in Malta and the Bishop's Palace at Witney on the microclimate of the archaeological sites.

The following research questions have been addressed:

1. How effective are the shelters at Hagar Qim and the Bishop's Palace (inside the shelter and towards the periphery) on reducing the outside microclimatic conditions in terms of:
  - 1.1. Temperature extremes and fluctuations
  - 1.2. Freeze-thaw cycles
  - 1.3. Relative Humidity extremes and fluctuations
  - 1.4. Dust deposition
2. Is there any difference in the degree of protection between the shelter at Hagar Qim and the Bishop's Palace in relation to the above terms?

## **8.2. Materials and methods**

The impact of the open shelter at Hagar Qim and the Bishop's Palace was evaluated by monitoring temperature, freeze-thaw cycles, RH (including NaCl crystallisation events) and dust deposition inside and outside the shelters from 29<sup>th</sup> July 2013 to 22<sup>nd</sup> July 2014. The monitoring positions were selected after examining literature and undertaking a visual assessment of the decay patterns and conservation state of the remains at both sites (Chapter 4). The most central location possible under the shelter was selected as a fully protected position and was compared with a fully exposed (outside) and a partly exposed location (periphery). The peripheral locations in Malta (SW) and at Witney (NW) were located towards the edge of the sites, where possible

problems with shelter design were detected (see Chapter 4). The monitoring of the peripheral location in Malta started later than the others, on the 18<sup>th</sup> October 2013, for logistical reasons. Temperature and RH loggers (i-button® hygrochron dataloggers, accuracy =  $\pm 0.5\%$ RH and  $\pm 0.5^\circ\text{C}$ ) were synchronised in all positions and sites to read at the same time every 60 minutes. The amount of dust deposited on horizontal surfaces inside and outside the shelters in Malta and at Witney was studied using self-adhesive vinyl film transparent patches during one week in October 2013 and three months between October 2013 and January 2014 (for more information see section 3.2 in Chapter 3). Table 8.1 summarises the methods used to produce the different sets of information.

**Table 8.1:** Data collection, handling and analysis methods used for the microenvironmental conditions able to affect stone decay

	<b>Data collection</b>	<b>Data handling</b>	<b>Data analysis</b>
<b>Temperature</b>	Hygrochrons (i-button)	Whole dataset, seasonal means of max and min T per day, monthly mean of daily T range and representative months (calculated with hourly means)	Mann Whitney Wilcoxon tests on annual and seasonal T means and standard deviations, and linear model for diurnal T range
<b>Freezing-thaw cycles</b>	Number of times a day $T \leq 0^\circ\text{C}$	Monthly mean of number of events	Poisson Generalized Linear Model for mean number of events per day in a year
<b>RH</b>	Hygrochrons (i-button)	Whole dataset and monthly mean of daily RH range	Mann Whitney Wilcoxon tests on annual and seasonal RH means and standard deviations
<b>Salt crystallisation events</b>	Number of times a day RH crosses 75%	Monthly mean of number of events and representative months (hourly means)	Means and 95% confidence intervals and linear model for mean number of events per day in a year
<b>Dust Deposition</b>	Self-adhesive transparent film patches	Pictures (after 3 months) and mean opacity values (for 1 week and 3 months)	Imaging processing techniques

Shelters should provide protection for the stone remains by reducing frequency and/or range of microclimatic causes of stone decay, such as temperature and RH cycles.

Based on literature review and data obtained from the previous year at Witney (Chapter 4), a number of predictions about the likely microclimatic conditions inside and outside the shelters were established (Table 8.2 and Table 8.3).

**Table 8.2:** Predictions of the range of specific microclimatic conditions outside, on the periphery and in the centre of the shelter at Hagar Qim, Malta\*

	<b>Outside</b>	<b>Periphery</b>	<b>Centre</b>
<b>Mean daily T in summer</b>	High	Medium	Medium
<b>Mean daily T in winter</b>	High	High	High
<b>Mean diurnal T range in summer</b>	High	Medium	Medium
<b>Mean diurnal T range in winter</b>	Medium	Low	Low
<b>Freezing events in a year</b>	Low	Low	-
<b>Mean daily RH</b>	Medium	Medium	Medium
<b>Mean diurnal RH range in summer</b>	High	Medium	Medium
<b>Mean diurnal RH range in winter</b>	Medium	Low	Low
<b>NaCl crystallisation events (mean number per day)</b>	Medium	Low	Low
<b>Mean opacity (%) of film patches</b>	Low		Medium

**Table 8.3:** Predictions of the range of specific conditions outside, on the periphery and in the centre of the shelter at the Bishop's Palace, Witney\*

	<b>Outside</b>	<b>Periphery</b>	<b>Centre</b>
<b>Mean daily T in summer</b>	Medium	Medium	Medium
<b>Mean daily T in winter</b>	Medium	Medium	Medium
<b>Mean diurnal T range in summer</b>	High	Medium	Medium
<b>Mean diurnal T range in winter</b>	Medium	Low	Low
<b>Freezing events in a year</b>	High	Medium	Medium
<b>Mean daily RH</b>	Medium	High	Medium
<b>Mean diurnal RH range in summer</b>	High	Medium	High
<b>Mean diurnal RH range in winter</b>	Medium	Low	Medium
<b>NaCl crystallisation events (mean number per day)</b>	Low	Low	Low
<b>Mean opacity (%) of film patches</b>	Low		Medium

\* For daily T in summer: HIGH=above 20°C, MEDIUM=20-10°C, LOW= below 10°C. For daily T in winter: HIGH= above 5 °C, MEDIUM=5 to -5°C, LOW= below -5°C. For diurnal T ranges: HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of freezing events: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For daily RH: HIGH=above 90%, MEDIUM=90-60%, LOW= below 60%. For diurnal RH ranges: HIGH=above 30%, MEDIUM=30-15%, LOW= below 15%. For annual mean NaCl crystallisation events per day: HIGH=above 3, MEDIUM=3-1, LOW= 1. For mean opacity (after 3 months): HIGH=above 60%, MEDIUM: 60-30%, LOW: below 30%.

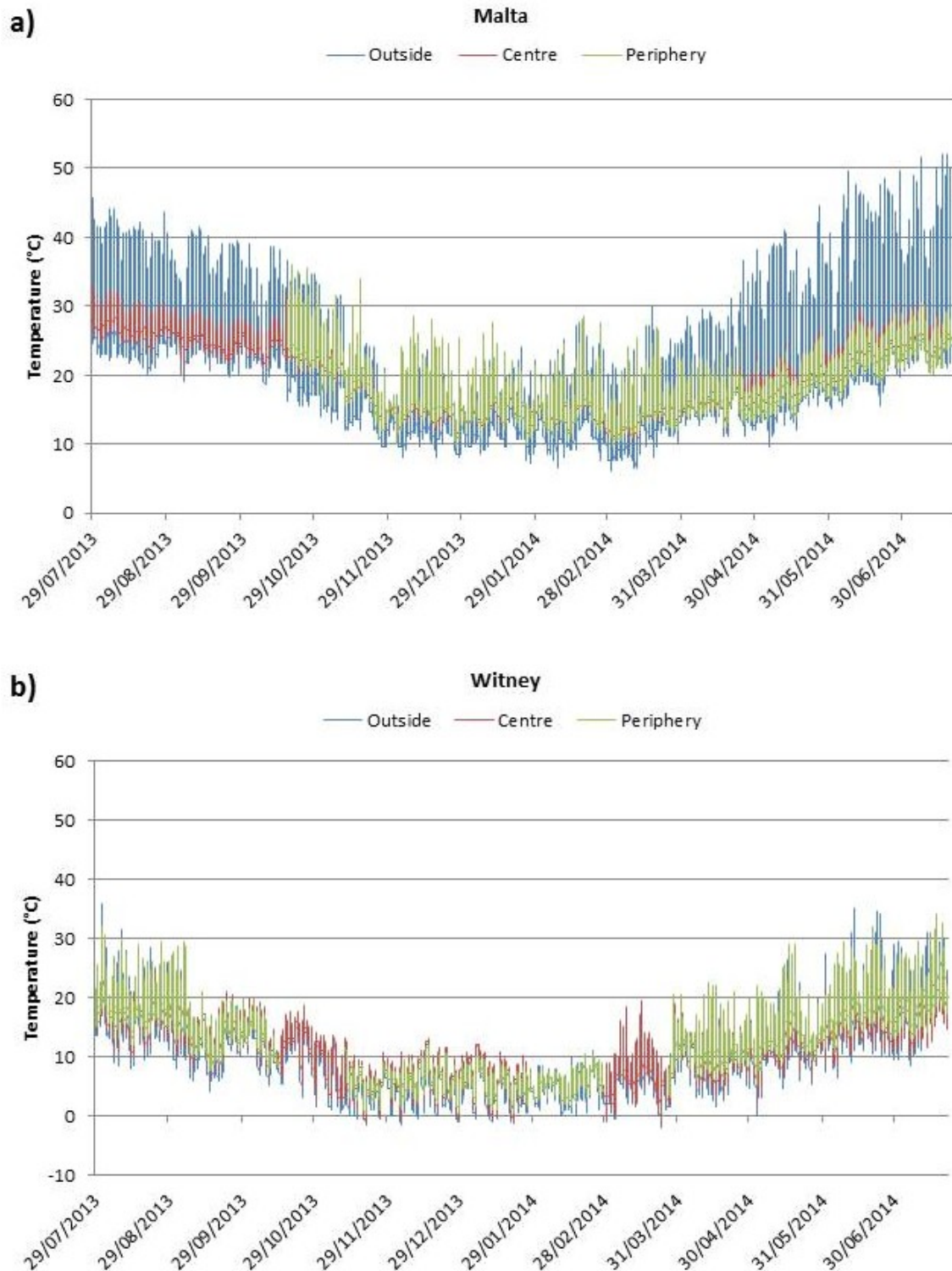
Relatively high RH values together with lower temperatures in winter can enhance frost weathering in Witney whereas in Malta freeze-thaw cycles are likely to be infrequent due to higher temperatures. At both sites, temperature and RH fluctuations are more likely to occur outside than inside the shelter, therefore the risk of salt weathering increases in those areas. In addition, dust deposition could be more relevant inside as the rain might wash away the deposits outside the shelters at both sites. The peripheral areas under the shelter are likely to be affected by a transitional environment between a fully covered central space and the outside.

## **8.3. Results**

### **8.3.1. Temperature**

Figure 8.1 , a) shows temperatures recorded outside and inside the shelter (centre and periphery) for a whole year in Malta. Temperature increased in summer and decreased in winter. The maximum temperature, 52 °C ( $\pm 0.5$ ), was recorded in July 2014 outside the shelter and there were no freezing temperatures recorded in winter for any position. Although temperature outside the shelter fluctuated more in relation to the centre and periphery of the shelter, both of them tracked the outer variations. The greatest differences between inside and outside the shelter can be seen in the daily maximum temperatures. Figure 8.1, b) illustrates temperature variations outside, in the centre of the shelter and the periphery at Witney during the same year. Temperature outside the shelter went up to 36.07 °C ( $\pm 0.5$ ) in August 2013 and dropped down to -1.98 ( $\pm 0.5$ ) °C in winter. The temperature inside the shelter (centre and periphery) also followed the temperature outside and exhibited similar daily and seasonal fluctuations. In general, the temperature range outside the shelter was

slightly greater than at the centre and on the periphery mainly due to the lower daily minimum temperatures outside. The differences between temperatures inside and outside the shelter during the year of record were greater in Malta than at Witney.



**Figure 8.1:** Temperature records a) outside, in the centre and on the periphery of the shelter in Malta and b) outside, centre and periphery of the shelter in Witney between 2013 and 2014

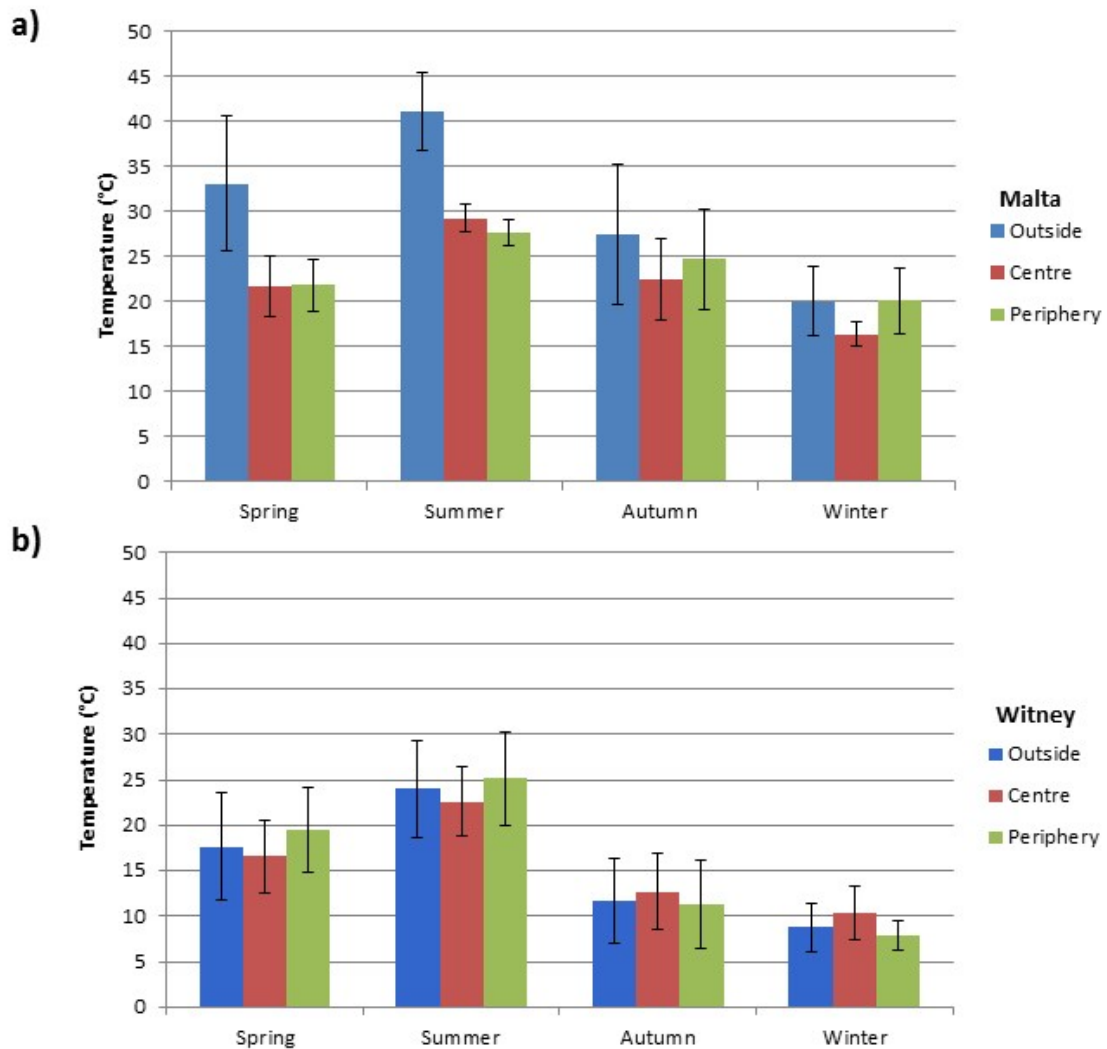
Non-parametric Mann-Whitney-Wilcoxon tests on daily mean temperatures in Malta extracted from the raw data in Figure 8.1, a) showed that in summer, the outside was warmer than the centre of the shelter ( $U=561$ ,  $P= 2.328e^{-10}$ ) and the centre was significantly warmer than the periphery ( $U=406$ ,  $P=3.986e^{-06}$ ). In winter, the central part of the shelter was warmer than outside ( $U=454$ ,  $P=2.398e^{-10}$ ) but the temperatures on the periphery were higher than in the centre of the shelter ( $U=455.5$ ,  $P=6.787e^{-10}$ ). Non-parametric Mann-Whitney-Wilcoxon tests on daily mean temperatures in Witney extracted from the raw data in Figure 8.1, b) showed that the periphery was warmer than the centre of the shelter in summer ( $U=236$ ,  $P=3.478e^{-10}$ ) and the centre was significantly warmer than outside during that season ( $U=2668.5$ ,  $P=5.258e^{-12}$ ). In winter, the centre of the shelter had higher temperature values than the periphery ( $U=694.5$ ,  $P=2709e^{-06}$ ) and the temperatures on the periphery were higher than outside ( $U=246.5$ ,  $P=9.293e^{-09}$ )

### ***8.3.1.1. Maximum and minimum temperatures***

Seasonal means and standard deviations of daily maximum and minimum temperatures were calculated for the outside, centre and periphery of the shelter in Malta and Witney in order to study the differences observed above in more detail.

Figure 8.2, a) illustrates the mean maximum temperatures per season in Malta. Outside maximum temperatures were higher than in the centre and on the periphery of the shelter in spring and summer and no clear differences could be observed between the centre and periphery of the shelter in those seasons. On the other hand, the periphery had higher maximum temperatures than the centre in autumn and winter, very similar to those depicted outside. Figure 8.2, b) shows the mean seasonal

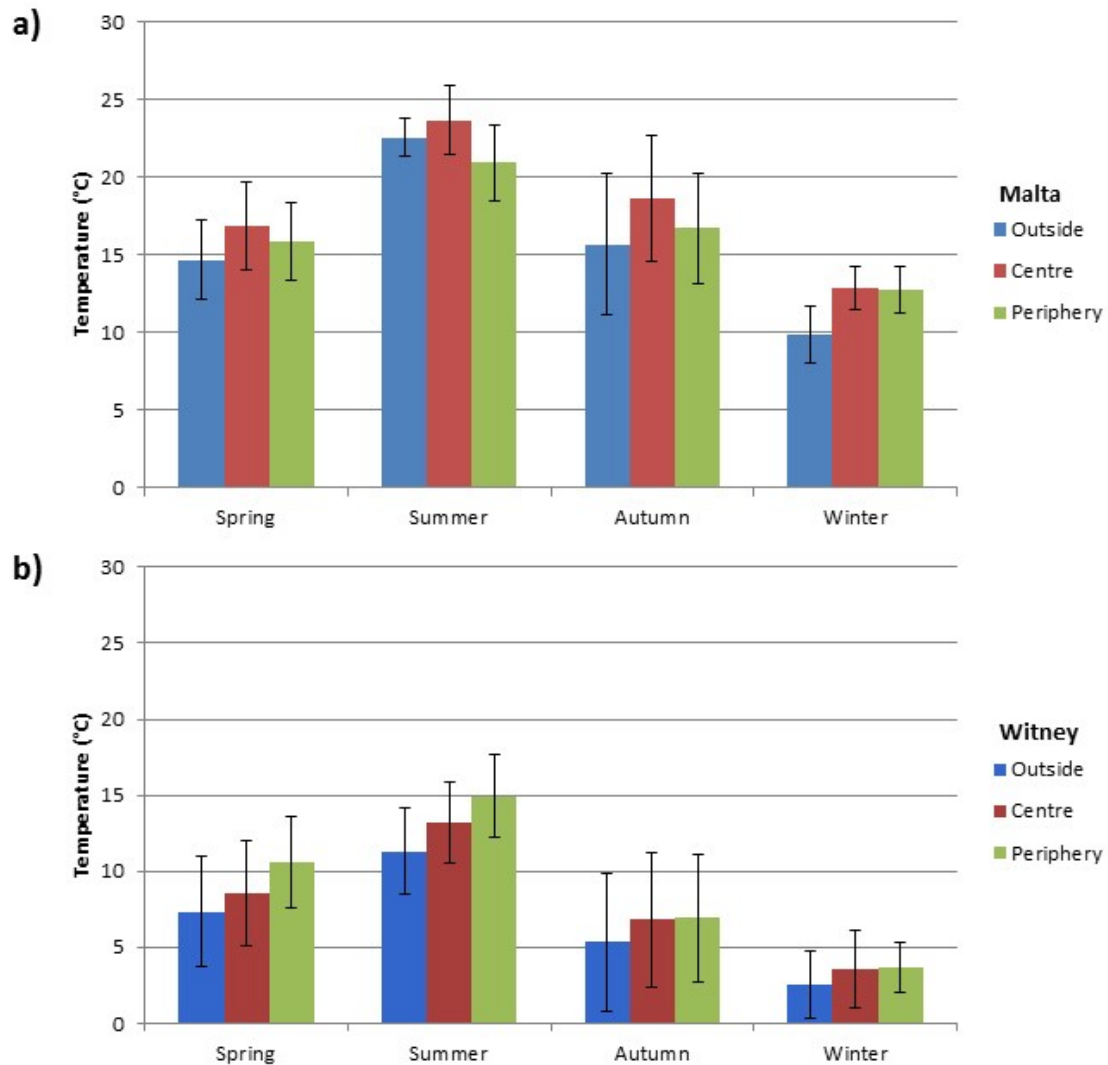
maximum temperatures at Witney. As we have also seen in Chapter 5, there were no differences between the outside, centre and periphery of the shelter in autumn and winter. However, in spring and summer, the centre of the shelter had slightly reduced maximum temperatures.



**Figure 8.2:** Mean and standard deviations of daily maximum temperature per season (a) outside, in the centre and on the periphery of the shelter in Malta and (b) outside, in the centre, on the periphery of the shelter at Witney

Figure 8.3, a) shows mean minimum temperatures per season in Malta. The centre of the shelter had higher minimum temperatures than outside and on the periphery during the majority of the year. In winter, both centre and periphery had higher minimum temperatures than outside. Figure 8.3, b) shows mean minimum

temperatures per season in Witney. The greater differences between positions were recorded in spring and summer when minimum temperatures on the periphery were higher than the ones in the centre and outside.



**Figure 8.3:** Mean and standard deviations of daily minimum temperature per season (a) outside, in the centre and on the periphery of the shelter in Malta and (b) outside, in the centre and on the periphery of the shelter at Witney

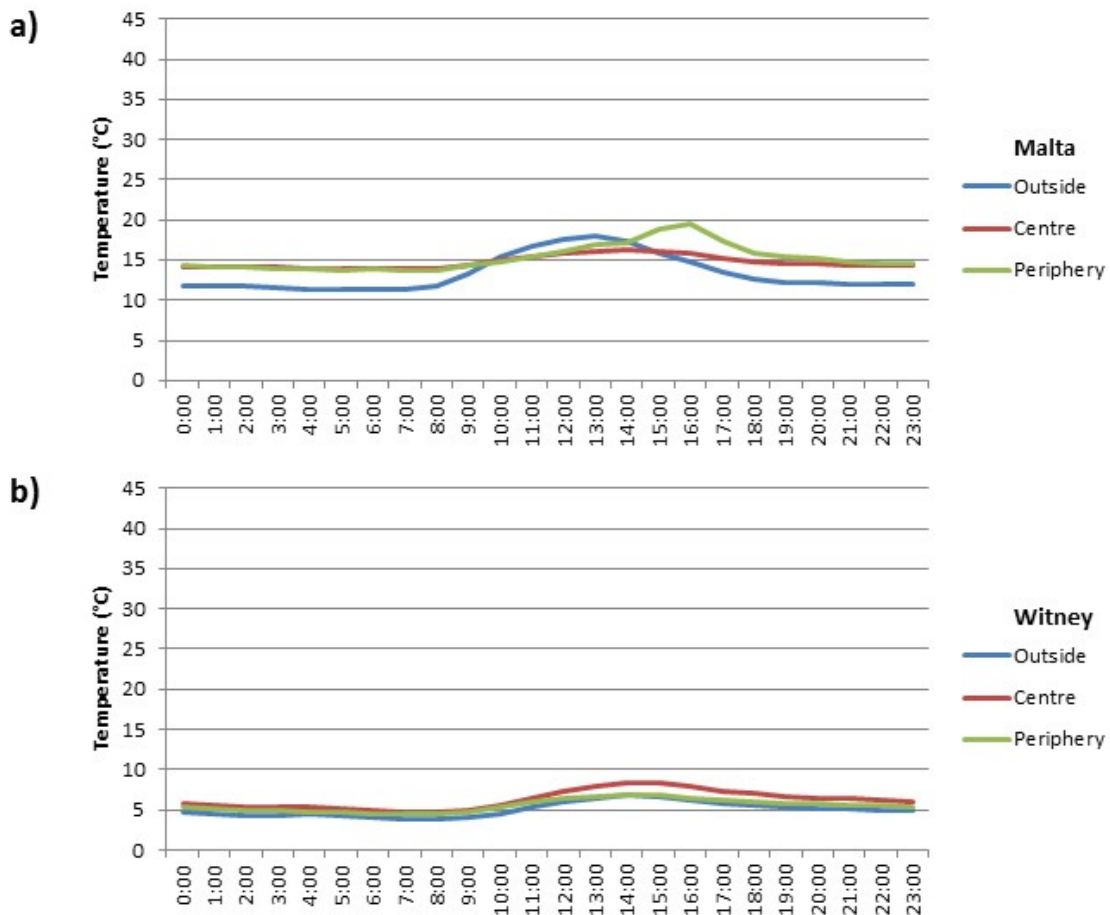
In Malta, the outside had the most unstable environment with the highest maximum temperatures in summer and the lowest in winter. Both maximum and minimum temperatures outside the shelter in Malta are in line with the data recorded from 1986 to 2006 at the site before it was sheltered (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). In addition, higher maximum

temperatures on the periphery indicate that this area was slightly warmer than the centre in winter; but in spring and summer the centre was warmer than the periphery, with higher minimum temperatures. At Witney, higher daily maximum and minimum temperatures on the periphery were recorded in summer and spring which indicate that this area was warmer than outside and the centre of the shelter during that time. The lower minimum temperatures were recorded outside the shelter during the whole year. These trends can also be seen in the previous year (Chapter 5).

#### ***8.3.1.2. Hourly temperature***

In order to study the impact of the shelter on temperature at different times of the day and year, a synthetic representative day in Malta and at Witney was calculated for every month with the hourly means.

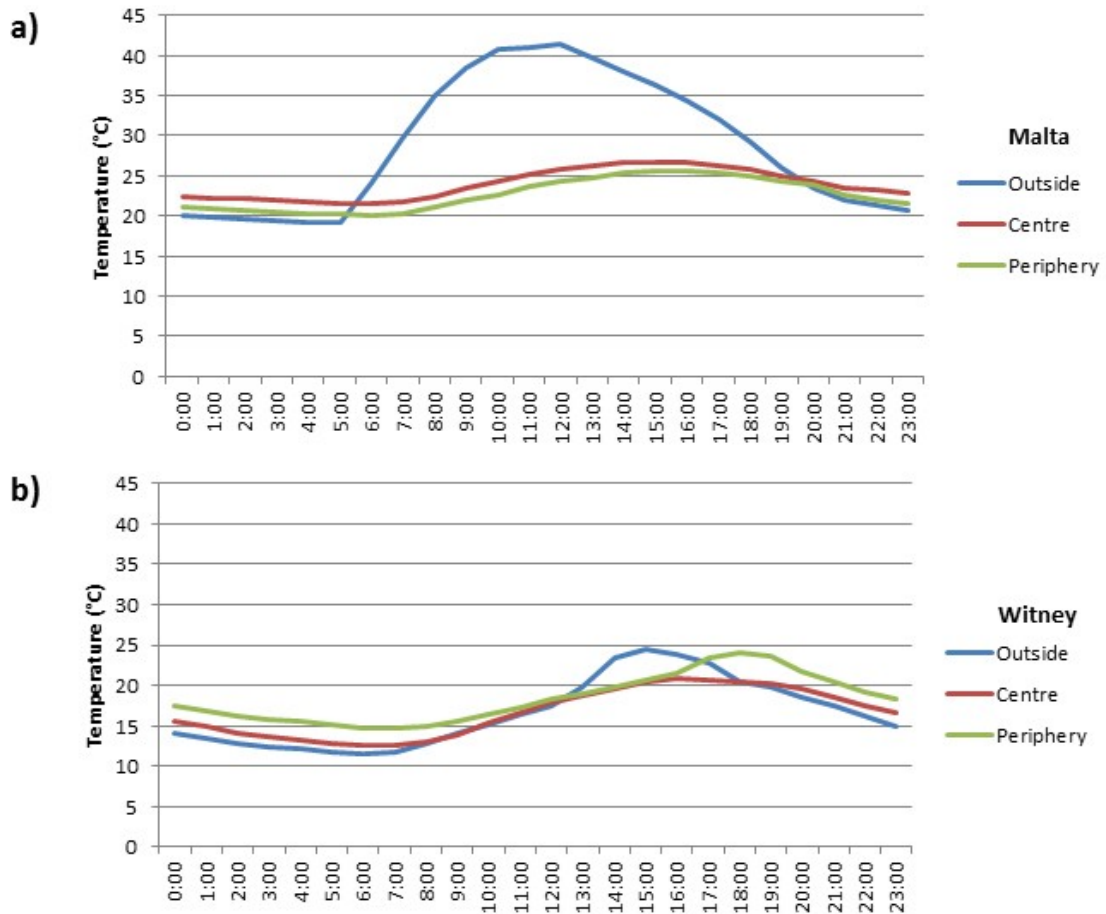
Figure 8.4 a) and b) represent the hourly means of temperature outside, in the centre and on the periphery of the shelter in Malta and at Witney in January 2014. In Malta, the lower temperatures were recorded outside the shelter at night and in early mornings. The temperature was higher outside than in the centre of the shelter around midday. In addition, temperatures increased on the periphery in early afternoon. At Witney, the central part of the shelter was slightly warmer than the other two positions but the difference between positions is very small.



**Figure 8.4:** Hourly means of temperature outside, in the centre and on the periphery of the shelter at a) Hagar Qim (Malta) and b) the Bishop’s Palace (Witney) in January 2014

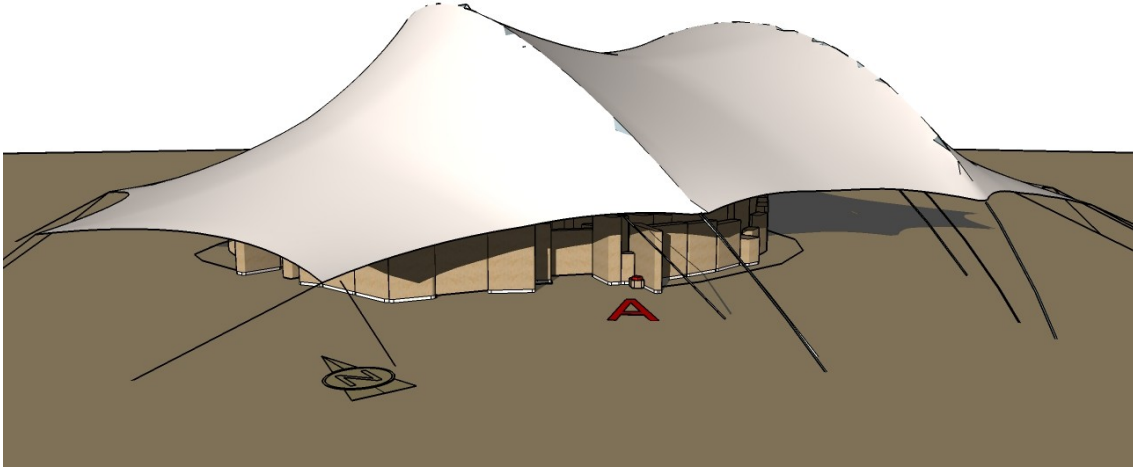
Figure 8.5 a) and b) show the hourly means of temperature outside, in the centre and on the periphery of the shelter in Malta and at Witney in June 2014. In Malta, lower temperatures were registered outside the shelter at night, but increased sharply in early morning and reached maximum values at around midday. The temperature was very similar in the centre and on the periphery of the shelter, although the centre was slightly warmer in general. At Witney, the outside also showed lower temperatures at night. On the other hand, the periphery was warmer not only than outside but also than the centre of the shelter at night. The central part of the shelter experienced reduced temperatures during early afternoon, whereas outside reached maximum

values. The periphery was warmer than outside and the centre of the shelter at around 18:00.



**Figure 8.5:** Hourly means of temperature outside, in the centre and on the periphery of the shelter at a) Hagar Qim (Malta) and b) the Bishop’s Palace (Witney) in June 2014

In Malta, the differences between winter and summer are very pronounced. The shelter is effectively protecting the site during the hottest months. In winter, this effect is not as clear. In addition, there is a peak in temperature on the periphery in autumn and winter. These results can be related to the effect of direct solar radiation. Figure 8.6 shows a representation of the shadows projected by the shelter on the site on the 15<sup>th</sup> January 2014 at 4 pm. The model was undertaken with Google SketchUp® and takes into account the real latitude, longitude, time zone and orientation of the site.



**Figure 8.6:** Simulation of shadows projected by the shelter at Hagar Qim on the 15<sup>th</sup> January 2014 at 4 pm. Point A is the location of the sensors on the periphery

In the case of Witney, the increases in temperature on summer afternoons on the periphery were also seen in the previous year (Chapter 5). This indicates that the shelter design is systematically allowing direct solar radiation affecting this area at this specific time every year.

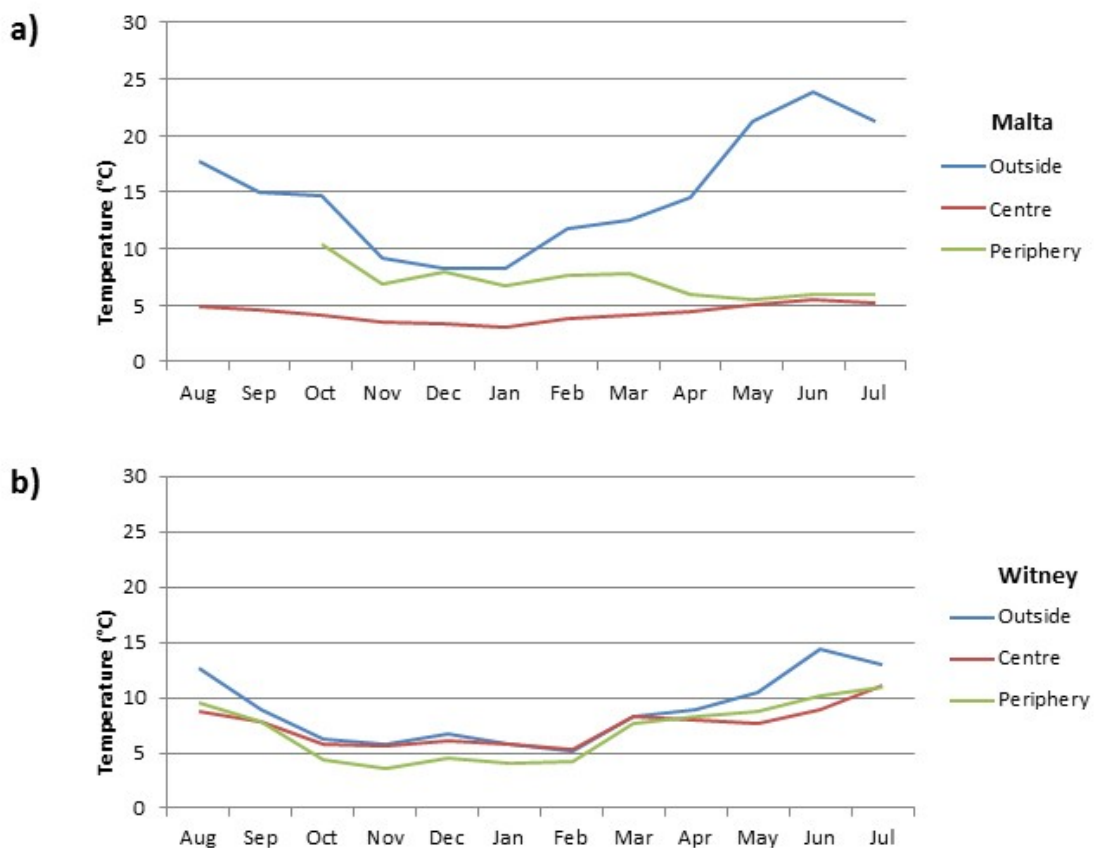
### ***8.3.1.3. Daily temperature fluctuations***

Non-parametric Mann-Whitney-Wilcoxon tests on the standard deviations of daily mean temperatures in Malta extracted from the annual raw data in Figure 8.1, a) showed that the variability of temperature outside the shelter was significantly greater than on the periphery ( $U=38735$ ,  $P<2.2e^{-16}$ ) and on the periphery, temperature was more variable than in the centre ( $U=37.5$ ,  $P<2.2e^{-16}$ ) during the whole year. On the other hand, non-parametric Mann-Whitney-Wilcoxon tests on the standard deviations of daily mean temperatures at Witney extracted from the annual raw data in Figure 8.1, b) showed that outside was significantly more variable than the periphery ( $U=43719$ ,  $P<2.2e^{-16}$ ) and the periphery fluctuated less than the centre ( $U=27799$ ,  $P=1.394e^{-14}$ ) during the whole year. In addition, the temperature range outside the

shelter was significantly higher than the centre only in summer ( $U=855$ ,  $P=1.54e^{-12}$ ).

These results were also observed in the previous year (see Chapter 5).

In addition, the differences between maximum and minimum temperatures per day were calculated to examine temperature fluctuations in detail. Monthly means of daily temperature range outside, in the centre and on the periphery of the shelter in Malta are shown in Figure 8.7, a). The daily temperature range was higher outside the shelter than in the centre and on the periphery across the whole year but the difference increased in spring and summer. The daily temperature range in the periphery of the shelter was higher than in the centre during autumn and winter.



**Figure 8.7:** Mean of diurnal temperature difference per month (a) outside, in the centre and on the periphery of the shelter in Malta and (b) outside, in the centre and on the periphery of the shelter at Witney

Figure 8.7, b) illustrates the monthly means of daily temperature range outside, in the centre and on the periphery of the shelter at Witney. The daily temperature range outside the shelter was higher than in the centre and on the periphery of the shelter, mainly in spring and summer. In addition, the central part of the shelter showed lower daily ranges than the periphery and outside in summer, probably due to a reduction in daily maximum temperatures. However, the periphery was more stable than outside and in the centre, with a lower daily temperature range in autumn and winter.

Table 8.4 shows the annual means and 95% confidence intervals of diurnal temperature ranges for the outside, centre and periphery of the shelter during the same year in Malta and at Witney. The diurnal temperature range outside the shelter in Malta was the highest with an annual mean of almost 14°C. Daily temperature differences on the periphery in Malta were slightly greater than in the centre but still much reduced compared to the outside. The differences in daily temperature ranges between inside and outside the shelter at Witney were less pronounced than in Malta. Mean daily temperature range outside the shelter at Witney was greater than inside the shelter but the difference is less than 1.5°C. Temperature ranges in the centre and on the periphery were very similar.

**Table 8.4:** Means and 95% confidence intervals for diurnal temperature differences (°C) outside, centre and periphery of the shelter in a year (2013-2014)

		Lower 95%	Mean	Upper 95%
MALTA	Outside	13.23	13.79	14.36
	Centre	3.96	4.19	4.42
	Periphery	6.35	6.66	6.98
WITNEY	Outside	7.70	8.08	8.46
	Centre	6.61	6.95	7.30
	Periphery	6.09	6.41	6.75

A multilevel linear model with day as random effect for the diurnal temperature ranges was fitted in order to find out if the differences depended upon location and site. Acceptable normality and stability of variance was obtained by transforming the response variable to a power of  $\frac{1}{4}$ . The statistical analysis indicates that there were significant differences in diurnal temperature ranges between outside and the periphery of the shelter and between the periphery and centre of the shelter in Malta (Table 8.5). The central part of the shelter was more stable than outside and on the periphery.

**Table 8.5:** Results of the multilevel linear model with day as random effect for the diurnal temperature range values. Reference position: periphery and Malta

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.614	0.011	1661	140.271	<0.001
Outside	0.315	0.012	1661	25.497	<0.001
Centre	-0.181	0.012	1661	-14.638	<0.001
Witney	-0.014	0.012	1661	-1.141	0.253

**Table 8.6:** Results of the multilevel linear model with day as random effect for the diurnal temperature range values. Reference position: outside and Witney

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.688	0.010	1661	161.997	<0.001
Centre	-0.058	0.012	1661	-4.996	<0.001
Periphery	-0.088	0.012	1661	-7.464	<0.001
Malta	0.241	0.011	1661	21.258	<0.001

**Table 8.7:** Results of the multilevel linear model with day as random effect for the diurnal temperature range values. Reference position: centre of the shelter and Witney

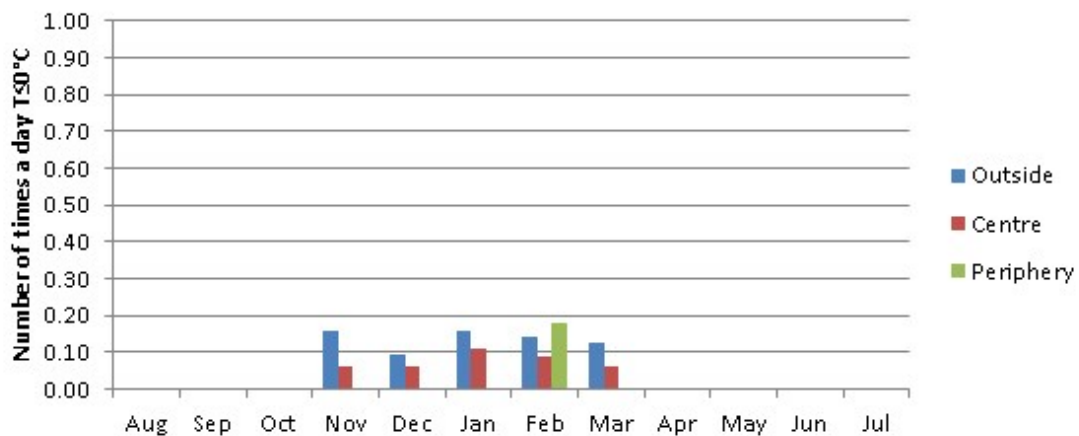
Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	1.630	0.010	1661	154.391	<0.001
Periphery	-0.030	0.012	1661	-2.537	0.011
Malta	-0.197	0.011	1661	-17.085	0.000

In addition, the differences between the periphery of the shelter and outside (Table 8.6) and between the periphery and the centre of the shelter (Table 8.7) at Witney

were statistically significant. The periphery was less variable than outside and the central part of the shelter. The daily temperature ranges on the periphery of the shelter in Malta were greater than in the same position at Witney but the difference is not statistically significant (Table 8.5). The diurnal temperature differences were significantly greater outside the shelter in Malta than outside the shelter at Witney (Table 8.6). However, diurnal temperature ranges in the centre of the shelter at Witney were greater than in Malta (Table 8.7).

### 8.3.2. Freeze-thaw events

There were no freezing temperatures in Malta during the year of record. At Witney, the number of times temperature dropped below 0°C per day in each position was counted and used as a proxy for freezing events. Figure 8.8 represents the monthly mean of number of freezing events per day.



**Figure 8.8:** Monthly mean of number of times per day temperature dropped below 0°C outside, in the centre and on the periphery of the shelter at Witney

A greater number of freezing events was registered outside than inside the shelter from November to March, with the exception of February, when the number of freezing events was greater on the periphery. Although this year was warmer than the

previous one (see Chapter 5), outside the shelter still had the greatest number of days with freezing events in a year (Table 8.8).

**Table 8.8:** Number of days in a year with freezing events outside, in the centre and on the periphery of the shelter at the Bishop's Palace at Witney

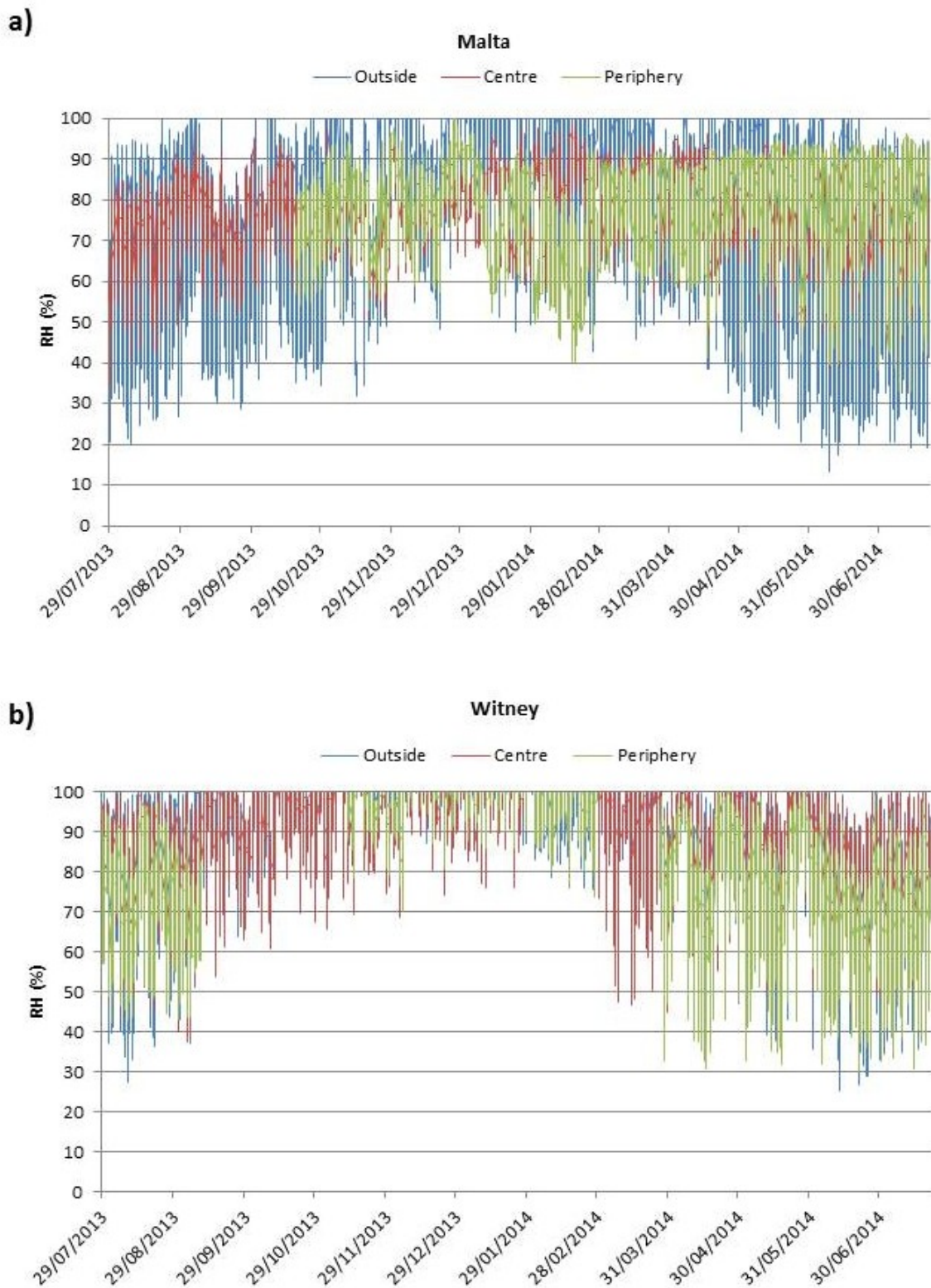
	Outside	Centre	Periphery
Witney 2012-2013	55	38	27
Witney 2013-2014	15	9	3

### 8.3.3. Relative Humidity

Figure 8.9, a) and b) illustrate the RH values recorded outside, in the centre and on the periphery of the shelter in Malta and at Witney respectively. RH was higher in winter, and in spring and summer the daily range increased. This could have led to frequent evaporation-condensation events. For the whole year, the maximum RH was very high in all positions at both sites but mainly at Witney. In Malta, the RH outside the shelter was higher and with greater variability than inside the shelter, and the periphery and centre of the shelter showed similar trends. However, RH on the periphery and in the centre of the shelter at Witney fluctuated more than in Malta, mainly in summer, and the differences between inside and outside were smaller in winter.

Non-parametric Mann-Whitney-Wilcoxon tests on daily mean RH values showed that RH outside the shelter in Malta was significantly higher than on the periphery ( $U=3873$ ,  $P=2.085e^{-13}$ ) and in the centre ( $U=3994$ ,  $P=3.767e^{-16}$ ) in winter. On the other hand, the RH in the peripheral area was higher than in the centre ( $U=8$ ,  $P=5.821e^{-09}$ ) and in the centre higher than outside ( $U=0$ ,  $P=2.328e^{-10}$ ) in summer. At Witney, the RH outside was significantly higher than in the centre of the shelter ( $U=42946.5$ ,  $P < 2.2e^{-16}$ ) during the whole year. RH outside the shelter was also higher than on the periphery in

summer ( $U=2202$ ,  $P=2.535e^{-12}$ ) but the periphery had higher RH values than outside in winter ( $U=220.5$ ,  $P=2.258e^{-09}$ ).



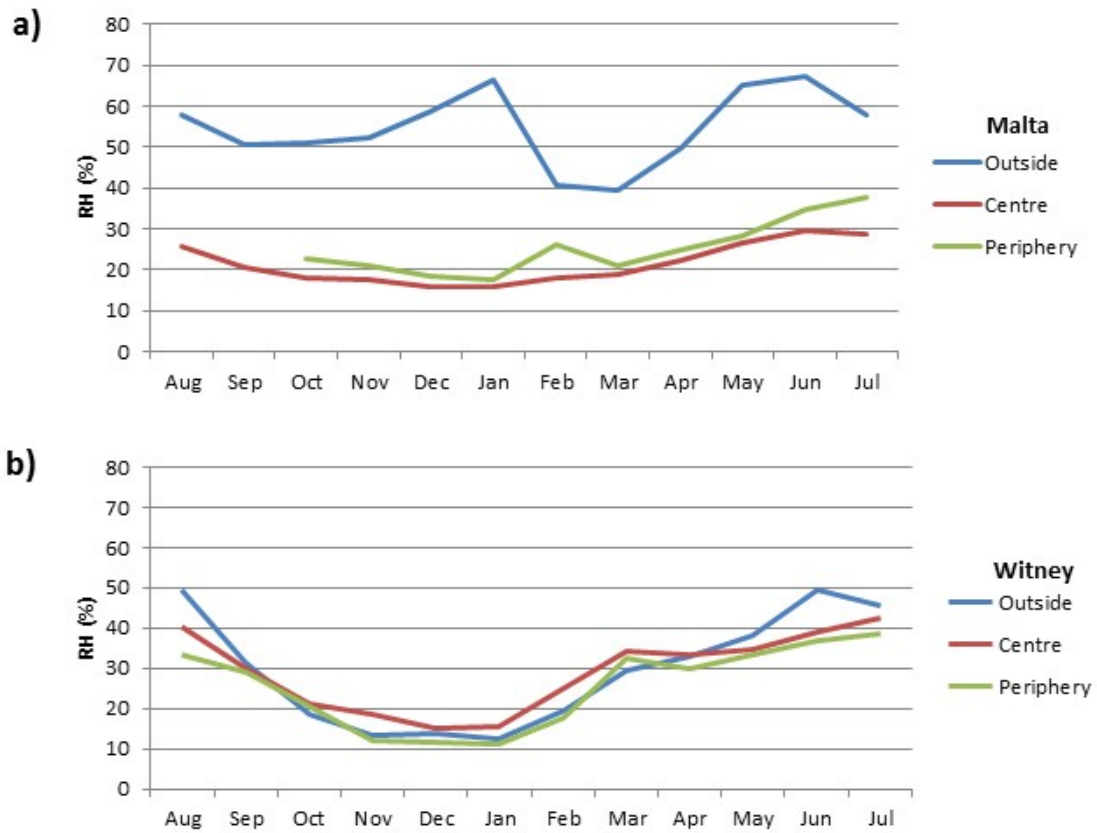
**Figure 8.9:** RH records a) outside, in the centre and on the periphery of the shelter in Malta and b) outside, in the centre and on the periphery of the shelter at Witney

### **8.3.3.1. RH fluctuations**

Fluctuations in RH are important as salt crystallisation in the stone pores is more likely to occur when RH changes are frequent and RH fluctuates over a broad range. Non-parametric Mann-Whitney-Wilcoxon tests on the standard deviations of daily mean RH extracted from the annual raw data in Figure 8.9 show that RH outside the shelter in Malta was significantly more variable than on the periphery ( $U=38255$ ,  $P<2.2e^{-16}$ ), and the periphery fluctuated more than the centre ( $U=8788.5$ ,  $P=2.751e^{-15}$ ) during the year of record. At Witney, both RH outside ( $U=31191.5$ ,  $P <2.2e^{-16}$ ) and in the centre of the shelter ( $U=27062$ ,  $P<2.2e^{-16}$ ) were significantly more variable than the periphery during the whole year. RH outside the shelter was more variable than in the centre in summer ( $U=2412$ ,  $P=1.896e^{-07}$ ) However, the RH at the central part of the shelter fluctuated more than outside in winter ( $U=68$ ,  $P=1.188e^{-05}$ ).

In order to study RH variability in more detail, differences between daily maximum and minimum RH values were calculated. Figure 8.10, a) shows the monthly means of the diurnal RH range outside, in the centre and on the periphery of the shelter in Malta. Daily RH differences were greater outside than in the centre and on the periphery of the shelter. The differences between inside and outside decreased in February and March, when high but constant RH were recorded. The centre of the shelter had the most stable RH. Figure 8.10, b) shows the monthly means of the diurnal RH range outside, in the centre and on the periphery of the shelter at Witney. The differences in RH range between inside and outside the shelter were smaller than in Malta but there were more seasonal fluctuations on the periphery and in the centre. These results are in line with those found in Chapter 5. RH fluctuated more in summer due to frequent temperature changes, mainly outside the shelter. In winter, the centre of the shelter

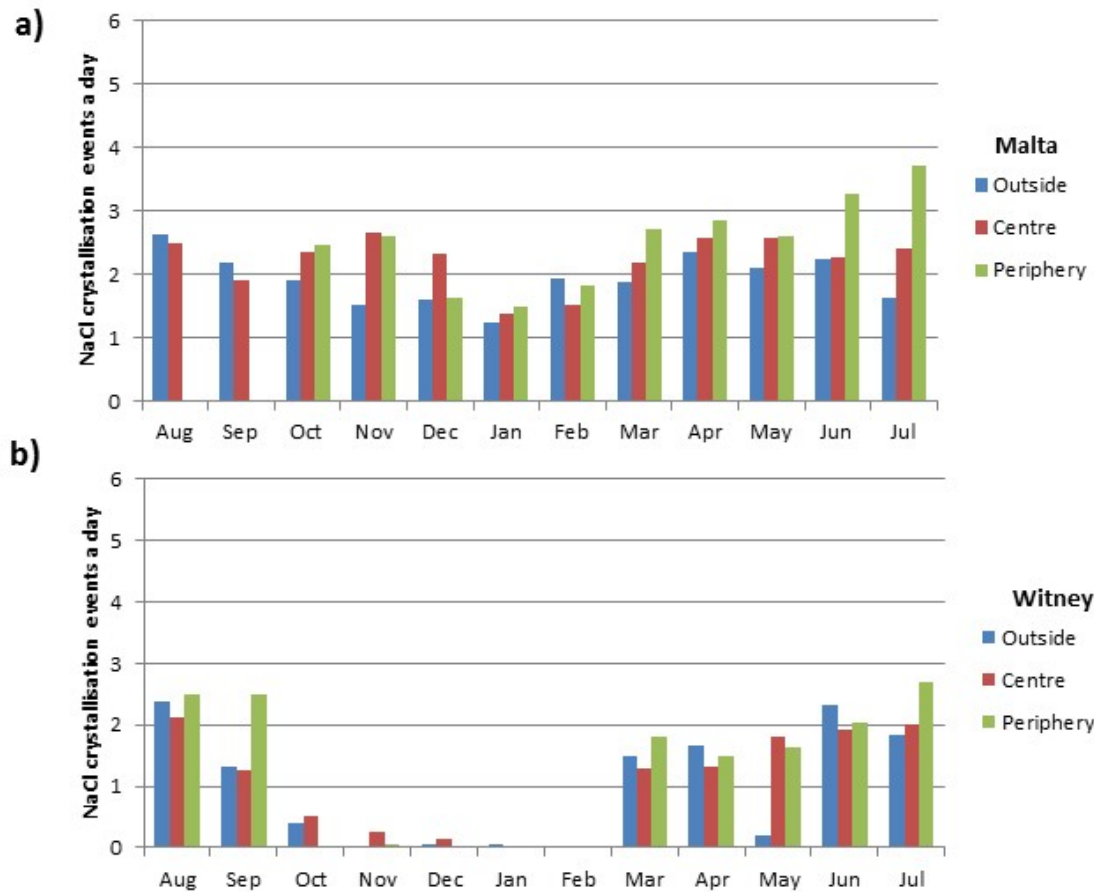
fluctuated more than outside, where constant lower temperatures were recorded. In addition, the periphery showed a more stable RH than the centre and outside during the year.



**Figure 8.10:** Mean of diurnal RH difference per month a) outside, in the centre and on the periphery of the shelter in Malta and b) outside, in the centre and on the periphery of the shelter at Witney.

### 8.3.3.2. NaCl crystallisation events

NaCl crystallises at 75% RH independent of temperature. As in previous chapters, the number of times RH crossed the 75% threshold was calculated for each location and used as a proxy for salt crystallisation events. Figure 8.11, a) and b) depict the monthly means of the number of times RH crossed 75% per day in each position during the year of record in Malta and at Witney respectively.



**Figure 8.11:** Monthly means of the number of times RH crossed the NaCl threshold per day a) outside, in the centre and on the periphery of the shelter in Malta and b) outside, in the centre and on the periphery of the shelter at Witney.

In Malta, the daily number of events was relatively constant in all positions during the majority of the year, with a slight decrease in winter. The centre of the shelter seems to have a greater number of events than outside but only the events on the periphery in June and July were distinctively higher than in the other locations. During these months high RH ranges were recorded in this area (Figure 8.9, a). At Witney, there were only few events in winter. This could be related to the frequent RH values above 75% recorded at that time (Figure 8.9, b). The differences between inside and outside the shelter in summer are not as clear as those observed in the previous year (see Chapter 5).

The annual means and the 95% confidence intervals of the number of NaCl crystallisation events per day in the different positions in Malta and at Witney are shown in Table 8.9. The number of events was greater on the periphery than in the central part of the shelter and outside at both sites.

**Table 8.9:** Means and 95% confidence intervals of the number of times RH crossed the 75% threshold (NaCl crystallisation events) per day during the year of record in the different positions in Malta and at Witney

		Lower 95%	Mean	Upper 95%
MALTA	Outside	1.67	1.83	2.00
	Centre	1.93	2.10	2.29
	Periphery	2.24	2.45	2.68
WITNEY	Outside	0.81	0.91	1.02
	Centre	0.94	1.05	1.18
	Periphery	0.96	1.09	1.23

The number of times the NaCl threshold was crossed in a year was fitted as the response in a Poisson Generalised Linear Model (GLM) with Location and Site as explanatory variables and with Day as the second level. The results showed that the differences in the number of events between outside and the centre and between outside and the periphery of the shelter in Malta are significant (Table 8.10). There were fewer NaCl crystallisation events outside the shelter than in the centre and periphery. In addition, the centre had significantly fewer events than the periphery (Table 8.11). At Witney, there were also fewer events outside than in the centre and periphery (Table 8.12). However, the difference in the number of events between the centre and periphery of the shelter at Witney is not significant (Table 8.13). In addition, there were twice as many NaCl crystallisation events outside (Table 8.10) and in the centre (Table 8.11) of the shelter in Malta than at Witney.

**Table 8.10:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallization events per day with outside as reference position and Malta as reference site

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	0.603	0.454	1590	13.261	<0.001
Centre	0.141	0.052	1590	2.695	0.007
Periphery	0.293	0.055	1590	5.305	<0.001
Witney	-0.694	0.066	1590	-10.431	<0.001

**Table 8.11:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallization events per day with centre of the shelter as reference position and Malta as reference site

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	0.744	0.043	1590	17.204	<0.001
Periphery	0.151	0.053	1590	2.837	0.004
Witney	-0.691	0.063	1590	-10.891	<0.001

**Table 8.12:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallization events per day with outside as reference position and Witney as reference site

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	-0.091	0.059	1590	-1.536	0.124
Centre	0.144	0.075	1590	1.914	0.055
Periphery	0.176	0.078	1590	2.235	0.025

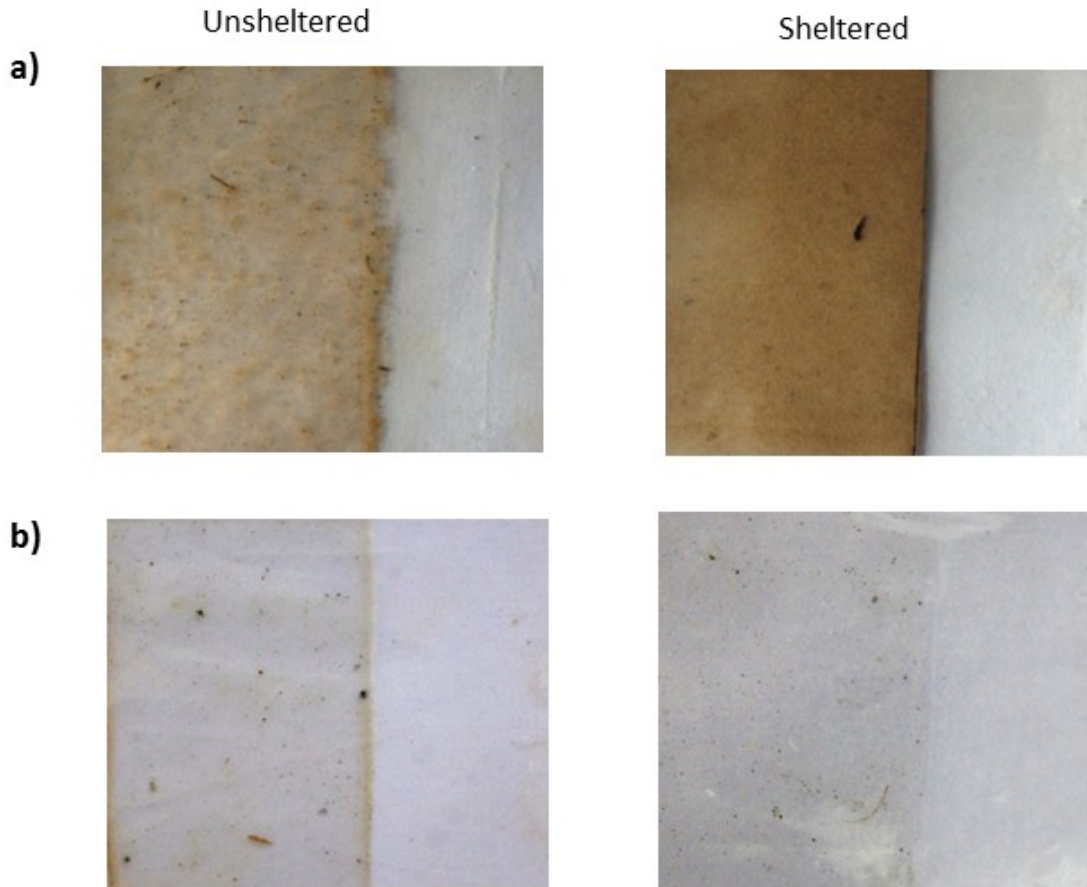
**Table 8.13:** Results of the Poisson Generalized Linear Model for mean number of NaCl crystallization events per day with centre of the shelter as reference position and Witney as reference site

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	0.053	0.057	1590	0.917	0.359
Periphery	0.031	0.077	1590	0.411	0.680

### 8.3.4. Dust deposition

Self-adhesive transparent film patches were placed inside and outside the shelter at Witney and in Malta to record the amount of dust deposition on horizontal surfaces during two test periods (one week and 3 months). A third of the surface remained covered during the exposure and was used as a control area. Figure 8.12 shows the pictures of the samples after 3 months of exposure. The samples were analysed with imaging processing techniques. The percentage of mean opacity in relation to the

control area was calculated by analysing the amount of light that passed through each sample (transmittance).



**Figure 8.12:** Pictures (detail) of the samples located outside and inside the shelter a) in Malta and b) at Witney for three months. The controls are the areas that can be seen on the right hand side

Table 8.14 shows the mean opacity (%) values of samples located outside and inside the shelter in Malta and at Witney during one week in October 2013 and three months between October 2013 and January 2014 in relation to controls.

**Table 8.14:** Mean opacity (%) values of unsheltered and sheltered samples in Malta and at Witney during one week and three months in relation to control areas. Mean values refer to the amount of pixels in the processed images (1280x960)

	Unsheltered		Sheltered	
	1 week	3 months	1 week	3 months
Malta	0.80	-54.42	-10.34	-381.68
Witney	-6.13%	-40.04	-13.52	-13.03

In general, samples show a greater decrease in light transmittance after three months than after a week, as expected. However, the sheltered sample at Witney depicts similar values after a week and after 3 months. This could indicate that the shelter reduced the deposition rate if it is compared with the sample outside the shelter. The samples located under the central part of the shelter in Malta show less light transmittance values than the ones located outside the shelter for the same amount of time. This means that there was more dust deposition inside the shelter. After three months of exposure, the sample located inside the shelter shows 380% less light transmittance than the control area. The amount of dust deposition could have even been bigger as the surface of the film became fully covered before the end of the experiment and could not collect more dust (Figure 8.12, a).

On the other hand, the samples placed outside the shelter at Witney depict more deposition than the sheltered ones after three months. The sample under the central part of the shelter shows 40% less light transmittance than the control area, whereas the sheltered sample shows 13%. Additionally, the data showed that there was more deposition in Malta than at Witney both inside and outside the shelter. This could indicate a difference in the source and means of transport. The shelter at Witney is surrounded by trees, which could affect wind speed and direction. The shelter also might be able to stop direct deposition of biological origin. Precipitation amount and frequency are also higher at Witney. Malta is characterised by high daily wind speed (up to 17.5 m/s as registered in February 2006) and soil dust from the arid surroundings (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). In addition, the dust deposition beneath the shelter in Malta could be highly affected by wind turbulence. A study of the wind speed and direction outside

and inside the shelter in Malta (Farrugia and Schembri, 2008) showed that the shelter reduces wind speed and there is turbulence probably due to the effect of the monument itself.

## 8.4. Discussion and conclusions

Table 8.15 and Table 8.16 summarise the results for temperature (means and ranges), freezing events, RH (mean, ranges and NaCl crystallisation events) and dust deposition in Malta and at Witney respectively. Some unexpected results were found when compared with predictions (Table 8.2 and Table 8.3). In Malta, temperatures inside the shelter were higher than expected. In addition, there were more salt crystallisation events and dust deposition than originally predicted both outside and inside the shelter. Predictions at Witney were based on results from the previous monitoring year (Chapter 5). This second year had higher daily temperatures in winter and therefore, fewer frost events. Otherwise, the results remained unchanged.

**Table 8.15:** Results and ranges of specific microclimatic conditions outside, on the periphery and in the centre of the shelter at Hagar Qim, Malta\*

	Outside	Periphery	Centre
Mean daily T in summer	29.8°C (High)	24.2°C (High)	26.5°C (High)
Mean daily T in winter	13.6°C (High)	14.9°C (High)	14.4°C (High)
Mean diurnal T range in summer	18.9°C (High)	6°C (Medium)	5°C (Medium)
Mean diurnal T range in winter	10.5°C (High)	7.2°C (Medium)	3.5°C (Low)
Freezing events in a year	-	-	-
Mean daily RH in summer	62.3% (Medium)	79.1% (Medium)	71.5% (Medium)
Mean daily RH in winter	91.2% (High)	75.8% (Medium)	81.6% (Medium)
Mean diurnal RH range in summer	57.6% (High)	35.8% (High)	26.1% (Medium)
Mean diurnal RH range in winter	51.7% (High)	20.6% (Medium)	16.9% (Medium)
NaCl crystallisation events (mean number per day)	1.8 (Medium)	2.4 (Medium)	2.1 (Medium)
Mean opacity (%) of film patches	-54.4% (Medium)		-381.7% (High)

**Table 8.16:** Results and ranges of specific microclimatic conditions outside, on the periphery and in the centre of the shelter at the Bishop’s Palace, Witney\*

	Outside	Periphery	Centre
Mean daily T in summer	16.4°C (Medium)	18.7°C (Medium)	17.6°C (Medium)
Mean daily T in winter	5.6°C (High)	5.7°C (High)	6.8°C (High)
Mean diurnal T range in summer	12.6°C (High)	10.2°C (Medium)	9.7°C (Medium)
Mean diurnal T range in winter	6.2°C (Medium)	4.2°C (Low)	6.7°C (Medium)
Freezing events in a year	17 (Low)	5 (Low)	9 (Low)
Mean daily RH in summer	80.8% (Medium)	70.4% (Medium)	78.1 (Medium)
Mean daily RH in winter	97.6% (High)	100% (High)	96.3% (High)
Mean diurnal RH range in summer	45.4% (High)	35.9% (High)	39.9% (High)
Mean diurnal RH range in winter	18% (Medium)	13.9% (Low)	21.5% (Medium)
NaCl crystallisation events (mean number per day)	0.9 (Low)	1.1 (Medium)	1 (Medium)
Mean opacity (%) of film patches	-40% (Medium)		-13% (Low)

\* For daily T in summer: HIGH=above 20°C, MEDIUM=20-10°C, LOW= below 10°C. For daily T in winter: HIGH= above 5 °C, MEDIUM=5 to -5°C, LOW= below -5°C. For diurnal T ranges: HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of freezing events: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For daily RH: HIGH=above 90%, MEDIUM=90-60%, LOW= below 60%. For diurnal RH ranges: HIGH=above 30%, MEDIUM=30-15%, LOW= below 15%. For annual mean NaCl crystallisation events per day: HIGH=above 3, MEDIUM=3-1, LOW= 1. For mean opacity (after 3 months): HIGH=above 60%, MEDIUM: 60-30%, LOW: below 30%.

The first objective of this chapter was to determine how effective the shelters at Hagar Qim and the Bishop’s Palace are in terms of modifying the microclimate inside and towards the periphery.

In Malta, temperatures outside the shelter fluctuated more than in the centre and on the periphery showing higher maximum temperatures in summer and lower in winter (Figure 8.2). However, the temperatures did not drop below 0°C at any time during the year of record. The maximum differences between inside and outside were registered during the hottest months. The shelter was able to reduce daily temperature differences and keep the temperatures in the centre of the shelter lower and stable (Figure 8.4 and Figure 8.5). The temperature on the periphery varied more than in the

centre, and a fault in the shelter design allowed direct solar radiation to significantly increase temperatures at this point during winter (Figure 8.6). In contrast to temperature, RH outside the shelter was higher than in the centre and on the periphery in winter, and lower in summer (see section 8.3.3). RH outside the shelter also fluctuated more than in the other locations. The periphery had higher RH values and more variability than the centre. It also has higher probability of NaCl crystallisation events (Table 8.9). The centre of the shelter had the most stable RH values. On the other hand, there was more dust deposition inside than outside the shelter.

At Witney, temperature on the periphery was higher and more variable than in the central part of the shelter in summer, and the inverse happened in winter (see section 8.3.1). The shelter could not prevent direct solar radiation from reaching this spot during the hottest months, increasing temperatures. In addition, outside temperatures were lower than inside the shelter during the whole year and a greater number of freezing events were recorded in this area (section 0). Temperatures outside the shelter also fluctuated more than in the centre and on the periphery of the shelter during the whole year. RH outside the shelter was higher than in the centre of the shelter. The periphery had very high RH values and it was more stable than the centre and outside the shelter during the monitoring year (Figure 8.10). In addition, there were probably fewer NaCl crystallisation events outside than inside the shelter (Table 8.9) but dust accumulation on horizontal surfaces was higher outside (Table 8.14).

The second objective of this chapter was to estimate if there was any difference in the degree of protection between the shelter at Hagar Qim and the Bishop's Palace in relation to microclimatic conditions.

Temperatures outside the shelter, mainly in summer, were greater at Hagar Qim than the Bishop's Palace due to differences in climate between Malta and England. On the other hand, the Bishop's Palace had lower temperatures, mainly in winter, which makes freezing events be more probable. The diurnal temperature and RH differences were greater outside the shelter in Malta than outside the shelter at Witney (Figure 8.7 and Figure 8.10). Despite it, the shelter in Malta was able to keep temperatures and RH in the centre of the shelter more stable during the whole year than the shelter at Witney. Diurnal temperature ranges in the centre of the shelter in Witney were greater than in Malta (Table 8.7). The effects of solar radiation were less extreme in Witney, although the shelter was still more effective in summer. This could indicate that lightweight, open shelters are more effective at decreasing temperatures by reducing direct solar radiation than protecting the shelter against lower temperatures and high RH values. Therefore their level of protection increases in areas with higher temperatures.

Peripheral areas of the shelter tracked the outer environment more closely than the centre of the shelter. They represent a transition environment between a fully protected and fully exposed one. These areas are the most problematic areas in terms of conservation as faults in the shelter design in terms of coverage are more probable. In the case of Malta, solar radiation hit some specific points of the ruins in winter (Figure 8.6). As temperature is not as high in this season than in summer the risk of

thermal stress is reduced. However, the probability to have more NaCl crystallisation events in this area than outside the shelter is higher. Although temperatures and RH on the periphery fluctuated over a more reduced range than outside, they were greater than in the centre. In addition, small fluctuations across the 75% RH threshold were more frequent (Table 8.9). In the case of Witney, the sun reached the ruins at some points on the periphery in summer but the general temperatures in Witney are lower than in Malta (Figure 8.1). Therefore, risk of thermal stress is also reduced. However, high and constant RH values in this area in winter, probably to direct rain water access, could lead to biological colonisation.

There are different dust deposition processes in Malta and at Witney. In Malta, dust from soil accesses the area under the shelter driven by high speed winds. Wind reduces velocity and increases turbulence under the shelter, therefore, dust accumulates on the horizontal surfaces of the remains. Dust comes from the arid surroundings and marine aerosols could be present because Malta is a coastal environment. There is, therefore, a potential risk for salt decay enhanced by the shelter. In Witney, the site is surrounded by trees which could reduce wind speed and act as physical barriers, reducing the access of particles from outside to inside the shelter. On the other hand, trees could be the source of the particles which accumulate on horizontal surfaces outside the shelter. Although, these particulates are washed away by rain, the amount of dust deposited on horizontal surfaces outside the shelter is still higher than inside. This makes the outside at higher risk of decay due to biological colonisation, and in this case, the shelter is protecting the site.

In relation to the methods used, temperature and RH measurements have proven to be useful in order to determine differential behaviour of shelters. Hygrochron dataloggers are a simple and inexpensive method to obtain information about temperature and RH values and ranges and can be programmed simultaneously. Number of freezing and NaCl crystallisation events are also an effective method to determine differences between positions and these data can be extracted from the temperature and RH readings. Self-adhesive patches are also suitable alternative to monitor dust deposition and obtain information in a short time period.

## **9. EVALUATING THE EFFECTS OF THE OPEN SHELTERS AT HAGAR QIM (MALTA) AND THE BISHOP'S PALACE (WITNEY) ON LIMESTONE DECAY WITH GLOBIGERINA AND CORALLINE LIMESTONE BLOCKS**

### **9.1. Introduction and aims**

This chapter studies surface and in-depth changes in stone blocks located inside and outside the open shelters at two archaeological sites: Hagar Qim in Malta and the Bishop's Palace at Witney. Stone blocks, cut from the same stone types, were exposed simultaneously during the same amount of time outside and under open shelters of similar design in two different geographical locations in order to undertake a comparative analysis. The comparisons of the durability of the stone blocks at each location and site may be indicative of the trend of weathering development, and may reveal which damage factors are particular active. This is a geographical comparison along the lines of the initiative undertaken by the (Getty Conservation Institute, 2009), which proposed a methodology based on visual assessments of mosaics under shelters in England and Israel in order to establish a correlation between mosaic condition and shelter construction.

This chapter aims to quantify and compare the degree and nature of limestone deterioration outside and inside the shelter at Hagar Qim (Malta) and the Bishop's Palace (Witney) using Globigerina and Coralline limestone blocks. As indicated in Chapter 6, the reason for using small blocks was to obtain representative information about decay within a short exposure period without invasive sampling of the remains themselves.

The following research questions have been addressed:

1. To what extent does each shelter affect the degree of deterioration of the stone blocks as quantified by:
  - 1.1. Dry weight change
  - 1.2. Change in elasticity
  - 1.3. Change in hardness
  - 1.4. Change in ultrasonic pulse velocity
2. How effective is each shelter at reducing environmental causes of deterioration in the stone blocks, such as:
  - 2.1. Moisture content and wetting events
  - 2.2. Surface temperature (fluctuations and freezing events)
3. How does each shelter influence the nature of deterioration and soiling in the stone blocks assessed by:
  - 3.1. Surface colour
  - 3.2. General appearance (through macroscopic and microscopic pictures)
4. Is there a difference in the degree and nature of deterioration of the stone blocks between Hagar Qim and the Bishop's Palace?

## **9.2. Materials and methods**

The degree and nature of deterioration and soiling were determined by monitoring change in dry weight, elasticity, surface hardness, ultrasonic pulse velocity, surface colour, macroscopic and microscopic characteristics, moisture content and surface temperature in Globigerina and Coralline limestone blocks. They were located outside and inside the shelter (centre) at Hagar Qim (Malta) and the Bishop's Palace (Witney).

Table 9.1 summarises the methods used to produce the different sets of information (see section 3.3 in Chapter 3).

**Table 9.1:** Pieces of equipment used to monitor changes in stone block properties and environmental factors of decay as well as data handling and statistical analysis methods

	<b>Equipment</b>	<b>Data handling</b>	<b>Statistical analysis</b>
<b>Dry weight</b>	Balance	Percentage of initial dry weight per block after a year	Two-way ANOVA tests per each stone type (variables: location and site). Three-way ANOVA test (variables: stone type, site and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>EMOD</b>	Grindosonic	Median EMOD per block (before and after)	Two-way ANOVA tests per each stone type and site (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Surface hardness</b>	Equotip	Median HL per block (before and after)	Two-way ANOVA tests per each stone type and site (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>UPV</b>	Pundit	Median UPV per block (before and after)	Two-way ANOVA tests per each stone type and site (variables: location and months). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Surface colour</b>	Spectro-photometer	dE*ab per block (overall colour change after a year), dE*ab, dL*, da* and db* means and reflectance of selected blocks	Two-way ANOVA tests per each stone type (variables: location and site). Three-way ANOVA test (variables: stone type, site and location). Post-hoc pairwise comparison tests (Holm-Sidak method)
<b>Macroscopy</b>	DSRL camera	Pictures (before and after)	
<b>Microscopy</b>	35x optical microscope	Pictures (before and after)	
<b>Moisture content</b>	Field balance	Means of percentage of initial dry weight per month (Witney) and every 3 months (Malta)	
<b>Wetting events</b>	Wetness loggers and time-lapse cameras	Wetness output (%) of the sensors and pictures	
<b>Surface temperature</b>	Hygrochrons (i-button)	Monthly means of daily surface temperature ranges and number of times $T \leq 0^{\circ}\text{C}$ per day	Linear model for diurnal T range and Poisson Generalized Linear Model for mean number of frost events per day

Four replicates of each stone type were exposed from 17<sup>th</sup> July 2013 to 22<sup>th</sup> July 2014 in Malta and from 29<sup>th</sup> July 2013 to 29<sup>th</sup> July 2014 at Witney. The tests to evaluate change in stone properties were carried out under the same conditions before and after exposing the blocks. When tests required a series of measurements per sample (hardness and ultrasonic pulse velocity), the median was selected as representative value (see section 3.3.2 in Chapter 3). The most central location possible under the shelter was selected in order to compare a protected location with an exposed one. Sample number 8 of Coralline limestone at Witney fell down from the support it was placed on (in the main pole of the shelter) in September 2013. This affected the weight lost by the sample and consequently, this information was not used in the statistical analysis. The data obtained from the other tests was considered with caution although it seems the incident did not affect the values significantly as the information is in line with the other replicates in that location.

Moisture content in the stone sensors was monitored in the field by change in weight (field balance OHAUS Compact Series Scale,  $\pm 0.1\text{g}$  accuracy). It was recorded once per month at Witney but only once every 3 months in Malta for logistical reasons. Additionally, wetting events were monitored during a week at each site in October 2013. Leaf wetness sensors (Tinytag leaf wetness logger, accuracy=0.4%,  $\pm 2$  units) and time-lapse cameras (TLC 200, Brinno, image sensor=1.3 MP) were placed inside and outside the shelters and were synchronised to record information every 10 minutes. In addition, surface temperature (i-button<sup>®</sup> hygrochron dataloggers, accuracy=  $\pm 0.5\%RH$  and  $\pm 0.5^\circ C$ ) was recorded every hour simultaneously in all positions. Only the common dates with records at both sites, from 29<sup>th</sup> July 2013 to 22<sup>nd</sup> July 2014, were taken into account for statistical analysis. Table 9.2 summarises the frequency of data collection.

**Table 9.2:** Summary of the time when data was recorded for each key factor of stone deterioration

	Dry weight	EMOD	Surface hardness	UPV	surface colour	Macroscopic microscopic characteristics	Moisture content (Malta)	Moisture content (Witney)	Surface T	Wetting events
0 months	✓	✓	✓	✓	✓	✓				
12 months	✓	✓	✓	✓	✓	✓				
Every month								✓		
Every 3 months							✓			
Every hour									✓	
Every 10 min										✓

The blocks (9x3x3 cm) were cut from Globigerina and Coralline limestones, which have been and are still used as the main local building material in Malta. Hagar Qim temple was only built with the softer Globigerina, but Coralline was used in other megalithic temples such as Ggantija. These stone types present different vulnerability to decay (see section 3.3.1 in Chapter 3 for information about stone properties). Globigerina is very soft and porous. Coralline limestone, on the other hand, is much harder and therefore more difficult to work (Cassar, 2010).

The main decay mechanisms which affect the Maltese buildings are related to salt weathering, temperature changes and wind erosion (Cassar, 2007a). Although there are some studies regarding weathering processes in Globigerina (Christaras, 1996, Cassar and Vannucci, 1999, Cassar, 2002, Cassar, 2007b, Cassar, 2007a, Rothert et al., 2007, Diana et al., 2014), Coralline has been less researched (Cassar and Vannucci, 1999, Cassar, 2010). In addition, there is a lack of information regarding the decay mechanism of these stones in other climates. Depending on the environmental conditions in each position (Chapter 8) and stone properties (Chapter 3), decay in the stone blocks was expected to be different.

A summary of the hypothesised changes in stone properties is shown in Table 9.3 and

Table 9.4.

**Table 9.3:** Predictions of changes (decrease for dry weight, EMOD, hardness and UPV) in key indicators of deterioration after a year of exposure in Malta \*

<b>MALTA</b>		Outside	Centre
Globigerina	Dry weight	High	Low
	EMOD	Medium	Low
	Hardness	Medium	Low
	UPV	Medium	Low
	dE*ab	High	Medium
	Macroscopy	Medium	Low
	Microscopy	Medium	Low
	Moisture	Low	-
	T fluctuation	Medium	Low
	Frost	Low	-
Coralline	Dry weight	Medium	Low
	EMOD	Low	-
	Hardness	Low	-
	UPV	Low	-
	dE*ab	Medium	Low
	Macroscopy	Medium	Low
	Microscopy	Medium	Low
	Moisture	Low	-
	T fluctuation	Medium	Low
	Frost	Low	-

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change (dE\*ab): HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=not noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For temperature fluctuations (diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH=above 80, MEDIUM=80-20, LOW= below 20. . For all measurements “-” means that no change is predicted.

**Table 9.4:** Predictions of changes (decrease) in key indicators of deterioration after a year of exposure in Witney\*

WITNEY		Outside	Centre
Globigerina	Dry weight	High	Low
	EMOD	Medium	-
	Hardness	Medium	-
	UPV	Medium	-
	dE*ab	High	Medium
	Macroscopy	Medium	Low
	Microscopy	Medium	Low
	Moisture	High	Low
	T fluctuation	Medium	Low
	Frost	Medium	Low
Coralline	Dry weight	Medium	Low
	EMOD	Low	-
	Hardness	Low	-
	UPV	Low	-
	dE*ab	Medium	Low
	Macroscopy	Low	-
	Microscopy	Low	-
	Moisture	Medium	-
	T fluctuation	Medium	Low
	Frost	Medium	Low

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change (dE\*ab): HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=not noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For temperature fluctuations (diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH= above 80, MEDIUM=80-20, LOW= below 20. . For all measurements “-“ means that no change is predicted.

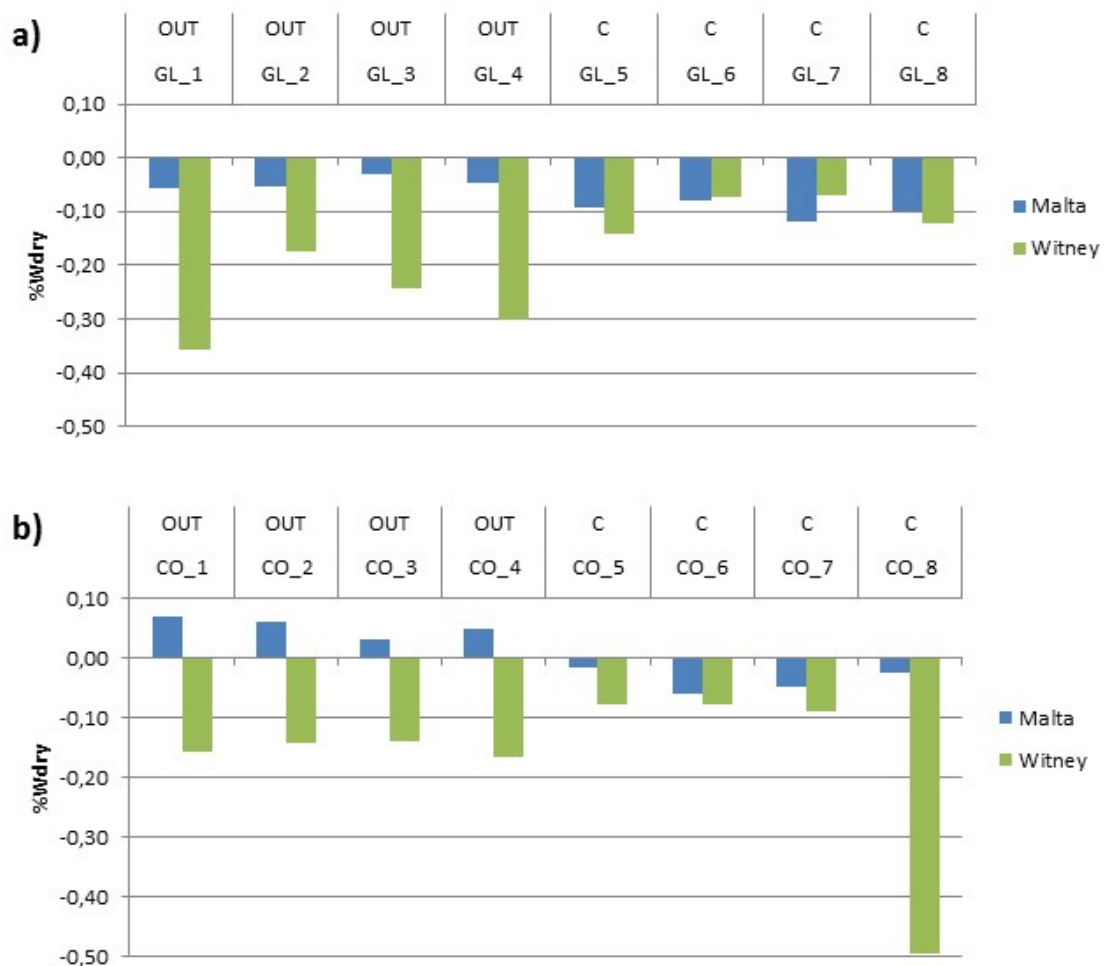
## 9.3. Results

### 9.3.1. Dry weight change

Changes in dry weight over a year, expressed as percentages of initial dry weight, were calculated for all samples. The changes represent a gain or loss of material. The main

causes of a gain in mass could be soiling and salt accumulation. On the other hand, rain and wind erosion and increase of inner cracks or pores are major causes of weight loss.

Figure 9.1 a) depicts the weight lost by Globigerina samples located outside and under the shelter at Hagar Qim (Malta) and the Bishop’s Palace (Witney). All samples lost weight over the course of a year. Samples located outside the shelter at Witney lost more weight than the ones inside. The reverse was found in Malta. At both sites, samples inside the shelter lost similar amounts of weight.



**Figure 9.1:** Dry weight change as percentage of initial dry weight of a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) at Hagar Qim (Malta) and the Bishop’s Palace (Witney) after a year. Sample CO\_08 was damaged during the experiment

Figure 9.1 b) shows the weight change in Coralline samples located outside and under the shelter in Malta and at Witney. Most samples lost weight over the course of the

year, except those located outside the shelter in Malta. At Witney, the loss was greater outside than inside the shelter. In Malta, samples located outside gained in weight whereas the Coralline samples placed inside lost weight. Sample number 8 (CO\_08) at Witney fell down from the support on which it was placed at the central part of the shelter in September with a subsequent significant loss in weight. This sample was not used in the statistical tests. The other samples located inside the shelter in Witney also lost slightly more weight than those in the equivalent position in Malta.

A two-way ANOVA statistical test was undertaken to find out if the changes in weight of *Globigerina* samples outside and inside the shelter in Malta and at Witney after a year of exposure was significantly different. The results showed that both position ( $F=6.823$ ,  $DF=1$ ,  $P=0.023$ ) and site ( $F=24.042$ ,  $DF=1$ ,  $P<0.001$ ) affected the weight loss. In addition, the interaction between position and site is significantly different ( $F=24.05$ ,  $DF=1$ ,  $P<0.001$ ). Post-hoc pairwise multiple comparison tests (Holm-Sidak method) showed that *Globigerina* samples located outside the shelter in Malta changed less in weight than the ones at Witney ( $t=7.07$ ,  $P<0.001$ ). However, there is no difference in the weight lost by *Globigerina* samples inside the shelter between Malta and Witney ( $t=0.140$ ,  $P=0.891$ ). In addition, there is no statistically significant difference between the weight lost by *Globigerina* samples outside and inside the shelter in Malta ( $t=1.621$ ,  $P=0.131$ ). However, the difference in *Globigerina* samples' weight losses between inside and outside the shelter at Witney is significant ( $t=0.167$ ,  $P<0.001$ ). A two-way ANOVA statistical test was also undertaken for weight changes in Coralline samples outside and inside the shelter in Malta and at Witney after a year of exposure. The results showed that there are no significant differences regarding position ( $F=1.388$ ,  $DF=1$ ,  $P=0.261$ ) or site ( $F=11.32$ ,  $DF=1$ ,  $P=0.006$ ).

A three-way ANOVA test on the weight change in Globigerina and Coralline samples placed inside and outside the shelter in Malta and at Witney after a year showed there is a statistically significant interaction between Position and Material ( $F=4.452$ ,  $DF=1$ ,  $P=0.045$ ) and Position and Site ( $F=5.851$ ,  $DF=1$ ,  $P=0.024$ ). Post-hoc pairwise comparison tests (Holm-Sidak method) established that Globigerina blocks outside the shelter lost more weight than Coralline ones ( $t=2.663$ ,  $P=0.014$ ). However, there is no statistically significant difference between Coralline and Globigerina samples inside the shelter ( $t=0.320$ ,  $P=0.751$ ). In addition, samples outside the shelter at Witney lost more weight than in Malta ( $t=5.316$ ,  $P<0.001$ ), but the difference between Witney and Malta is not statistically significant for samples located inside the shelter ( $t=1.895$ ,  $P=0.07$ ).

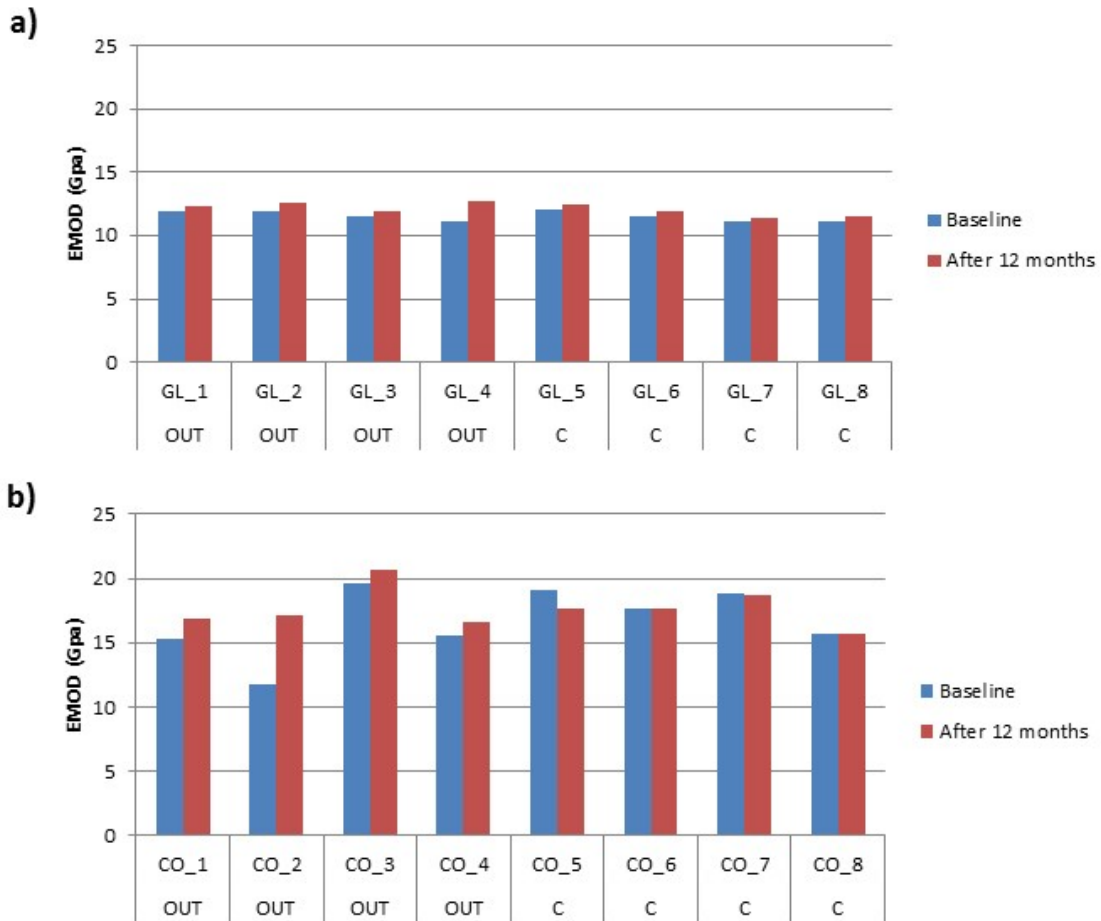
To summarise, only Globigerina samples outside the shelter at Witney lost significantly more weight than samples inside the shelter at Witney and outside the shelter in Malta. In addition, Globigerina blocks lost more weight than Coralline ones outside the shelter.

### **9.3.2. Elasticity changes**

The elastic modulus quantifies the elastic properties of materials. As we have seen before in Chapter 6, stiffer materials have higher EMOD. Globigerina stone blocks had an EMOD mean of 11.59 GPa before the exposure whereas Coralline had 28.57 GPa. These values are in line with previous research (Christaras, 1996).

Figure 9.2 shows the EMOD values of Globigerina and Coralline samples located outside and inside the shelter before and after 12 months of exposure at Hagar Qim (Malta). Globigerina samples tended to increase in EMOD and it is not possible to see a

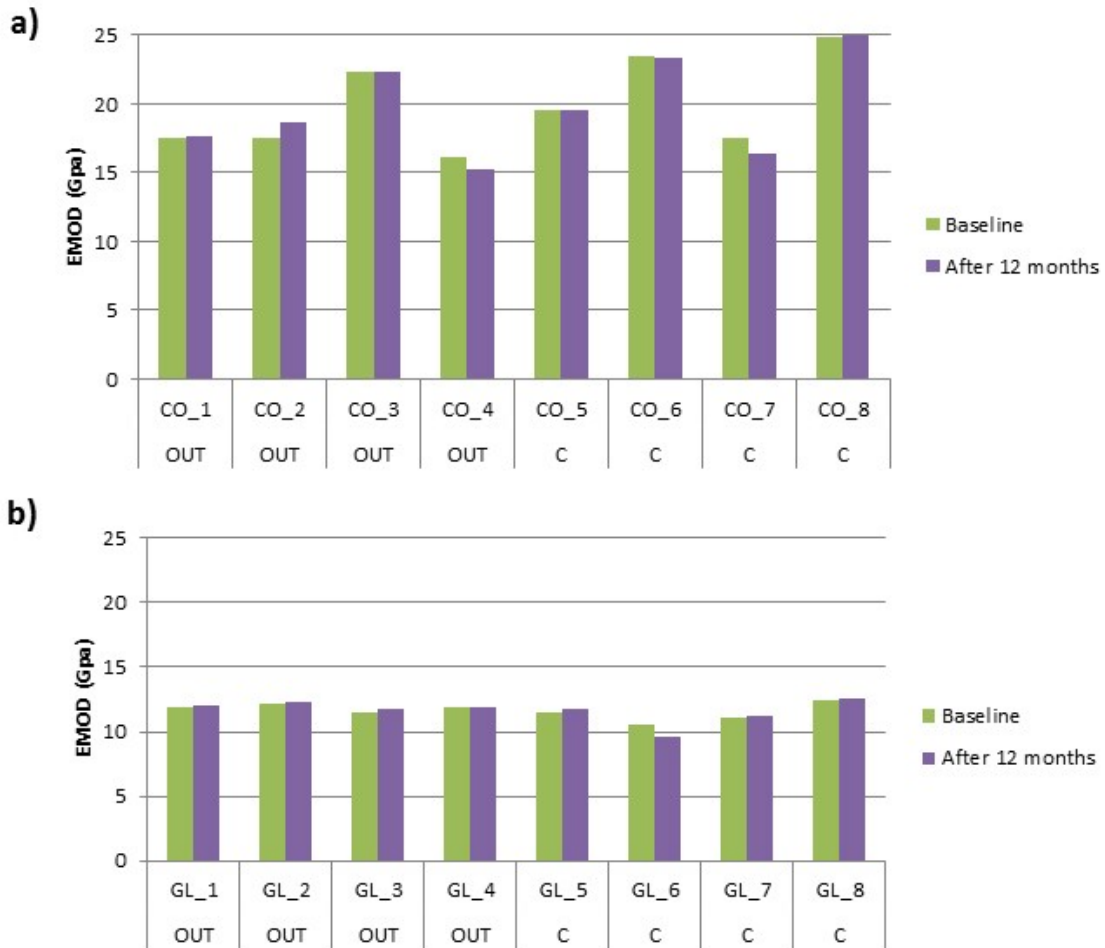
great difference between the centre of the shelter and outside. On the other hand, Coralline samples also increased in EMOD but only outside.



**Figure 9.2:** Median of EMOD values (GPa) in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) at Hagar Qim (Malta) before and after a year of exposure

Two-way ANOVA statistical tests on EMOD values in samples inside and outside the shelter in Malta showed that there are no significant differences between locations either in Globigerina ( $F=3.525$ ,  $DF=1$ ,  $P=0.08$ ) or Coralline samples ( $F=0.785$ ,  $DF=1$ ,  $P=0.393$ ). Additionally, the differences between before and after exposure did not depend on the positions. The interaction between Position and Month is not significant for Globigerina ( $F=1.200$ ,  $DF=1$ ,  $P = 0.250$ ) or Coralline ( $F=1.462$ ,  $DF=1$ ,  $P=0.250$ ).

Figure 9.3 shows the EMOD values of Globigerina and Coralline samples inside and outside the shelter before and after 12 months at the Bishop’s Palace. There are no noticeable differences between inside and outside the shelter for any of the stone types.



**Figure 9.3:** Median of EMOD values (GPa) in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) at the Bishop’s Palace (Witney) before and after a year of exposure

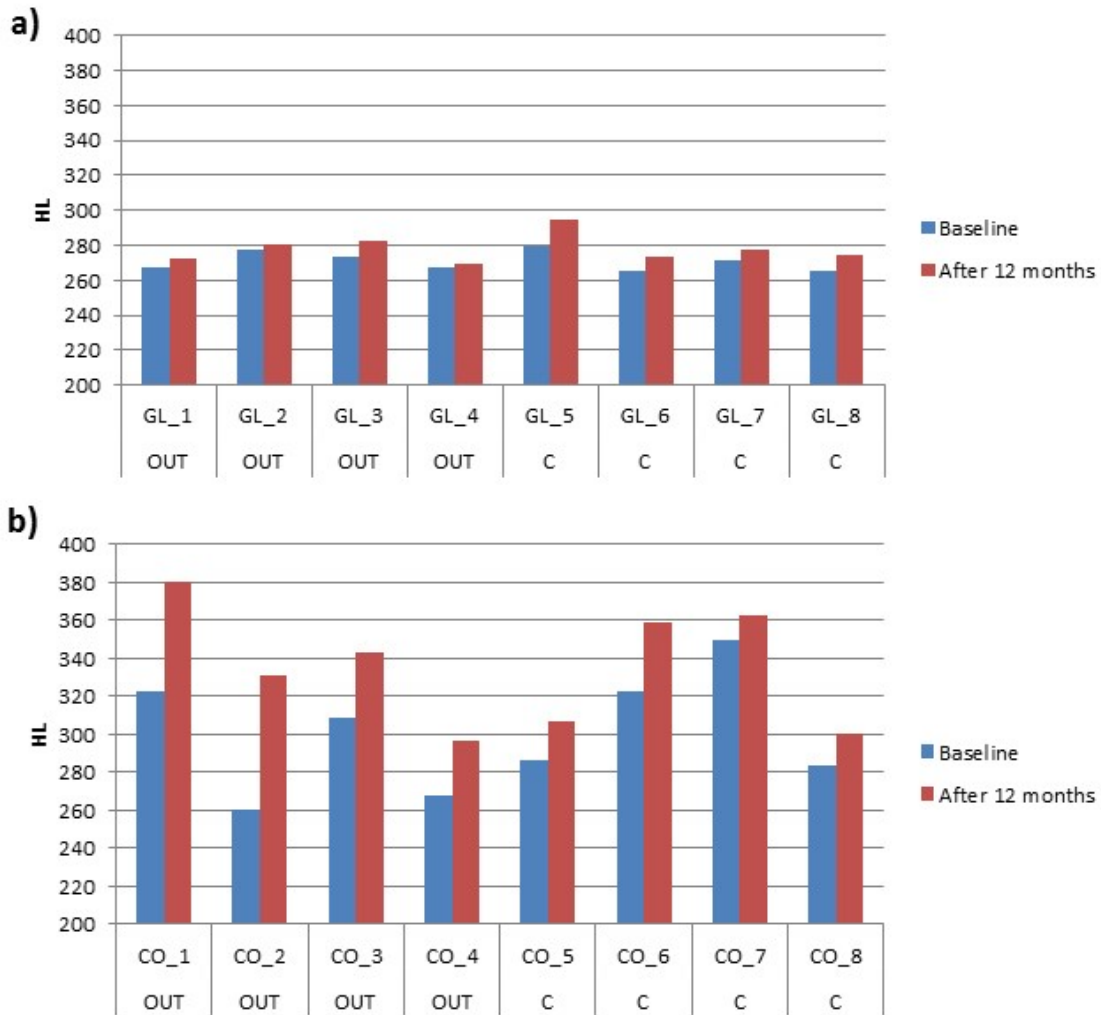
A two-way ANOVA statistical test on the difference in EMOD values in Globigerina samples located inside and outside the shelter in Witney showed that the difference in the mean values among the different positions is not great enough to exclude the possibility of random sampling variability ( $F=2.464$ ,  $DF=1$ ,  $P=0.142$ ). In addition, there is no statistically significant difference in EMOD values before and after a year of

exposure ( $F=0.000$ ,  $DF=1$ ,  $P=0.975$ ). Similar results were obtained with Coralline samples. A two-way ANOVA statistical test on the difference in EMOD values in Coralline stones located inside and outside the shelter at Witney showed that there is no statistically significant difference between positions ( $F=2.967$ ,  $DF=1$ ,  $P=0.111$ ) or months ( $F=0.002$ ,  $DF=1$ ,  $P=0.958$ ). Consequently, no conclusion can be made based on the results from EMOD values. The samples might need more time of exposure to give significant results.

### **9.3.3. Surface hardness changes**

The hardness mean for all Globigerina limestone samples at the start of the experiment was 267.38 HL while for Coralline it was 306.09 HL. Coralline limestone is a harder stone type.

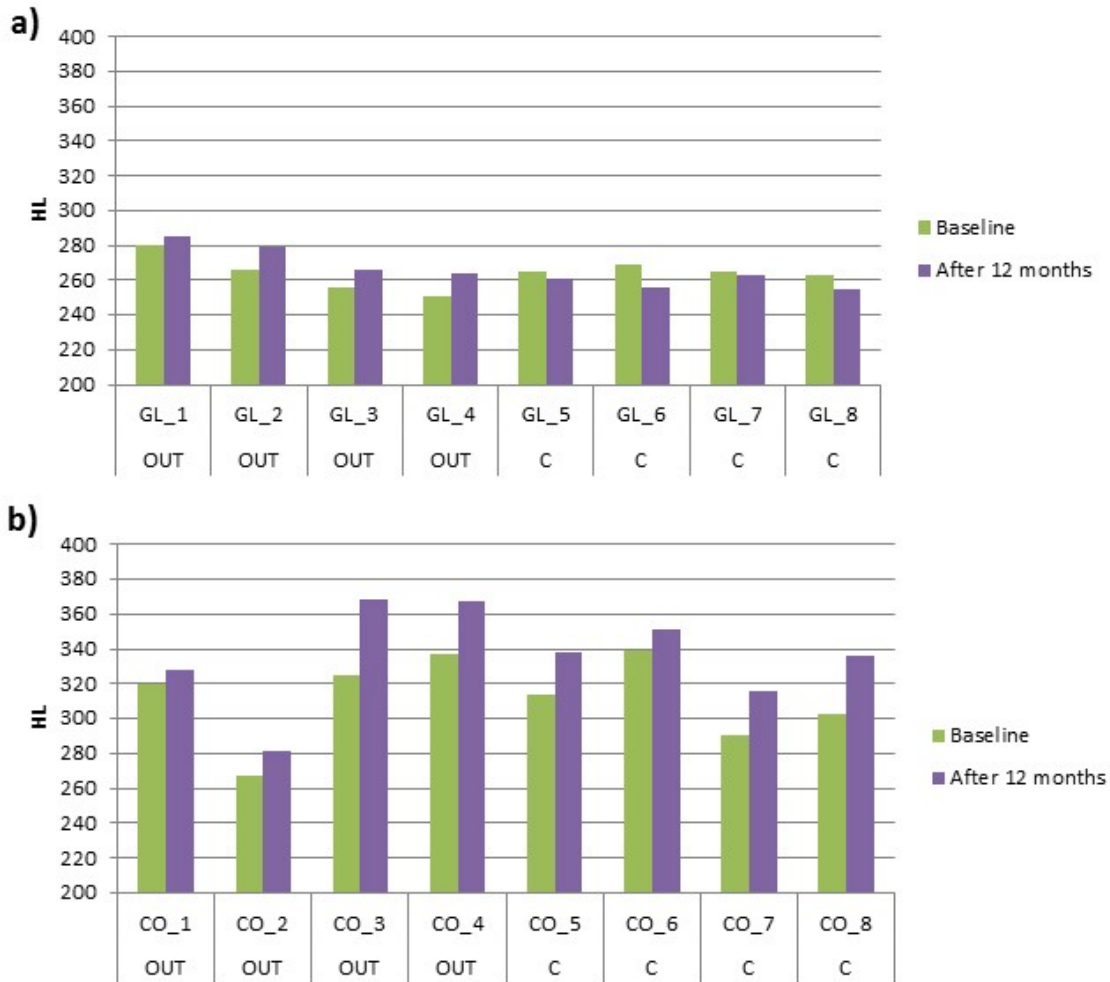
Figure 9.4 shows the hardness values in Globigerina and Coralline samples located in Malta, under the central part of the shelter and outside, initially and after 12 months. All the samples in Malta increased in hardness but especially the Coralline blocks placed outside. A two-way ANOVA statistical test on the hardness values of Globigerina and Coralline samples located inside and outside the shelter in Malta before and after a year showed that increase in hardness with time either in Globigerina ( $F=0.350$ ,  $DF=1$ ,  $P=0.565$ ) or Coralline samples ( $F=0.632$ ,  $DF=1$ ,  $P=0.442$ ) did not depend on the position. The increase in hardness in blocks placed outside is not significant from those inside the shelter.



**Figure 9.4:** Median of the hardness values (HL) in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) in Malta before and after a year of exposure

Figure 9.5 depicts the hardness values in Globigerina and Coralline samples located inside and outside the shelter at Witney. Samples located outside increased in hardness, although Coralline samples increased more than Globigerina blocks. On the other hand, Globigerina samples located under the shelter decreased in hardness whereas the hardness values in Coralline samples located in the same position increased. Two-way ANOVA statistical tests in the hardness values of Globigerina and Coralline samples located inside and outside the shelter at Witney showed that there was no a significant difference in hardness values between before and after a year of exposure either in Globigerina ( $F=0.245$ ,  $DF=1$ ,  $P=0.63$ ) or Coralline ( $F=2.788$ ,  $DF=1$ ,

P=0.121) samples. In addition, hardness values did not depend on the position in which the Globigerina (F=1.052, DF=1, P=0.327) or Coralline (F=0.002, DF=1, P=0.959) samples were placed.



**Figure 9.5:** Median of the hardness values (HL) in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) at Witney before and after a year of exposure

Previous studies have shown that the weathering process of Globigerina starts with the dissolution and reprecipitation of calcite, which at first leads to the formation of a thick and compact superficial crust and an increase in hardness (Rothert et al., 2007). As the increase in hardness in Coralline samples is even more pronounced (see graphs b) in comparison with a) in both Figure 9.4 and Figure 9.5), it is possible to infer that a similar weathering process is taking place for this stone type. However, the degree of

change does not depend on the position. This increase could be the result of natural ageing due to the intrinsic properties of the stones used and any interpretation from HL change cannot be related to the effect of the shelter.

#### **9.3.4. Changes in ultrasonic pulse velocity (UPV)**

UPV values are used to indicate the presence of inner cracks or increase in pore size. The initial UPV values of Globigerina limestone are lower than Coralline. While the mean value of all Globigerina samples at the start of the experiment was 2864.94 m/s, Coralline samples had a mean value of 3347.31 m/s. This indicates that Globigerina is a less dense stone type. These results are similar to previous studies about Globigerina limestone (Christaras, 1996, Rothert et al., 2007) and confirm the results of EMOD and hardness values. In addition, UPV values obtained in this study are comparable to the values of Franka (Diana et al., 2014), which is the type of Globigerina more resistant to weathering (Cassar, 2004). The UPV is reduced when stone weathers as the amount of air trapped inside a block slows down the propagation of the waves.

Figure 9.6 shows the UPV values of Globigerina and Coralline samples inside and outside the shelter in Malta. After a year of exposure, there are no clear changes in Globigerina samples at any location. However, the UPV value increased in Coralline blocks both inside and outside the cover. A two-way ANOVA statistical test on UPV values in Globigerina samples in Malta before and after a year shows that there is no significant difference in the UPV readings before and after exposure ( $F=0.006$ ,  $DF=1$ ,  $P=0.938$ ) and the difference in the mean values among the different positions is not great enough to exclude random sampling variability ( $F=0.233$ ,  $DF=1$ ,  $P=0.638$ ). In addition, a two-way ANOVA statistical test on UPV values in Coralline samples in Malta

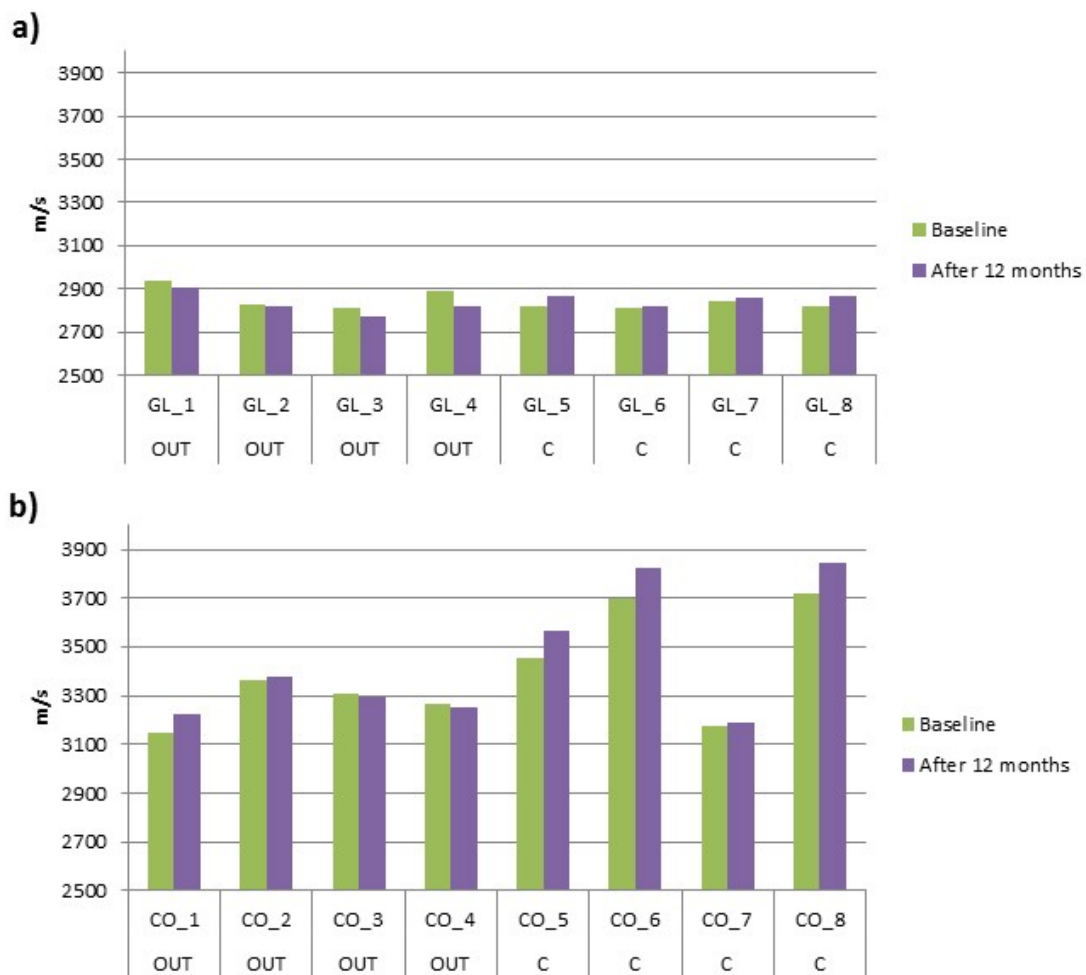
showed that there are no statistically significant differences between positions ( $F=0.004$ ,  $DF=1$ ,  $P = 0.946$ ) and time of exposure ( $F=0.917$ ,  $DF=1$ ,  $P = 0.357$ ).



**Figure 9.6:** Median of the UPV values in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) in Malta before and after a year of exposure

Figure 9.7 shows the UPV values of Globigerina and Coralline blocks under the shelter and outside at Witney. Similarly to Globigerina samples in Malta, there are no changes in UPV after a year. By contrast, Coralline samples located inside increased in UPV more than the ones outside. A two-way ANOVA statistical test on the UPV values in Globigerina samples inside and outside the shelter at Witney showed that there are no significant differences between locations ( $F=0.296$ ,  $DF=1$ ,  $P=0.596$ ) and time of exposure ( $F=0.004$ ,  $DF=1$ ,  $P=0.828$ ). In addition, a two-way ANOVA statistical test on the UPV values in Coralline samples inside and outside the shelter at Witney showed

the differences in UPV before and after the year of exposure did not depend on positions. There is no statistically significant interaction between Position and Months ( $F=0.136$ ,  $DF=1$ ,  $P=0.718$ ). As a result, UPV data cannot be considered useful indicators of the state of decay of Globigerina and Coralline samples outside and under the shelter at the Bishop's Palace and Hagar Qim. This could change with a greater amount of exposure time.



**Figure 9.7:** Median of the UPV values in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) at Witney before and after a year of exposure

### 9.3.5. Surface colour changes

Colour differences of Globigerina and Coralline samples outside and inside the shelter in Malta and at Witney before and after 12 months were compared using the CIELAB

dE\*ab values, which indicate the overall colour change per sample. Globigerina samples changed colour more dramatically than Coralline samples, especially in Malta.

Figure 9.8 a) shows the colour change (dE\*ab) in Globigerina samples located outside and under the central part of the shelter in Malta and at Witney. Samples in Malta changed in colour more than in Witney. In addition, Globigerina samples located under the shelter changed less than the samples outside in both Malta and at Witney.



**Figure 9.8:** Overall colour difference (dE\*ab) in a) Globigerina and b) Coralline samples located outside (OUT) and in the centre of the shelter (C) in Malta and at Witney after a year of exposure

Figure 9.8 b) illustrates the colour changes (dE\*ab) in Coralline samples placed outside and inside the shelter in Malta and at Witney. It seems that there are no clear trends in colour change in Coralline samples placed inside and outside the shelter either in

Malta or in Witney. In addition, there are no clear differences between Malta and at Witney for this stone type. As we have seen in Chapter 6, a CIELAB overall colour difference of 1.8 dE\*ab is already visible to the naked eye (Bieske and Vandahl, 2008). All samples, apart from Globigerina samples located inside the shelter at Witney, passed this threshold. Furthermore, the majority of the samples in Malta and the blocks located outside at Witney went over 3.8 dE\*ab, which indicates that the change is distinctively perceptible to the naked eye. Globigerina samples placed outside in Malta were the most affected by the colour change with an average of 12.875 dE\*ab.

A two-way ANOVA statistical test on the overall colour change in Globigerina samples located inside and outside the shelter in Malta and at Witney after a year showed that there is a statistically significant interaction between positions and sites ( $F= 21.567$ ,  $DF=1$ ,  $P<0.001$ ). Post-hoc pairwise comparison tests (Holm-Sidak method) showed that Globigerina samples located outside the shelter changed in colour more than the blocks placed inside at both sites, in Malta ( $t=13.668$ ,  $P<0.001$ ) and at Witney ( $t=13.668$ ,  $P<0.001$ ). In addition, Globigerina samples in Malta changed in colour significantly more than at Witney after a year for both positions, outside the shelter ( $t=18.567$ ,  $P<0.001$ ) and inside ( $t=11.999$ ,  $P<0.001$ ).

On the other hand, a two-way ANOVA statistical test on the overall colour change in Coralline samples placed inside and outside the shelter in Malta and at Witney after a year showed that there are no significant differences in colour change between positions ( $F=4.102$ ,  $DF=1$ ,  $P=0.066$ ) and sites ( $F=1.450$ ,  $DF=1$ ,  $P=0.252$ ). In addition, the interaction between positions and sites is not significant ( $F=3.553$ ,  $DF=1$ ,  $P=0.084$ ). A three-way ANOVA statistical test on colour change in Globigerina and Coralline

samples, placed inside and outside the shelter in Malta and at Witney, was undertaken. There is a significant interaction between positions, types of stone and sites ( $F=13.033$ ,  $DF=1$ ,  $P=0.001$ ). The results of the post-hoc pairwise comparison tests (Holm-Sidak method) showed that Globigerina limestone changed more in colour than Coralline in Malta but only outside ( $t=9.752$ ,  $P<0.001$ ). However, Coralline limestone changed more in colour than Globigerina at Witney ( $t= 2.544$ ,  $P=0.018$ ).

Additionally, CIELAB differences in  $dL^*$  (lightness/darkness),  $da^*$  (red/green) and  $db^*$  (yellow/blue) were examined to determine the characteristics of colour change. Table 9.5 summarises the mean differences in  $dE^*ab$ ,  $dL^*$ ,  $da^*$  and  $db^*$  in Globigerina and Coralline samples after a year.

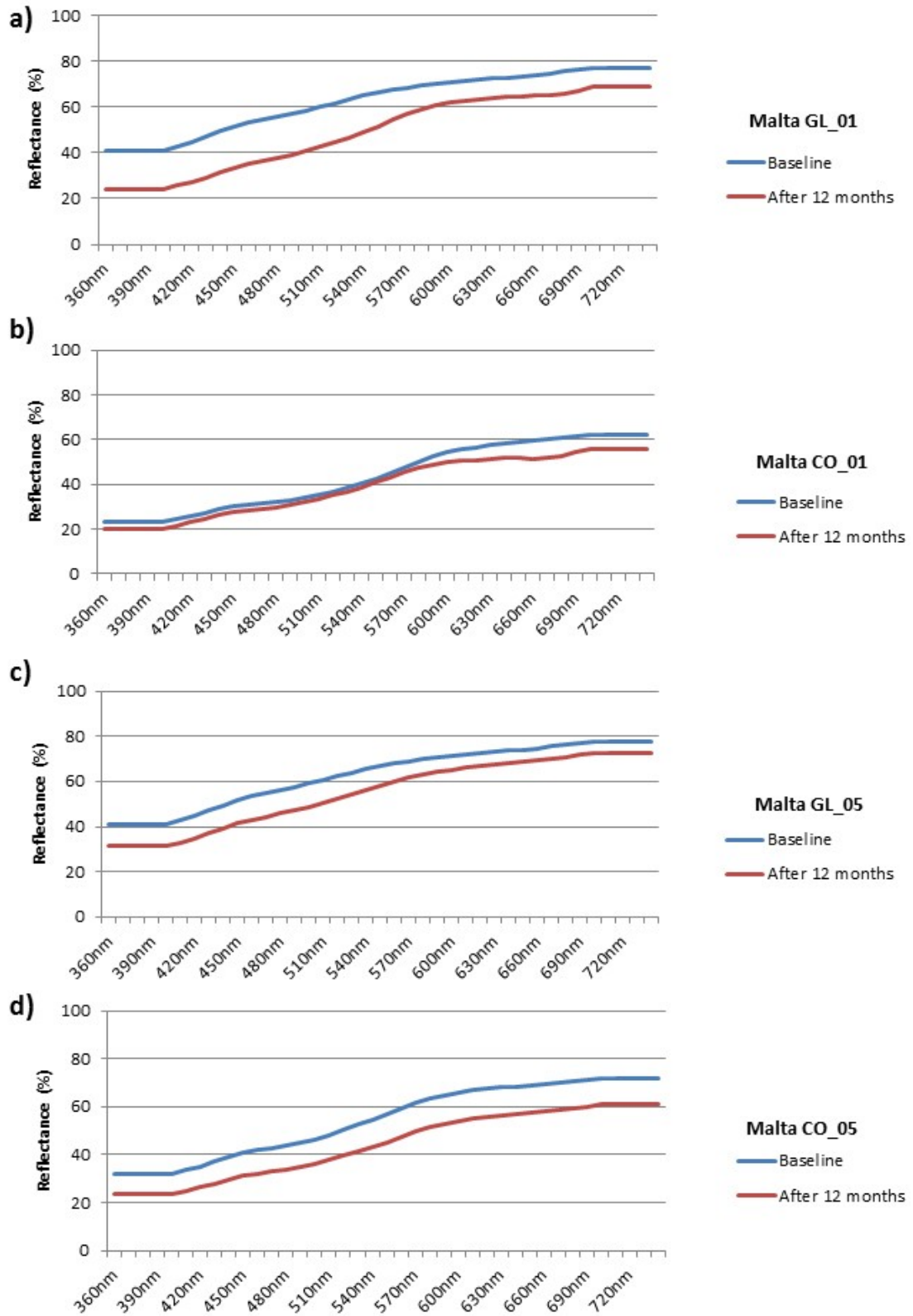
**Table 9.5:** Colour difference mean as  $dE^*ab$ ,  $dL^*$ ,  $da^*$  and  $db^*$  in Globigerina and Coralline samples after 12 months of exposure ( $n=4$  in each position). The results exclude the spectral component (SCE measurements).

	Stone	Position	$dE^*ab$ (D65)	$dL^*$ (D65)	$da^*$ (D65)	$db^*$ (D65)
Malta	Globigerina	Outside	12.88	-8.22 darker	4.74 Less green	8.70 yellower
		Centre	6.59	-4.55 darker	2.18 Less green	4.22 yellower
	Coralline	Outside	5.08	-4.49 darker	-0.43 greener	0.40 yellower
		Centre	5.18	-5.03 darker	0.30 Less green	0.17 yellower
Witney	Globigerina	Outside	4.34	-4.03 darker	0.50 Less green	-0.67 Less yellow
		Centre	1.07	-1.02 darker	0.03 Less green	-0.12 Less yellow
	Coralline	Outside	5.57	-5.17 darker	-0.63 greener	-1.33 Less yellow
		Centre	2.72	-0.75 darker	-0.77 greener	-2.05 Less yellow

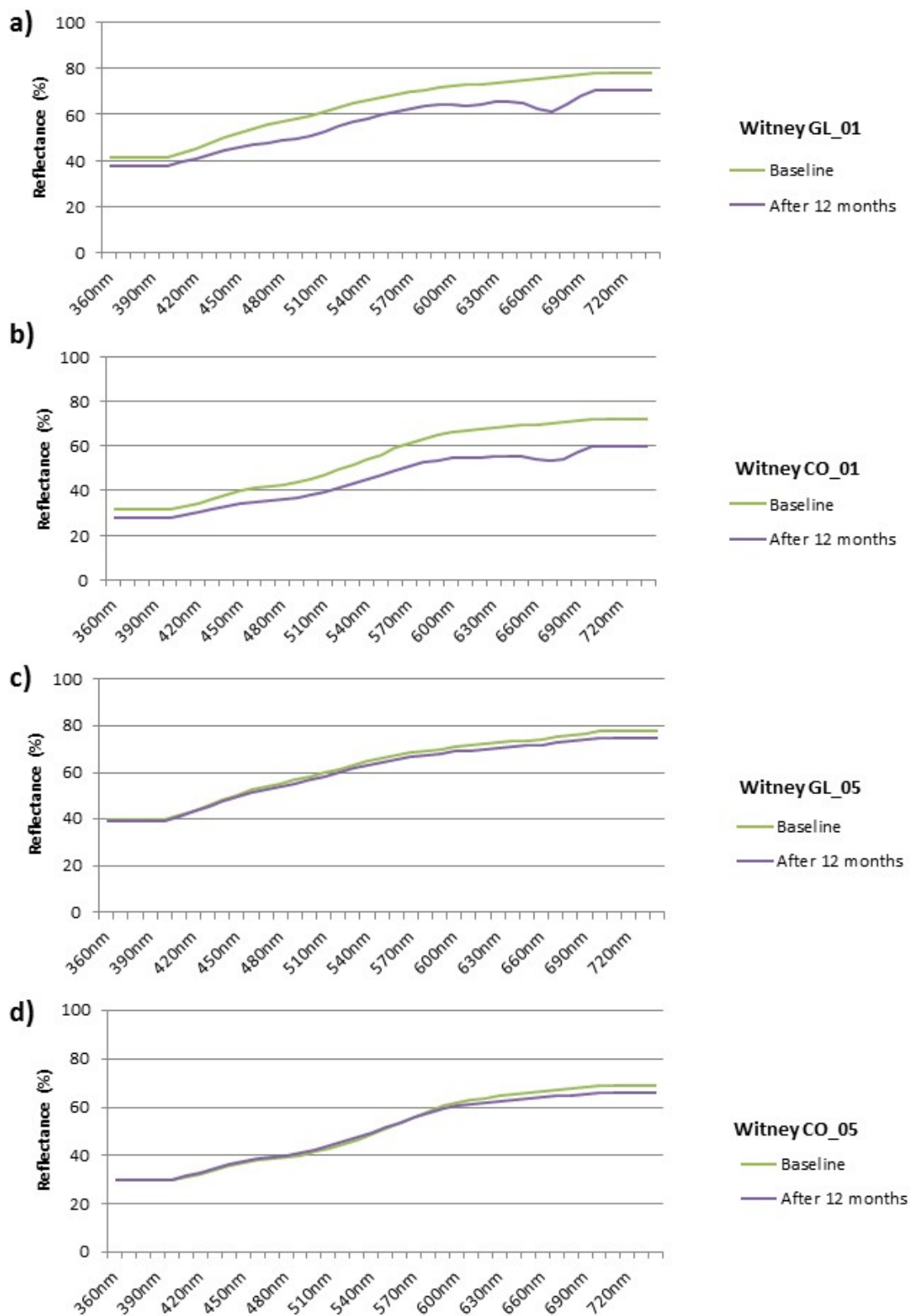
Globigerina and Coralline samples in Malta became yellower and darker in both positions, inside and outside the shelter. On the other hand, both Globigerina and Coralline samples turned darker but less yellow inside and outside the shelter at

Witney. The differences between locations for the same stone type and between stone types in the same location lie in the degree of change. The  $da^*$  values indicate differences in the red/green vector of the CIELAB colour space. Coralline samples at Witney showed slight greening of the surface.

A study on the reflectance of selected samples in Malta and at Witney was undertaken to verify the changes seen with the mean values of  $dL^*$ ,  $da^*$  and  $db^*$  (Figure 9.9 and Figure 9.10). Figure 9.9 shows the reflectance of Globigerina and Coralline samples outside and inside the shelter at Hagar Qim (Malta). The Globigerina sample placed outside the shelter had a decrease in reflectance in all wavelengths but especially in the shorter ones (Figure 9.9, a). It became much darker and yellower than the one inside the shelter. On the other hand, the Coralline sample placed outside the shelter showed less decrease in reflectance than the sample inside the shelter (Figure 9.9, b). It became slightly less dark and yellow. Figure 9.10 illustrates the reflectance of Globigerina and Coralline samples outside and inside the shelter at the Bishop's Palace (Witney). The Globigerina sample located outside the shelter at Witney turned darker than the one inside as seen in the general reduction of reflectance. The Coralline sample outside the shelter also became darker and slightly yellower.



**Figure 9.9:** Reflectance of the a) Globigerina (GL\_01) and b) Coralline (GO\_01) samples outside the shelter; and c) Globigerina (GL\_05) and d) Coralline (CO\_05) samples under the central part of the shelter in Malta. SCE measurements

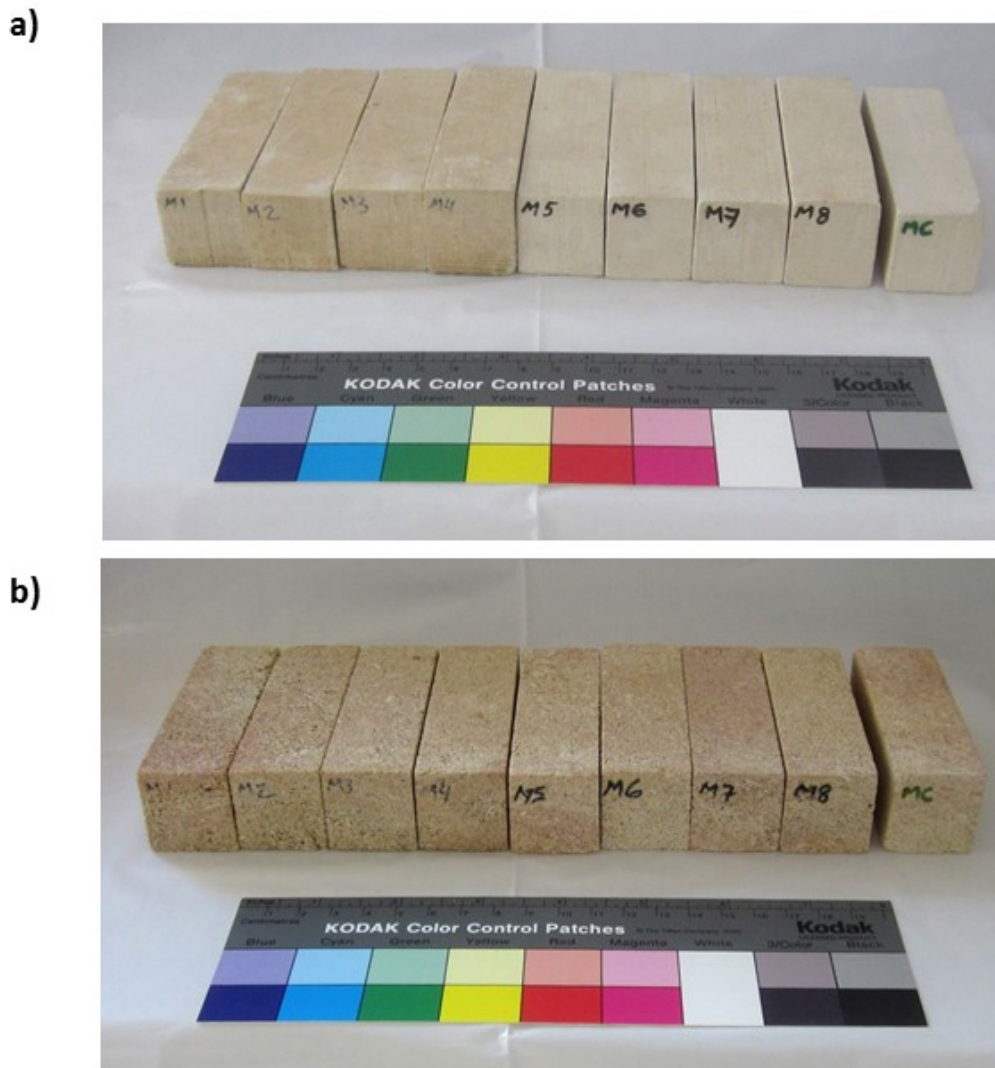


**Figure 9.10:** Reflectance of the a) Globigerina (GL\_01) and b) Coralline (CO\_01) samples outside the shelter; and c) Globigerina (GL\_05) and d) Coralline (CO\_05) samples under the central part of the shelter at Witney. SCE measurements

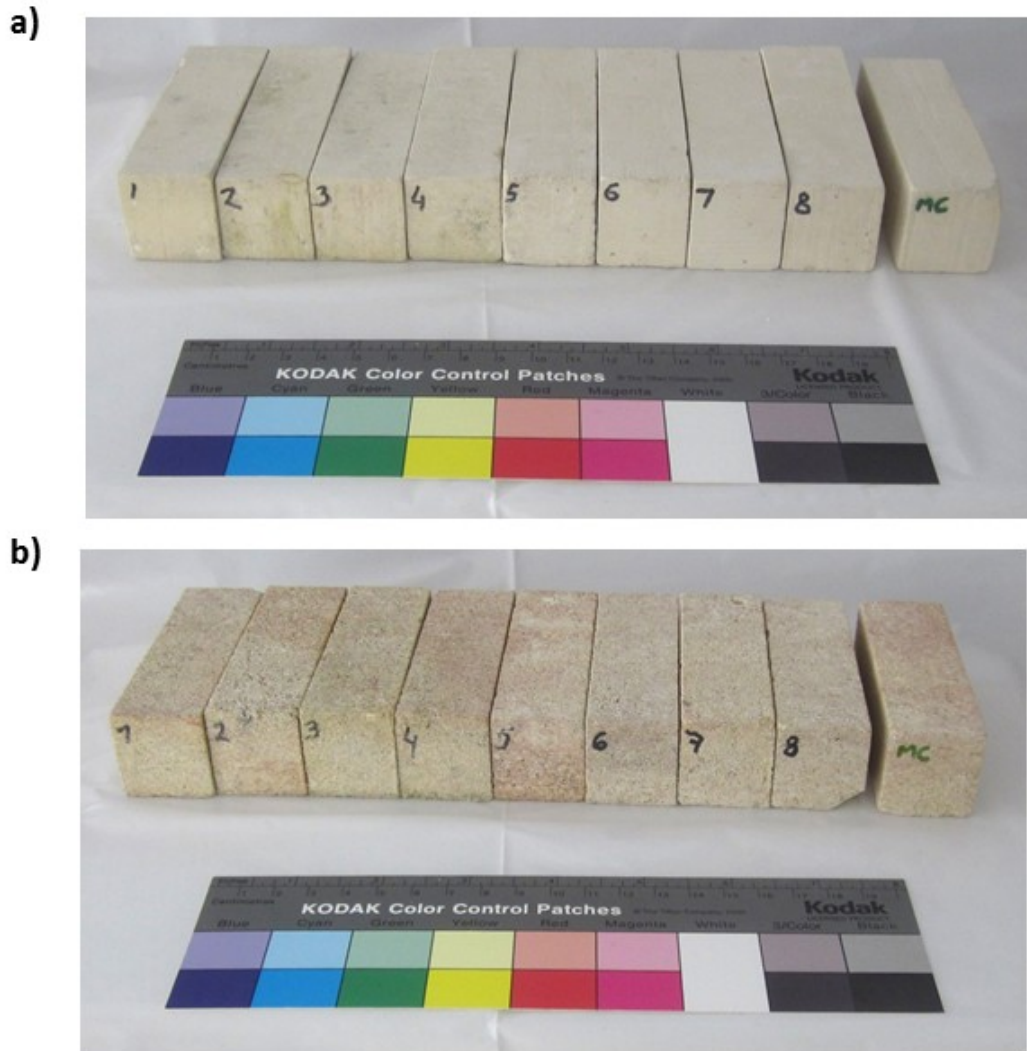
### 9.3.6. Macroscopic and microscopic surface changes

A general picture of all samples was taken after 12 months to determine visual colour differences (Figure 9.11 and Figure 9.12). All samples in Malta became darker and yellower with time, but especially Globigerina blocks located outside (Figure 9.11, a).

All samples at Witney became darker but there are no visual differences between positions either for Globigerina or Coralline (Figure 9.12). These results were also detected by comparing initial and final  $dL^*$  values on the top horizontal surface (Table 9.5).

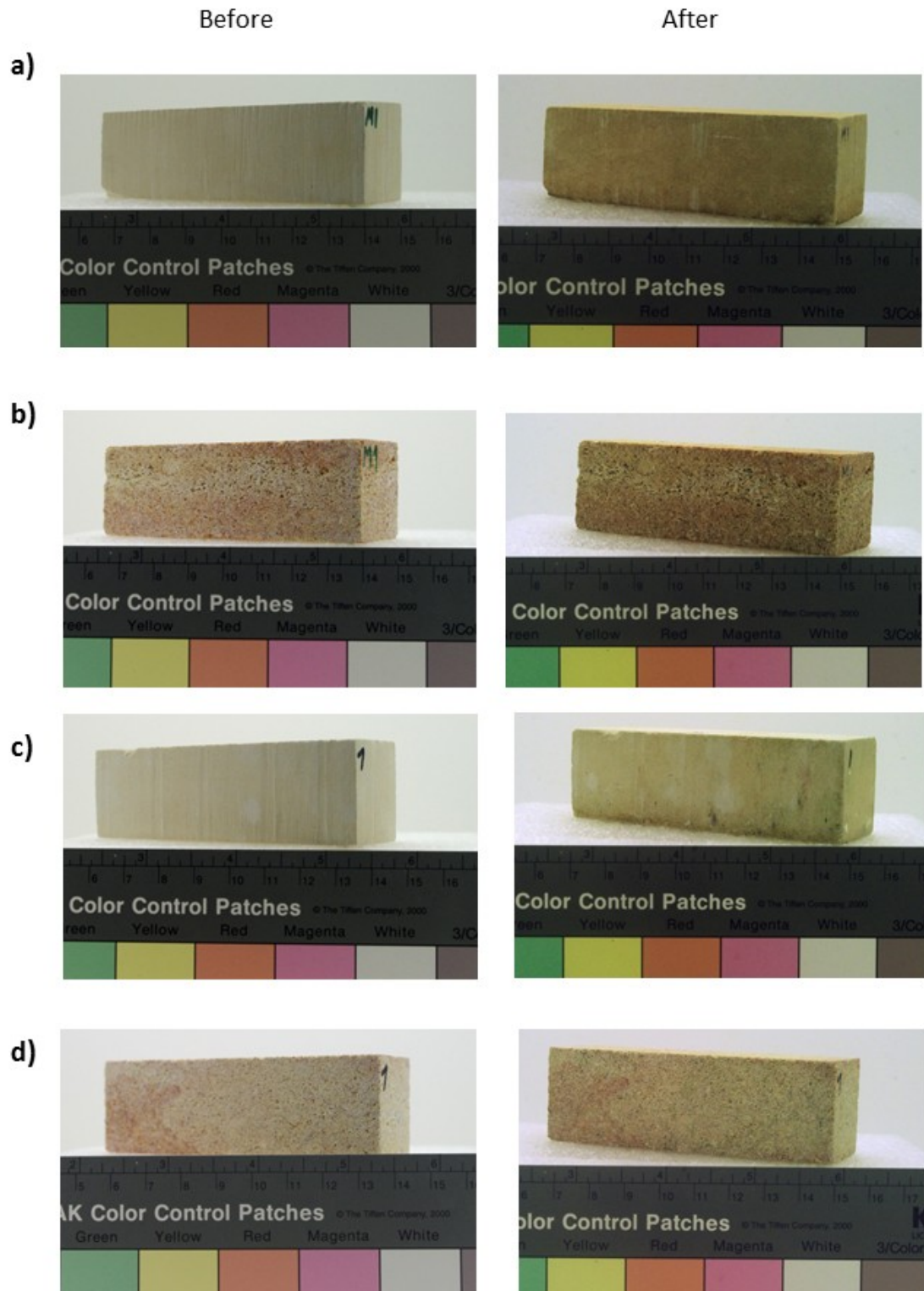


**Figure 9.11:** Macroscopic pictures of a) Globigerina and b) Coralline samples located in Malta after a year. Samples outside the shelter: numbers 1 to 4 (first four starting from the left). Samples inside the shelter: numbers 5 to 8 (first four starting from the right). Control: MC

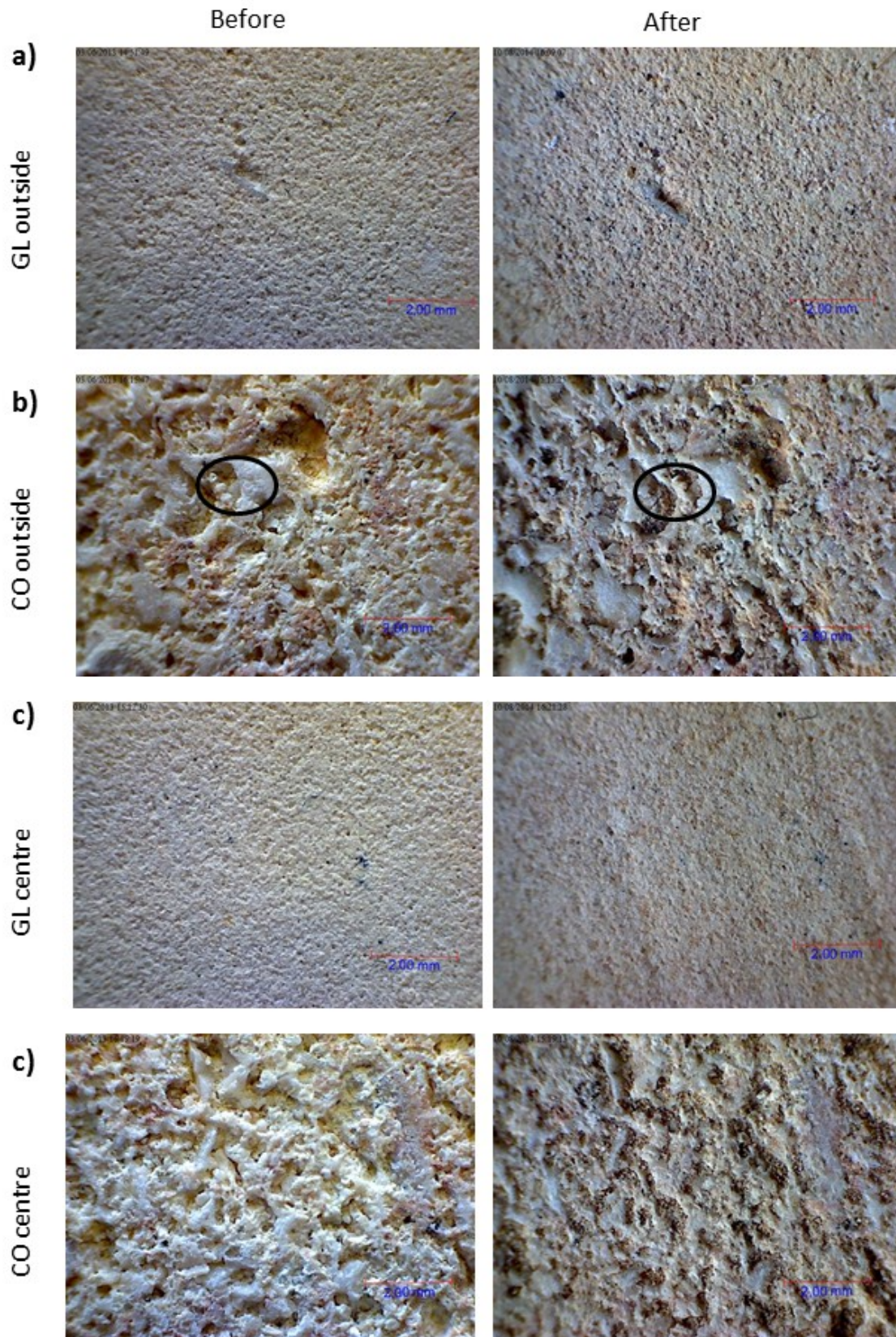


**Figure 9.12:** Macroscopic pictures of a) *Globigerina* and b) Coralline samples located in Witney a after a year of exposure. Samples outside the shelter: numbers 1 to 4 (first four starting from the left). Samples inside the shelter: numbers 5 to 8 (first four starting from the right). Control: MC

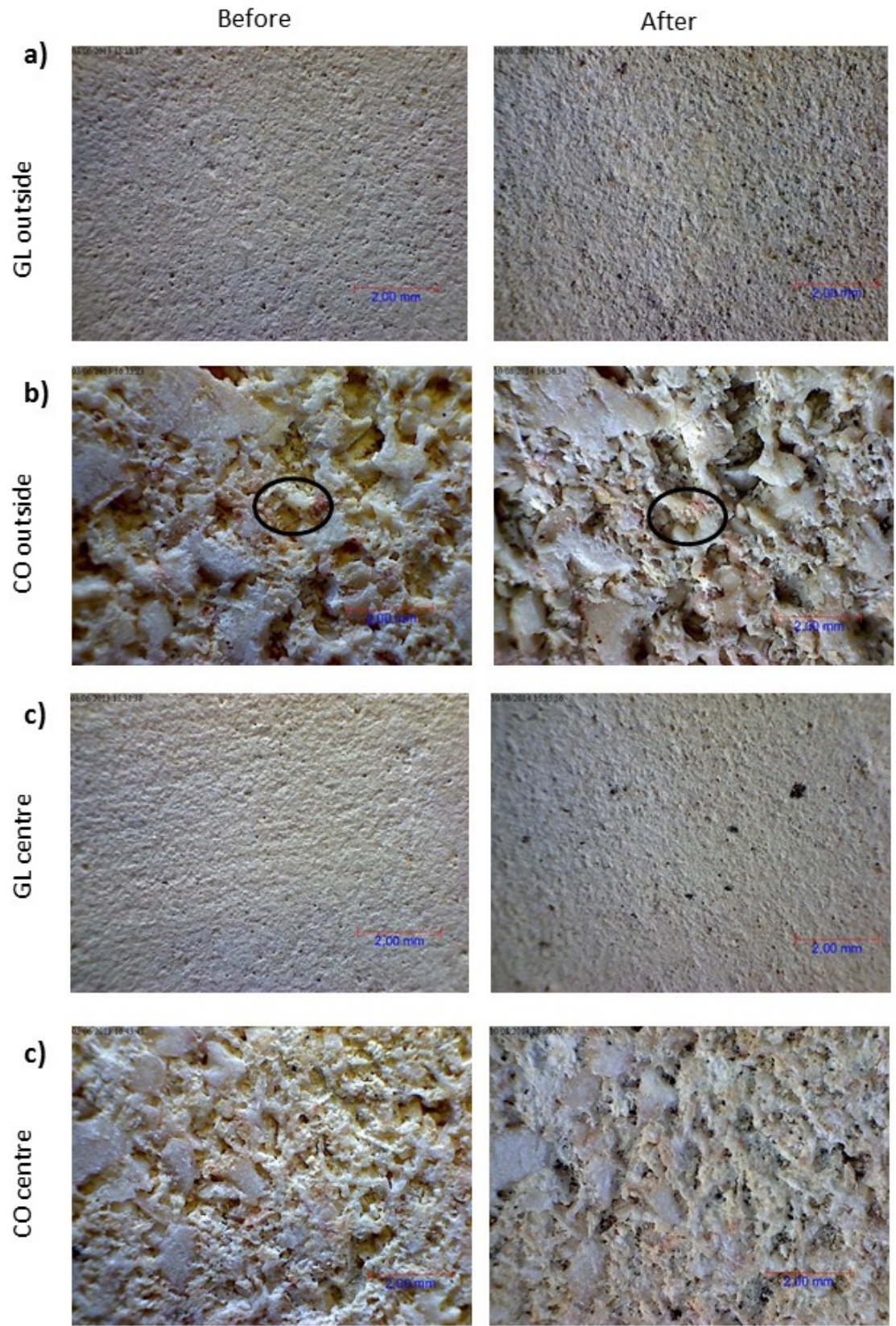
In addition, individual pictures of each sample were taken at the start and after a year of exposure in order to monitor change in general appearance. Figure 9.13 shows the macroscopic pictures of representative *Globigerina* and Coralline samples placed outside the shelter in Malta and at Witney. The samples did not show any substantial macroscopic change in terms of erosion or cracks. However, there is some evidence of biological growth and soiling on the vertical faces.



**Figure 9.13:** Macroscopic pictures of a) Globigerina (GL\_01) and b) Coralline (CO\_01) samples placed outside the shelter in Malta and c) Globigerina (GL\_01) and d) Coralline (CO\_01) samples placed outside the shelter at Witney before and after a year of exposure



**Figure 9.14:** Microscopic pictures of a) Globigerina (GL\_02) and b) Coralline (CO\_03) outside the shelter; and c) Globigerina (GL\_07) and d) Coralline (CO\_05) under the central part of the shelter in Malta before and after a year of exposure



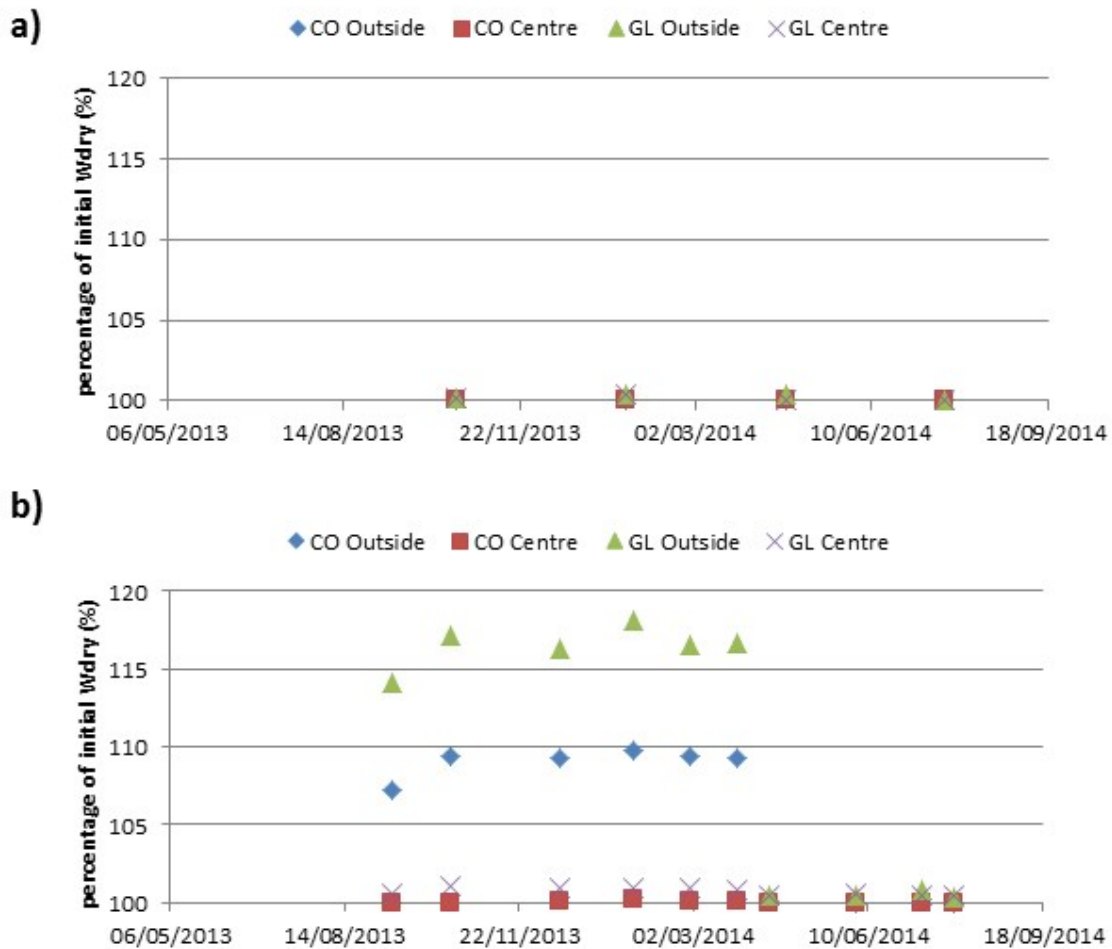
**Figure 9.15:** Microscopic pictures of a) Globigerina (GL\_02) and b) Coralline (CO\_02) outside the shelter; and c) Globigerina (GL\_06) and d) Coralline (CO\_07) under the central part of the shelter at Witney before and after a year of exposure

Detailed pictures of the surface of Globigerina and Coralline blocks were taken with a 35x optical microscope initially and after a year of exposure in Malta (Figure 9.14) and Witney (Figure 9.15). In Malta (Figure 9.14), there is an increase in surface roughness in Globigerina samples and surface erosion and loss of stone grains in Coralline samples outside the shelter. In addition, there is evidence of soiling in the samples placed inside. There was no evidence of salt efflorescences. At Witney (Figure 9.15), samples present the same decay phenomena as seen in Malta, with a slight increase in soiling inside the shelter. The degree of decay assessed by macroscopic and microscopic pictures is very similar at both sites.

### **9.3.7. Moisture content and wetting events on stone blocks**

Moisture content of Globigerina and Coralline samples placed inside and outside the shelter in Malta and at Witney was monitored by weight change.

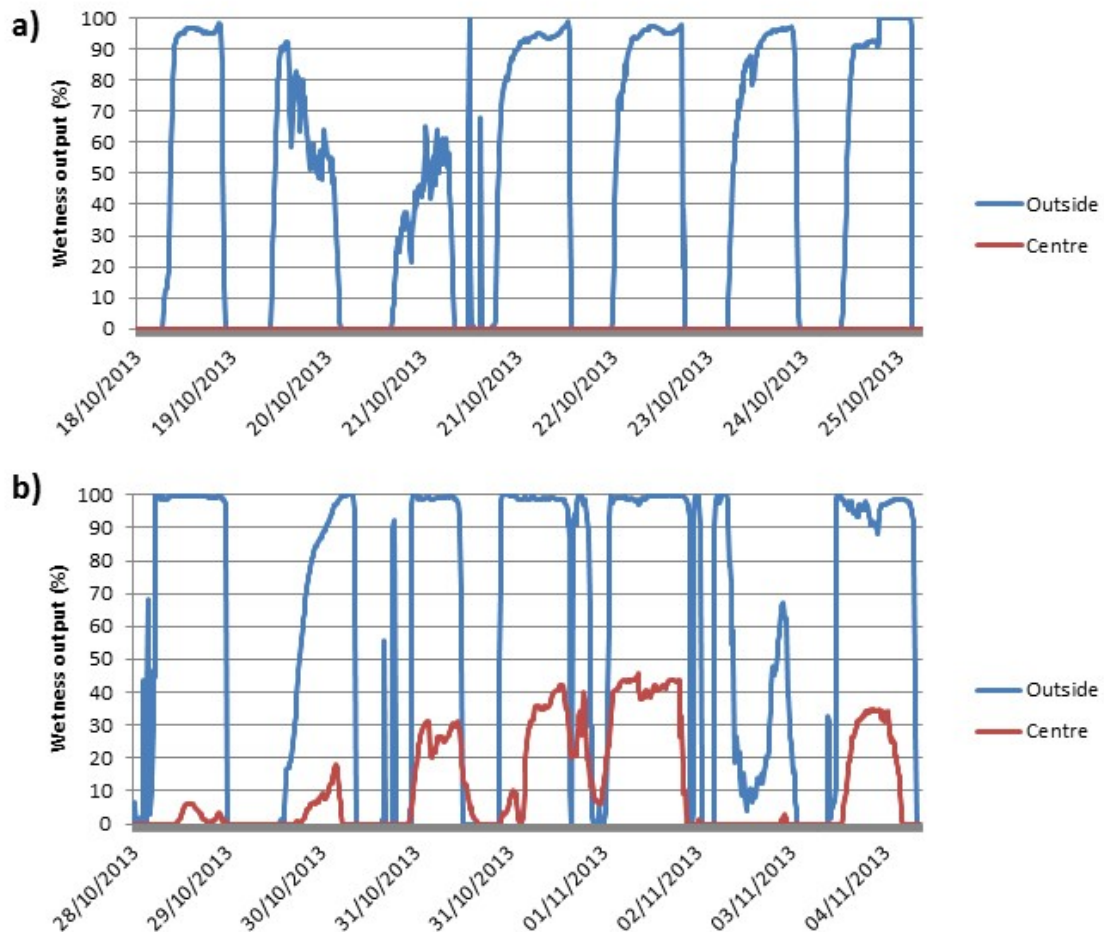
Figure 9.16 illustrates the mean percentage of initial dry weight in Globigerina and Coralline samples in Malta and at Witney on the days the measurements were taken. In general, the moisture content of the samples placed outside the shelter at Witney was higher than the ones placed inside during autumn and winter, especially for Globigerina stones. The moisture content in the samples in Malta was kept very low during the whole year. However, the reduced number of data collected in Malta makes it difficult to determine a clear trend in the moisture content changes during the year of record.



**Figure 9.16:** Means of the difference between weight and initial dry weight expressed as percentage of initial dry weight (%) for Globigerina (GL) and Coralline (CO) samples a) in Malta and b) at Witney between August 2013 and July 2014 (n=4 in each position)

Wetting events were monitored with leaf wetness sensors and time-lapse cameras. They were placed inside and outside the shelters for a week at each site in October 2013. They were synchronised to record information every 10 minutes. Figure 9.17 a) shows the differences in wetness percentage between outside and inside the shelter in Malta between 18/10/2013 and 25/10/2013. There were no wetting events recorded inside the shelter. However, there was a daily pattern of wetting events outside. Wetness went up to very high values, which can reach up to 100%, and decrease to 0% every day.

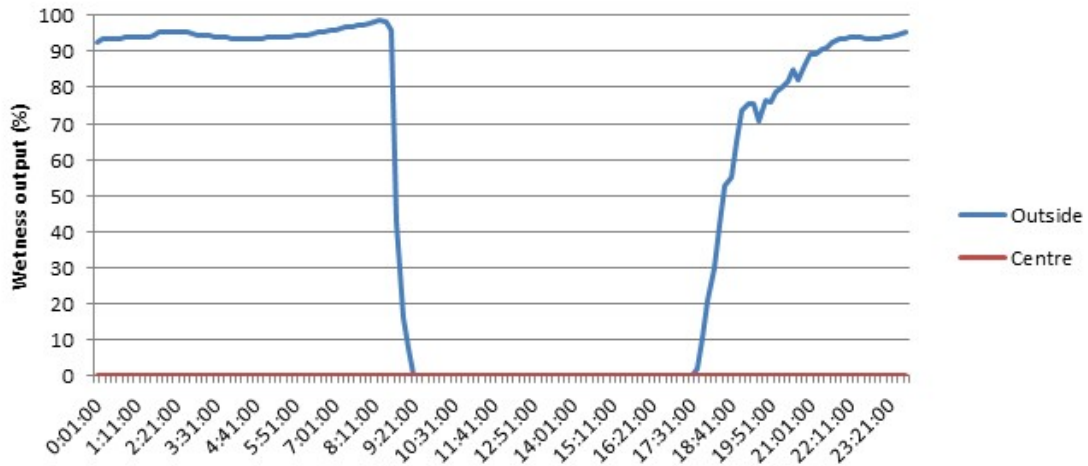
Figure 9.17 b) depicts the differences in wetness percentage between outside and inside the shelter at Witney between 28/10/2013 and 04/11/2013. In contrast to Malta, there were not only daily wetting events outside but also inside the shelter. However, the percentage did not reach the high values recorded outside.



**Figure 9.17:** Wetness output (%) of the sensors located outside and at the centre of the shelter in a) Malta between 18/10/2013 and 25/10/2013 and b) at Witney between 28/10/2013 and 04/11/2013

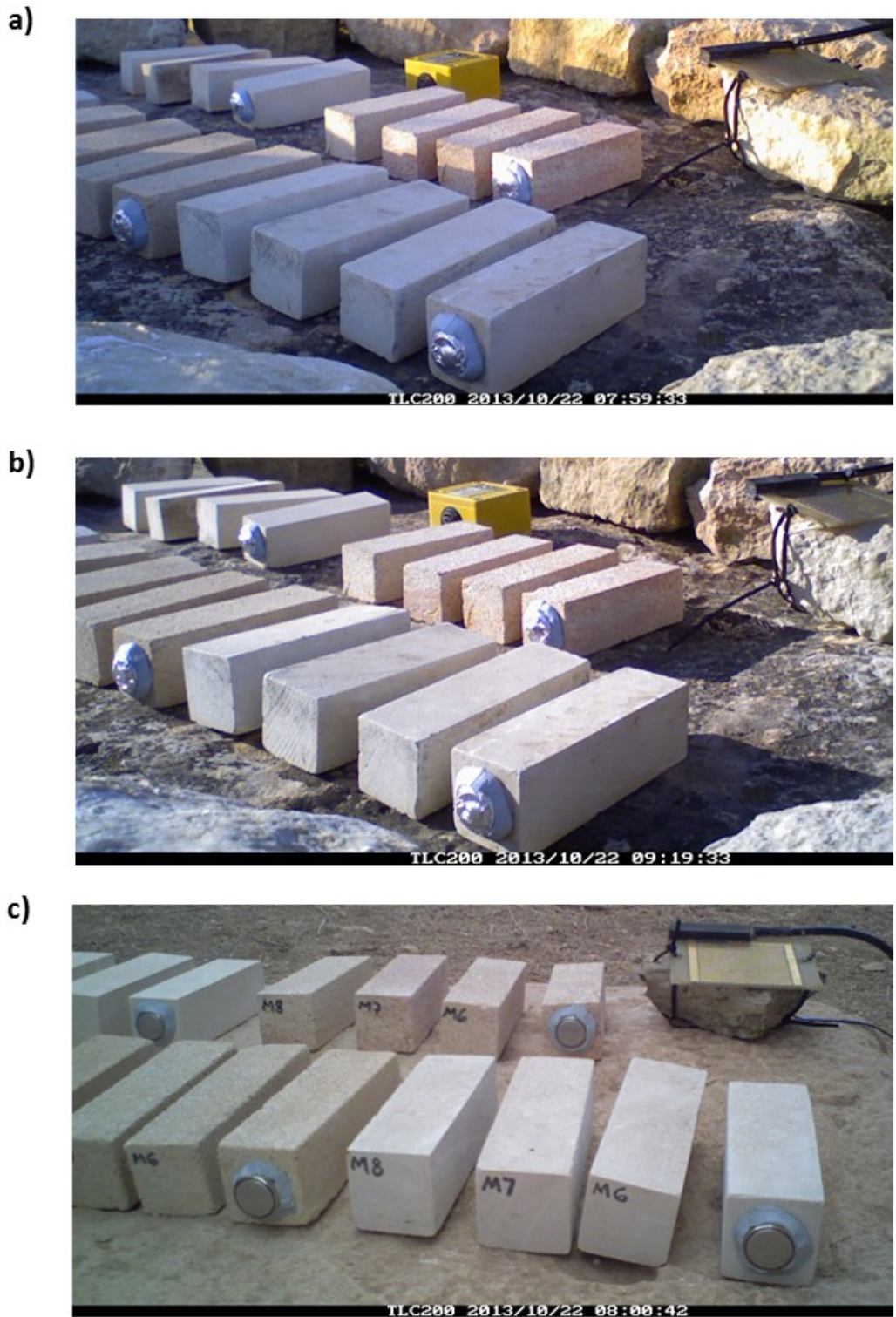
A representative day per site was chosen to examine the degree of surface wetness in Globigerina and Coralline samples placed inside and outside the shelter. It did not rain during those days, therefore, the wetting events are probably mainly due to condensation. Figure 9.18 illustrates the wetness output of the sensors inside and outside the shelter in Malta on the 22/10/2013. Wetting of the surface is more likely to

occur in samples placed outside the shelter at night. During the day, the wetness percentage is reduced to a minimum.



**Figure 9.18:** Wetness output (%) outside and at the centre of the shelter in Malta on the 22/10/2013

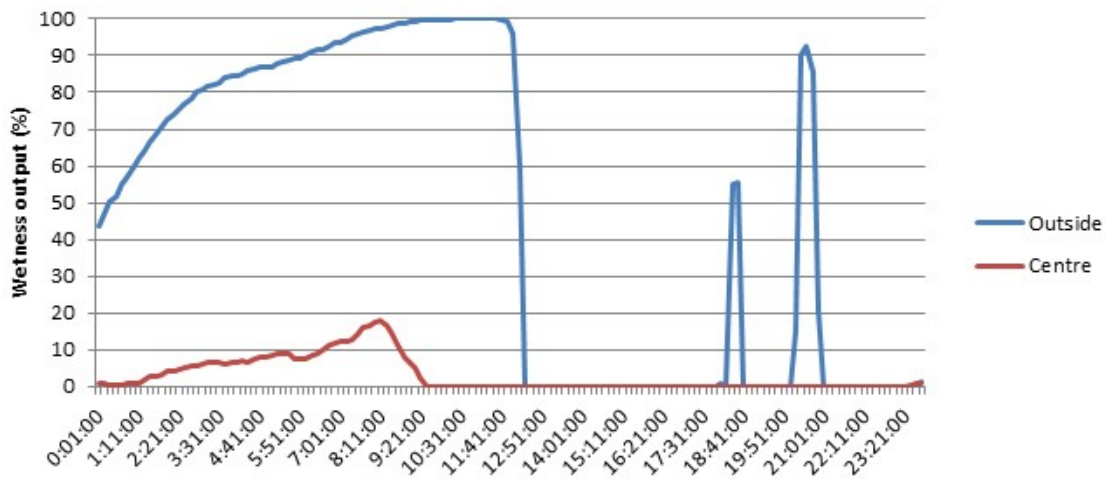
Figure 9.19 shows the images recorded in Malta by the time-lapse camera on the 22/10/2013. Figure 9.19 a) shows the samples outside the shelter at 7:59 am, when the wetness sensor recorded 100%. Figure 9.19 b) depicts the samples outside the shelter at 9:19 am, when the wetness sensor recorded 0%. Figure 9.19 c) shows the samples inside the shelter at 8:00 am, when the wetness sensor recorded 0%. In the pictures it is possible to see greater saturation in stone colours of the samples placed outside around 8 am, which may indicate high moisture contents. At about 9:20 am, the sun hit the samples completely and they would have started drying out. This corresponds to the time the wetness output dropped to 0%. On the other hand, samples inside the shelter do not show any evidence of condensation.



**Figure 9.19:** Pictures from the time-lapse camera taken in Malta on the 22/10/2013. a) Samples outside the shelter at 7:59 am, b) samples outside the shelter at 9:19 am and c) samples inside the shelter at 8:00 am

Figure 9.20 shows the wetness output of the sensors inside and outside the shelter at Witney on the 30/10/2013. The wetness values outside the shelter were very high at

night and up to midday, with some peaks during the day probably due to accidental wetting. The presence of near trees in the surroundings can make this area very wet until the sun reaches the samples completely. On the other hand, wetness inside the shelter is much lower and condensation is reduced to early morning.

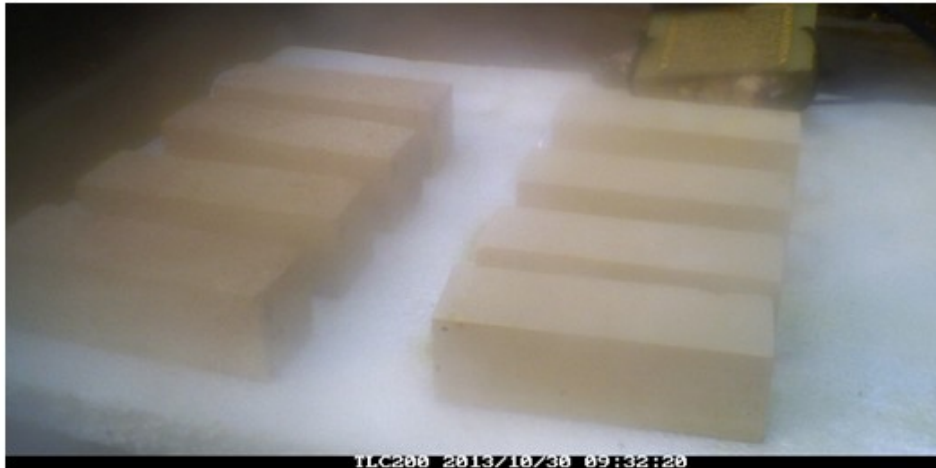


**Figure 9.20:** Wetness output (%) outside and at the centre of the shelter at Witney on the 30/10/2013

Figure 9.21 shows the images recorded by the time-lapse camera at Witney on the 30/10/2013. Figure 9.21 a) shows the samples outside the shelter at 9:32 am, when the wetness sensor recorded 100%. Figure 9.21 b) shows the samples outside the shelter at 12:22 pm, when the wetness sensor recorded 0%. Figure 9.21 c) shows the samples inside the shelter at 9:22 am, when the wetness sensor recorded 2.3%. The condensation of the camera lens does not allow observing changes in the appearance of the samples outside the shelter, although the ambient conditions might have been very wet for condensation to occur. Around midday, the samples outside the shelter were very wet in comparison with those placed inside. The sensors might have recorded wetness values similar to those experienced by the stone surfaces but they do not take into account moisture content at depth and evaporation. Condensation

could have happened inside the shelter but the lower wetness levels do not make it impossible to be visible to the naked eye.

a)



b)



c)



**Figure 9.21:** Pictures from the time-lapse camera taken at Witney on the 30/10/2013. a) Samples outside the shelter at 9:32 am, b) samples outside the shelter at 12:22 pm, and c) samples inside the shelter at 9:22 am

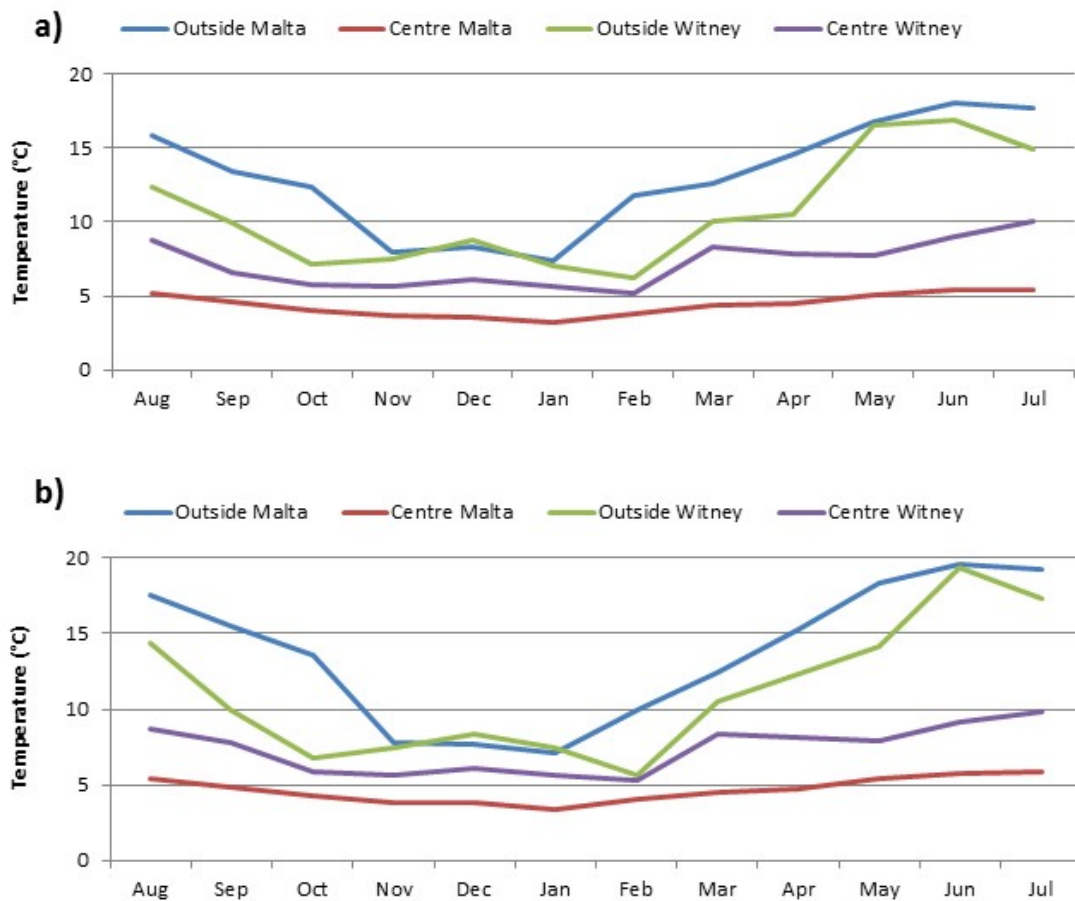
There are daily wetting events outside the shelter in Malta and at Witney. High surface wetness values were recorded at night until the sun dried out the samples in the morning. In the case of Witney, this takes place at midday as the trees in the surroundings do not allow the sun to hit the samples earlier. Therefore, the samples outside the shelter at Witney are kept wetter for longer. Condensation can occur inside the shelter in early morning but the wetting event is shorter and reduced if compared with outside. There are also seasonal wetting cycles. Moisture content of the samples placed outside the shelter at Witney was higher than the ones placed inside during autumn and winter, especially for *Globigerina* stones. The moisture content in the samples in Malta was lower than at Witney at both inside and outside the shelter. The drying process could have been shorter in Malta because of the higher temperatures. In addition, it seems that the leaf wetness loggers indicate the moment when the stone surface could have started drying out. However, the process could be longer due to the moisture accumulated inside the stone during the night.

#### **9.3.8. Surface temperature**

Near surface temperature data was used to determine the effect of the shelter on two physical weathering mechanisms: surface temperature fluctuations and frost events in the stone blocks. Diurnal surface temperature fluctuations were quantified as differences between maximum and minimum temperatures per day and were calculated for *Globigerina* and Coralline samples located inside and outside the shelter in Malta and at Witney.

Figure 9.22 a) shows the monthly means of daily surface temperature ranges on *Globigerina* samples located outside and under the central part of the shelter in Malta

and at Witney. In general, the difference between maximum and minimum temperatures per day increased during spring and summer, mainly outside the shelter. However, the difference in diurnal temperature fluctuations between inside and outside the shelter is greater in Malta than at Witney. On the other hand, surface temperature ranges inside the shelter are more stable in Malta.



**Figure 9.22:** Monthly means of daily surface temperature ranges on a) Globigerina and b) Coralline samples located outside and the centre of the shelter in Malta and at Witney

A study carried out at Hagar Qim with an infrared thermal imaging camera before the site was sheltered (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006) detected greater diurnal surface temperature differences on the monument stones than the ones recorded in this study for

Globigerina and Coralline samples located outside the shelter (see Table 9.6).

Differences in the method used and size of samples could be the reason.

**Table 9.6:** Mean daily temperature differences on Globigerina site monoliths at Hagar Qim before sheltering (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006)

<b>Autumn</b>	<b>Winter</b>	<b>Spring</b>	<b>Summer</b>
29°C	42°C	37°C	23°C

Figure 9.22 b) illustrates the monthly means of daily surface temperature ranges on Coralline samples placed outside and centre of the shelter in Malta and at Witney. The trends are very similar to the ones observed in Globigerina blocks.

A multilevel linear model with day as random effect for diurnal temperature ranges was fitted to find out if the differences between positions, stone types and sites are statistically significant. Normality and homoscedasticity of the residuals was obtained by log-transforming the response variable. The results showed that the daily temperature ranges due to stone type alone, after adjustment for position and site, are smaller for Globigerina samples than Coralline (Table 9.7). On average, the daily temperature range in Coralline samples is 1.036 times greater than in Globigerina. However, there is no significant difference for stone type in the interaction with sites and positions ( $t=0.854$ ,  $DF=2312$ ,  $P=0.393$ ). This means the differences between stone types are consistent independently of position or site. In addition, the results showed that the daily temperature ranges in the samples placed outside the shelter were significantly greater than inside in both Malta (Table 9.7) and at Witney (Table 9.8). In addition, the difference in daily surface temperature in samples located outside the shelter was significantly greater in Malta than at Witney (Table 9.7). On average, the

temperature range was 1.32 times bigger in Malta. However, the temperature range for samples located inside the shelter was smaller in Malta than at Witney (Table 9.7).

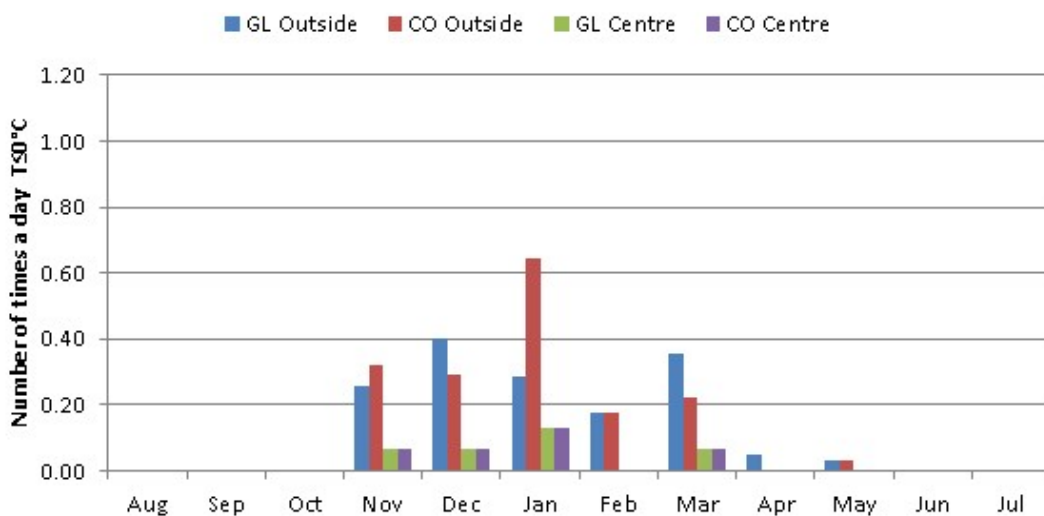
**Table 9.7:** Results of the multilevel linear model with day as random effect for the diurnal surface temperature range values. Reference position, stone type and site: outside, Globigerina and Malta

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	2.491	0.022	2315	112.949	<0.001
Centre	-1.036	0.016	2315	-61.775	<0.001
Witney	-0.276	0.017	2315	-15.814	<0.001
Coralline	0.035	0.012	2315	2.967	0.003
Position Centre: Site Witney	0.701	0.024	2315	29.085	<0.001

**Table 9.8:** Results of the multilevel linear model with day as random effect for the diurnal surface temperature range values. Reference position, stone type and site: outside, Globigerina and Witney

Position	Value	Std.Error	DF	t-value	P-value
(Intercept)	2.214	0.022	2315	100.618	<0.001
Centre	-0.335	0.017	2315	-19.356	<0.001

Additionally, the number of times stone surface temperatures went below 0°C per day was used to estimate the risk of frost weathering in the different positions.



**Figure 9.23:** Monthly mean of number of times surface temperatures of Coralline (CO) and Globigerina (GL) samples placed outside and inside the shelter at Witney went below 0°C in a day

There were no freezing temperatures in Malta during the year of record. The monthly mean of number of times Globigerina and Coralline samples had temperatures below 0°C per day at Witney is illustrated in Figure 9.23. Stone samples located outside the shelter showed more freezing events than the samples inside from November to May, especially in January.

The number of times the surface temperature went below 0°C per day at Witney during the year of record was fitted as the response of a 2-level Poisson Generalised Linear Model (GLM) with position and stone type as explanatory variables. Results showed that there were higher probability of having fewer freezing events inside the shelter than outside but the difference is not significant. Results are shown in Table 9.9.

**Table 9.9:** Results of the Poisson Generalized Linear Model for number of freezing events per day. Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 '' 1

Reference: Outside of the shelter and Coralline stone	Estimate	Std. Error	z value	Pr(> z )	Significance
(Intercept)	0.358	0.123	2.918	0.003	**
Position Centre of the shelter	-0.156	0.275	-0.567	0.570	
Stone type Globigerina	0.029	0.199	0.150	0.880	

## 9.4. Discussion and Conclusions

Globigerina and Coralline stone blocks presented changes in their physical properties after a year of exposure outside and under the central part of the shelter in Malta and at Witney. Some results were as expected (Table 9.3 and Table 9.4) whereas others differed from the predictions. The most relevant results are related to weight and colour changes and temperature fluctuations. Table 9.10 and Table 9.11 summarise the results obtained from the analysis of dry weight, elasticity, hardness, UPV, dE\*ab

and macroscopic and microscopic changes as well as moisture content, daily temperature fluctuations and number of frost events.

**Table 9.10:** Results of changes in key indicators of deterioration after a year of exposure in Malta. The degree of change refers to the mean values of the samples (n=4) and when it is significantly different to the other location it is marked in red. The trend of the change is indicated by an arrow in the case of dry weight, elasticity hardness and UPV change\*.

MALTA		Outside	Centre
Globigerina	Dry weight	- ↓	Low ↓
	EMOD	Medium ↑	- ↑
	Hardness	- ↑	- ↑
	UPV	- ↑	- ↓
	dE*ab	High	High
	Macroscopy	High	Medium
	Microscopy	High	Medium
	Moisture	-	-
	T fluctuation	High	Low
	Frost	-	-
Coralline	Dry weight	Low ↑	- ↓
	EMOD	High ↑	- ↓
	Hardness	High ↑	- ↑
	UPV	- ↑	- ↑
	dE*ab	High	High
	Macroscopy	High	Medium
	Microscopy	High	Medium
	Moisture	-	-
	T fluctuation	High	Low
	Frost	-	-

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change: HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=not noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For T fluctuations (mean diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For all measurements “-” means that change is close to the change in controls (Table 3.9).

**Table 9.11:** Results of changes in key indicators of deterioration after a year of exposure at Witney. The degree of change refers to the mean values of the samples (n=4) and when it is significantly different to the other location it is marked in red. The trend of the change is indicated by an arrow in the case of dry weight, elasticity hardness and UPV change.

WITNEY		Outside	Centre
Globigerina	Dry weight	Low ↓	Low ↓
	EMOD	- ↑	- ↓
	Hardness	- ↓	- ↓
	UPV	Low ↓	Low ↑
	dE*ab	High	Low
	Macroscopy	High	Medium
	Microscopy	Medium	Low
	Moisture	High	-
	T fluctuation	High	Medium
	Frost	Medium	Low
Coralline	Dry weight	Low ↓	Low ↓
	EMOD	- ↑	- ↓
	Hardness	Medium ↓	- ↓
	UPV	- ↑	- ↑
	dE*ab	High	Medium
	Macroscopy	High	Medium
	Microscopy	Medium	Low
	Moisture	Medium	-
	T fluctuation	High	Medium
	Frost	Medium	Low

\* For dry weight change: HIGH=above 1%, MEDIUM=1-0.5%, LOW= below 0.5%. For EMOD, hardness and UPV: HIGH= difference above 10%, MEDIUM=10-5%, LOW=below 5%. For colour change: HIGH=above 3.8 dE\*ab, MEDIUM=3.8-1.8, LOW=below 1.8. For macroscopic and microscopic changes: HIGH: very noticeable, MEDIUM=noticeable, LOW=not noticeable. For moisture content: HIGH=above 115% Wdry, MEDIUM=115-105%, LOW=below 105%. For T fluctuations (mean diurnal T ranges): HIGH=above 10°C, MEDIUM=10-5°C, LOW= below 5°C. For number of frost events in a year: HIGH= above 80, MEDIUM=80-20, LOW= below 20. For all measurements “-“ means that change is close to the change in controls (Table 3.9).

The first objective of this chapter was to examine to what extent the open shelters at Hagar Qim and the Bishop’s Palace affected the degree of deterioration of the stone blocks. The results are analysed together with the moisture content and surface temperature results, which refers to objective number 2.

The main environmental cause of stone decay in Malta seems to be the great temperature ranges outside the shelter, mainly in spring and summer, probably due to the high maximum temperatures. However, the shelter is effective in reducing the difference between maximum and minimum temperatures per day (Figure 9.22). It is also effective in reducing wetting events and subsequently, biological growth (Figure 9.16). On the other hand, the shelter at Witney is also reducing temperature ranges in spring and summer. However, the main environmental causes for stone decay at Witney are frost and wetting events, mainly in autumn and winter. At that time, stone samples are wetter for longer and the minimum temperatures are low. As a result, biological growth appears on the surface and water can freeze in the pores causing physical damage, mainly in the softer Globigerina, which also showed higher moisture content than Coralline. All samples located outside the shelter at Witney lost weight, in particular Globigerina (Figure 9.1). This is also visible at a surface level with signs of erosion and increase in surface roughness (Figure 9.15).

As there are no great differences in weight lost by Globigerina and Coralline samples between inside and outside the shelter in Malta, it is possible to consider that the great temperature ranges outside have a low effect on weathering. However, it is also possible to assume that there is an increase in weight due to, for example, accumulation of salts, and the combined effect with temperature fluctuations resulting in a final slight change of weight. In fact, NaCl was found in samples collected from the ruins before sheltering the site (Consiglio Nazionale delle Ricerche and Istituto di Scienze dell'Atmosfera e del Clima, 2006). In addition, Coralline samples outside the shelter in Malta gained in weight and the increase in hardness in all of the samples but mainly in Coralline outside the shelter could be related to this process.

Therefore, great temperature ranges outside the shelter in combination with the effect of salts could be the main cause of stone decay in Malta. Although samples placed inside lost weight, the shelter reduced temperature fluctuations and could also have reduced the access of salt aerosols from the sea, minimizing the risk of physical weathering.

These results are in line with the main decay mechanisms identified in the ruins at Hagar Qim and the Bishop's Palace (Chapter 4). After a condition survey at Hagar Qim, cracking, scaling, alveolization and soiling were found to be relevant. The first three are related to physical weathering and salt weathering has been considered the main cause (Cassar, 2002). On the other hand, the main causes of decay at the Bishop's Palace were biocolonisation, detachment of material and soiling. In this case, physical weathering processes could be connected with freeze-thaw cycles.

Objective number 3 of this chapter was to determine how the shelters influence the nature of deterioration and soiling in the Globigerina and Coralline stone blocks. The results are analysed together with the moisture content and surface temperature (objective number 2).

Globigerina samples outside the shelter in Malta and at Witney changed more in colour than the ones inside. They turned darker and yellower. Coralline samples placed outside the shelter in Malta and at Witney became slightly more yellow than the ones inside, and in the case of Witney, darker. These changes are noticeable to the naked eye (Table 9.5). Although samples inside the shelter in Malta and at Witney had lower overall colour change than the samples outside, they present an increase in soiling, visible on the samples' microscopic pictures (Figure 9.14 and Figure 9.15) Soiling was

also identified as one of the main decay mechanisms at both sites (Chapter 4). In addition, there is no evident greening of the top horizontal surface of the samples, measured by changes in  $da^*$ . However, the macroscopic pictures of the samples show a visible greening on vertical faces of samples located outside in Witney and Malta (Figure 9.13). These areas presumably have longer wetting events as evaporation of the surface moisture is slower on shaded vertical surfaces.

Objective number 4 of this chapter was to find out if there were differences in the deterioration of the stone blocks depending on the site at which they were placed.

There is no difference in the weight changes in Globigerina and Coralline samples inside the shelter between sites. However, Globigerina blocks outside the shelter at Witney lost more weight than in Malta. In addition, Coralline samples outside the shelter at Witney lost weight whereas in Malta they gained in weight. These dissimilarities could be related to different decay mechanisms. All Globigerina blocks in Malta changed in colour more than the samples at Witney whereas colour change in Coralline blocks is similar at both sites after a year. Globigerina blocks outside the shelter in Malta changed in colour to a greater extent. Stone colour changes might indicate natural aging and the variations could be due to different environmental conditions.

The shelter at Witney is reducing stone surface temperature fluctuations inside but the one in Malta is even more effective despite the great temperature ranges outside. Frost events are only important for samples located at Witney.

The degree of change depended on the type of stone, with Globigerina being more vulnerable. Globigerina limestone has lower EMOD and hardness values than

Coralline. It also shows higher ultrasonic velocity values, which indicates lower density and higher porosity. This is connected with the information obtained through the study of the water absorption; open porosity and apparent density in Chapter 3. Globigerina samples could be a good option for monitoring not only change in appearance (colour and macroscopic and microscopic changes) but also physical weathering in different environments.

In relation to the methods used, dry weight is a good option to compare physical weathering in different locations and sites and colour change is a good alternative for biological colonisation and soiling. As we have seen in Chapter 6, elasticity, hardness and UPV would need a longer exposure time to obtain significant results, but they will complete the information about physical weathering processes. In addition, there could be some limitations in surface temperature measurements as the method used (ibuttons loggers) only detects near-surface changes.

Leaf wetness sensors are not effective at monitoring wetting events in terms of duration, as it depends on the moisture content of the stone samples. However, in combination with time-lapse cameras, they are a good method for monitoring moisture content changes on stone samples and calculating the time when the horizontal surface of the samples will start to dry out (see section 9.3.7).

## **10. DISCUSSION AND CONCLUSIONS**

This chapter summarises the results obtained in previous sections and evaluates the proposed methodology for shelter assessment. The findings from the different aspects of the research are connected to answer the stated objectives in Chapter 1. In addition, key results of the research are identified in the conclusions.

Recommendations in the literature called for a critical review of existing shelters, especially to determine their role in deterioration of heritage sites, and the development of methodologies to guide shelter assessment. In addition, the study of shelters with similar typology and research on possible indicators of decay were encouraged (see section 1.3.3). In response, this study has established scientific evidence of the influence of micro-environmental conditions inside and outside shelters on the deterioration of bioclastic limestone decay. In addition, this research has evaluated in-depth the effects of two lightweight, open shelters in two climatic contrasting conditions. The design of a methodology for shelter assessment based on low-cost and easily carried out monitoring methods, which take into consideration not only environmental factors and visual assessments but also a scientific evaluation of stone decay, has been proposed. The use of stone blocks made of the same type of limestone provided information on the decay potential of different parts of the ruins and the relative effectiveness of the shelters at different sites.

### **10.1. Addressing objective number 1**

This section presents an assessment of the effects of the shelter at the Bishop's Palace (Witney, England) on the preservation of limestone remains. Environmental conditions inside, outside and on the periphery of the lightweight, open shelter at the Bishop's

Palace were assessed to determine the effectiveness of the shelter on the preservation of the archaeological remains (see Chapter 5 and the section related to Witney in Chapter 8). A representative wall inside the shelter was also studied to determine which areas of the site are at higher risk of decay (Chapter 5). In addition, deterioration processes outside and inside (NE, SW and the centre) of the shelter were identified and quantified using Chalk, Cotswold and Portland limestone blocks (Chapter 6). The exhaustive assessment was completed with a specific study on the effects of the shelter on dissolution, soiling and biological colonisation using Portland limestone tablets located under the central part of the shelter and outside (Chapter 7).

Temperature and RH fluctuations, solar irradiation and freezing events tended to be higher outside than in the centre and on the periphery of the shelter (see Figure 5.8, Figure 5.10 and Figure 5.11). The results showed that the Bishop's Palace would be exposed to more damaging conditions if the site were not sheltered. However, there were some unexpected results which indicate that the shelter could enhance decay on the periphery.

The peripheral areas of open shelters tracked the environment outside. Therefore, there is more likelihood of stone deterioration at the edge of the shelter than under the central part. However, the degree of deterioration on the periphery increases if the site does not have a suitable drainage system. In addition, an insufficient covering area could lead to an increase in temperatures on the periphery due to solar irradiation or a greater amount of wetting events due to for example, wind-driven rain. Possible inadequacies in the shelter, which might direct rain onto the ruins, were observed after a visual assessment of the site (see Chapter 4). This study has demonstrated that there was an increase in temperatures in this area in summer,

when the sun hit the ruins directly (Figure 5.4 and Figure 5.5), and there was more probability of having wetting events on the periphery than under the central part of the shelter and outside (Table 5.13). In addition, higher levels of RH on the periphery than in the centre and outside the shelter (section 5.3.4) could enhance biological growth. These results indicate that the overall protective effect of the shelter is reduced on the periphery and, this is highly relevant for sites in locations with high rainfall activity, such as England.

In relation to the site walls, the microclimatic conditions on the lower sections were found to be more stable than in the middle and on the top parts. However, the bottom parts tended to be wetter than the middle or top probably due to water rising from the ground (Chapter 5). Therefore, biocolonisation might become the main decay mechanism. On the other hand, frost or salt crystallisation events were more likely to happen on the top parts of the wall given that these areas evidence more variability in temperature and RH (see Figure 5.8, b and Figure 5.13, b). The microclimatic conditions on the middle section of the wall studied were closer to the bottom part. However, higher risk of decay is expected for areas slightly higher up on the wall. The decay risks for the middle sections of the ruined walls will depend on where the evaporation zone is exactly located.

Chalk, Cotswold and Portland limestone blocks under the shelter were less affected than the ones outside, although the shelter did not stop decay completely. Stone blocks located outside the shelter at the Bishop's Palace lost more weight than those located inside the shelter (Figure 6.1). These samples were wetter for longer (section 6.3.7) and were exposed to lower temperatures (section 5.3.1). Although the diurnal surface temperature differences were higher in summer (Figure 6.15), they probably

did not affect stone decay as much as the effect of the winter, especially frost events. Cotswold limestone changed significantly more in colour than Chalk and Portland limestone outside the shelter (Figure 6.5). In addition, Cotswold limestone and mainly Chalk were more affected by weight loss than Portland limestone. As was expected (see section 3.3.1), those stone types are more vulnerable to decay in temperate maritime climates. In addition, the limestone blocks placed inside the shelter changed less in colour (Figure 6.5) and showed fewer visual signs of physical weathering (section 6.3.6). However, blocks located at the NE edge of the shelter changed significantly more in colour than those in the centre or on the SW edge, becoming darker or less light (Table 6.9). This area could be affected by high constant RH values, represented by low surface temperature ranges (Table 6.10) and few frost events (Table 6.11). The NE edge of the site was selected as a monitoring location because biocolonisation was determined to be the main deterioration phenomena after a visual assessment of the remains (Chapter 4). Therefore, change in colour could be related to this process. However, no other difference was found between blocks inside the shelter (NE, SW, and centre).

Portland limestone tablets outside the shelter also lost more weight (Figure 7.5) and changed more in colour (Figure 7.1) than those located inside. They became darker and greener. As this is a relatively unpolluted site (Table 7.6), the change in colour in tablets outside the shelter could be of biological origin due to higher water availability. Biofilms could contribute to the loss of weight but dissolution of calcium carbonate and different microenvironmental conditions between the inside and the outside the shelter (Chapter 5) seems to be the main reason.

Salts tended to accumulate in sheltered tablets but, in comparison with the sites of the NMEP (Butlin et al., 1995), the amount of sulphates, nitrates and chlorides was lower than expected. In addition, there were no significant differences in NaCl crystallisation events, in terms of the number of times the RH crossed 75%, between the inside and the outside the shelter (section 5.3.4.2). Therefore, the risk of salt weathering is low.

The main purpose of the shelter was to exclude frost and extreme temperatures and minimise water entry (Chapter 4). Although freezing events were minimised, they occurred occasionally (Figure 5.10). The extreme temperatures were also reduced due to the shadow effect of the shelter. However, problems with the covering area of the shelter can make the ruins on the periphery and top parts of the wall more vulnerable to deterioration. Water entry from raining events is reduced but moisture on the ruins due to, for example, water uptake from the ground or condensation is very high, mainly on the periphery and bottom parts of the walls.

## **10.2. Addressing objective number 2**

This section presents a comparative assessment of the effects of the shelters at Hagar Qim (Malta) and the Bishop's Palace (Witney, England) on the preservation of limestone remains. Environmental conditions inside, outside and on the periphery of the lightweight, open shelters in Malta and at Witney were comparatively assessed to determine differences in their degree of protection (Chapter 8). In addition, deterioration processes were identified and quantified using *Globigerina* and Coralline limestone blocks outside and under the central part of the shelters (Chapter 9).

At Hagar Qim in Malta, temperature and RH outside the shelter fluctuated more than in the centre and on the periphery (Figure 8.7, a and 8.10, a). Additionally, the

temperature was more extreme outside the shelter than in the other two positions due to the higher maximum temperatures mainly in summer (section 8.3.1.1). These results demonstrate that Hagar Qim would be exposed to more damaging conditions if the site were not sheltered. However, temperature and RH on the periphery fluctuated more than under the central part (section 8.3.1.3 and 8.3.3.1) and a fault in the shelter design made temperatures increase on the periphery when the sun reached the ruins at specific times of the day in winter (Figure 8.6). This indicates that the ruins on the periphery are at higher risk of decay than those under the centre of the shelter. Furthermore, the shelter could even enhance salt weathering on the periphery and dust deposition under the central part of the shelter. This study has demonstrated that there were more NaCl crystallisation events on the periphery than under the central part of the shelter and outside because of the number of fluctuations around 75% RH (Table 8.9). This result is particularly relevant for coastal environments, such as Malta, where salt weathering could be aggravated because of the presence of marine aerosols. In addition, there was more dust deposition inside than outside the shelter (Table 8.14), probably due to the effects of the shelter on wind speed and turbulence.

The shelter at Hagar Qim is effective in reducing wetting events and subsequently, the possibility of biological growth on the ruins. However, alveolisation, often related to the action of salts, was found to be the main decay mechanism at the site after the preliminary visual assessment (Chapter 4). Globigerina and Coralline limestone blocks exposed inside and outside the shelter at Hagar Qim showed differences regarding change in weight (Figure 9.1). Results indicate that limestone blocks could be affected by a combination of physical weathering due to temperature fluctuations and accumulation of salts, mainly in samples located outside the shelter. In addition,

blocks placed outside had an increase in surface roughness, whereas inside they had an increase in soiling (section 9.3.6). Globigerina blocks placed outside changed more in colour than those inside, becoming darker and yellower, but there was no significant difference for the Coralline blocks (Figure 9.8), which could indicate a natural weathering process.

At the Bishop's Palace, there were more freezing events and temperature fluctuations outside than in the centre and on the periphery of the shelter. On the other hand, the periphery tended to have higher RH values than the centre and outside and an increase in temperatures in early afternoon during summer could be seen as a sign of a fault in the shelter design. These results corroborate the assessment undertaken in Chapter 5. A study on dust deposition showed that areas outside the shelter were more affected than those inside probably due to particles of biological origin from nearby trees.

Coralline and Globigerina limestone blocks outside the shelter at the Bishop's Palace lost more weight (Figure 9.1) and became darker in colour (Table 9.5) than those located inside. They also showed more signs of physical weathering, for example loss of grains in the case of Coralline samples and increase in surface roughness in Globigerina blocks (Figure 9.15). Stone blocks outside the shelter at Witney seem to be more affected by decay processes, such as biocolonisation, than those inside.

The shelter at Witney reduced temperature fluctuations inside but the one in Malta was even more effective despite the great temperature ranges outside (Figure 8.7). Frost events were only important for samples located at Witney. The effects of solar radiation were less extreme at Witney, although the shelter was still more distinctively

effective in summer. This could indicate that lightweight, open shelters are more effective at decreasing temperatures by reducing direct solar radiation than protecting the shelter against lower temperatures and high RH values. Although the shelters at both sites reduced the effect of the environment outside, the level of protection from lightweight, open shelters tends to increase in climates with higher mean temperatures. Differences in weight change in Globigerina and Coralline blocks are related to differences in decay mechanisms at the two sites. The blocks outside the shelter at the Bishop's Palace have most probably been more affected by frost weathering and biocolonisation whereas in Malta, salt weathering is probably the dominant process. Therefore, minimum temperatures, RH and moisture content are key parameters for shelter assessment in temperate maritime climates while salt accumulation and temperature extremes and fluctuations are important at Mediterranean sites. Globigerina limestone was the most affected by weight loss at both sites (Figure 9.1), indicating that this stone type is more vulnerable to physical weathering than Coralline in both Mediterranean and temperate maritime climates. Globigerina limestone also changed more in colour than Coralline in Malta. However, Coralline limestone changed more in colour than Globigerina at Witney, perhaps because it is more susceptible to biocolonisation (Figure 9.8).

At both sites, it is likely that rain washed deposits, dust and salts off stone samples located outside the shelters, while these tended to accumulate on the sheltered samples. However, at coastal sites in the Mediterranean basin such as Hagar Qim, lower precipitation and the presence of marine aerosols also encourage the accumulation of salts in the stone outside the shelter, observed as an increase in weight (Figure 9.1). In addition, if the open shelter reduces wind-speed and/or

increases turbulence, dust from the surroundings can accumulate on horizontal surfaces inside the shelter (section 8.3.4). In urban environments such as the Bishop’s Palace, the amount of decay depends highly on the concentration of pollutants in the air. In addition, low dust deposition inside the shelter could indicate low wind speeds. Although soiling was visible in the microscopic pictures of stone blocks located inside the shelter at both sites (Figure 9.14 and Figure 9.15), the different surroundings (e.g. trees, main roads, arid environments) of the sites could contribute to the nature of deposition.

### 10.3. Addressing objective number 3

This section presents an evaluation of the methodology used to address objectives 1 and 2. The proposed methodology is based on the use of stone blocks and tablets for exposure trials, an established technique in the field of geomorphology but adapted to determine the effectiveness of open shelters on the preservation of limestone remains at archaeological sites. A summary of benefits and drawbacks is shown in Table 10.1

**Table 10.1:** Advantages and disadvantages of the methodology used in this study

<b>Advantages</b>	<ul style="list-style-type: none"> <li>• Non-destructive for the ruins</li> <li>• More information than studying the ruins directly</li> <li>• Rapid results (early-warning method to detect decay)</li> <li>• Greater variety of techniques (destructive and non-destructive)</li> <li>• Stable conditions for measurements if taken to a laboratory</li> <li>• Possibility of having replicates for strong statistical results</li> <li>• Suitable for sites with low budgets</li> <li>• Suitable to be undertaken by non-experts</li> <li>• Adaptable by choosing different stone types or analytical techniques</li> <li>• Different positions with simultaneous monitoring of decay</li> <li>• No necessity to close the site to the public (samples are small and discreet)</li> <li>• Comparisons of sites/environments possible through the use of the same materials</li> </ul>
<b>Disadvantages</b>	<ul style="list-style-type: none"> <li>• May be difficult to match decay mechanisms seen in the stone samples with those on the ruins because of previous weathering, interventions, exact stone type, etc</li> <li>• Sample size could be too small to accurately represent conditions of the ruins</li> <li>• Samples can be stolen/lost</li> </ul>

This study has proven that a wide range of microclimatic conditions can be determined by just monitoring temperature and RH. Calculating the number of freezing and NaCl crystallisation events are also an effective method to determine differences between positions and these data can be extracted easily from the temperature and RH readings. In addition, hygrochrons are a simple and inexpensive method to obtain this information. The monitoring can be done simultaneously at different locations allowing comparisons. However, there are some limitations in surface microclimatic measurements using hygrochrons as they only detect near-surface changes. Wetness events are especially difficult to monitor. The wetness loggers are not as effective as dew point temperature calculations at finding out if condensation happened on the stone surface. However, they are good in combination with other techniques, such as time-lapse cameras, and additional information about duration and frequency of wetting events can be obtained. Self-adhesive patches are a suitable method to monitor dust deposition and obtain information in a short time period.

Small blocks and tablets are easy to transport, discreet and, in general, need shorter exposure times to give results. In general, stone samples with very rough surfaces and a heterogeneous surface colour increase the variability of baseline data and are not good indicators of decay. Stones with low apparent density, high water absorption and high open porosity such as Chalk and Globigerina limestone are likely to weather after only a short time in situ. Stones with higher apparent density but which are fine-grained, such as Portland limestone, are also good indicators of decay but the time of exposure needed to obtain significant results may be long. The techniques used in this study were selected to monitor a wide variety of physical, chemical and biological weathering processes.

Table 10.2 summarises the pieces of equipment used in this study for the monitoring of microclimatic conditions. A summary of the techniques used to determine stone decay in the samples is presented in Table 10.3. Advantages and disadvantages of the methods and parameters addressed are included in both tables. An overall evaluation refers to the recommendations of the author after taking into consideration the simplicity of use and the results obtained.

**Table 10.2:** Summary of the techniques used in this study for microclimatic monitoring

	<b>Equipment</b>	<b>Purpose</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Overall</b>
<b>Ambient T and RH</b>	Hygrochrons	T and RH changes (fluctuations and extremes)	Discreet, continuous monitoring, easy to obtain other indicators (i.e. frost events) from these data, can be set up for simultaneous monitoring at different locations	Data loss when malfunction occurs, errors when RH is constantly very high	✓
	<b>Dust</b>	Self-adhesive film	Deposition (amount and type)	Low cost, easy to use, can be set up for simultaneous monitoring at different locations	Only valid until saturation of film
<b>Condensation</b>	Wetness logger	Wetting events (amount and frequency)	Continuous monitoring, useful with rain events (but only for comparisons), extra information obtained when used with cameras	It needs calibration to match wetness levels on the ruins, no accurate with condensation	
	Hygrochrons (T and RH)	Calculation of dewpoint T to determine condensation	Discreet, continuous monitoring, can be set up for simultaneous monitoring at different locations	Requires accuracy in temperature and RH measurements	
	Time-lapse camera	Moisture content (by saturation in colours) and raining events	Continuous monitoring, easy to use, can be set up for simultaneous monitoring at different locations	Qualitative, only suitable for short periods	✓
<b>Air pollution</b>	Diffusion tubes	SO <sub>2</sub> and NO <sub>2</sub> content	Easy to use, precise, can be set up for simultaneous monitoring at different locations	Expertise needed to prepare them or a cost to analyse them	✓
<b>Rain acidity</b>	pH meter	Rain water pH	Easy to use	A relatively large amount of rain taken during the same event is needed, and analysis needs to be carried out soon after collection	✓

**Table 10.3:** Summary of the techniques used in this study for the monitoring of stone property changes

	<b>Equipment and purpose</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Overall</b>
<b>Weight</b>	Balance: material loss/ deposition	Precise, easy to use, low cost, can detect changes in short time periods, non-destructive	Highly affected by handling errors, laboratory conditions and dried samples needed	✓
<b>Elasticity</b>	Grindosonic: change in EMOD (increase in pores and inner cracks)	Easy to use, non-destructive	Only good for very homogenous stones, more than 1 year of exposure needed for significant results, influenced by environmental conditions, samples of specific shape needed, high variability between replicates	
<b>Hardness</b>	Equotip: change in surface hardness (weathering /deposition)	Easy to use, field work equipment	Many measurements needed (large sample surfaces), micro-destructive, more than 1 year of exposure needed for significant results, influenced by environmental conditions, high variability between replicates	
<b>UPV</b>	Pundit: change in UPV (increase in pores and inner cracks)	Easy to use, field work equipment, non-destructive	Stain samples, no good for samples with irregular surfaces, more than 1 year of exposure needed for significant results, influenced by environmental conditions, dried samples needed, high variability between replicates	
<b>Colour</b>	Spectrophotometer: colour change (soiling/ biofilms)	Precise, easy to use, field work equipment, non-destructive	Influenced by environmental conditions	✓
<b>Visual changes</b>	DSLR camera and USB microscope: Surface erosion/ soiling	Easy to use, field work equipment, non-destructive, good for before/after	Only visible changes, low magnification	✓
<b>Surface T</b>	Hygrochrons: T changes (fluctuations and extremes)	Discreet, continuous monitoring	Only near surface temperature obtained, data loss when malfunction occurs, errors when RH is constantly very high	
<b>Moisture</b>	Field balance: moisture content (weight)	Precise, easy to use, low cost, non-destructive	Only spot measurements obtained, affected by wind	✓
	FMW meter: moisture content	Easy to use, good correlation with weight, low cost, non-destructive	Only spot measurements obtained, no good for high moisture content, small changes are difficult to detect	✓
<b>Salts</b>	Ion chromatography: salt content (amount and type)	Precise	Requires preparation of samples (time consuming and expertise required), micro-destructive	✓

Dry weight change is a good option for comparing physical weathering at different locations and sites. It is suitable for sites with low budgets and significant results might be obtained in short exposure times. Elasticity, hardness and ultrasonic pulse velocity are potentially good indicators of physical weathering. However, longer exposure times than a year or greater blocks might be needed. In addition, colour change is a good alternative for monitoring biological colonisation and soiling.

#### **10.4. Suggestions for future research**

This research has addressed a broad variety of problems related to shelters at archaeological sites but there are some areas that would benefit from future research. This section identifies a number of topics worthy of development. Different stone types could be tested under the same shelters used as field sites in this research in order to widen the choices for indicators of decay in Mediterranean and temperate maritime climates. The advantage of using the same case study sites is that previous results can be compared with the new ones and this could clarify the effects of shelters over time. Additionally, lightweight open shelters at sites with different climates could be studied using similar methods to create a broad database. The limitations or benefits of this type of shelter located in different environmental conditions could help heritage managers to decide the best option for the protection of their archaeological sites. In addition, studies with longer exposure times (over 2 years) could help to determine if field techniques such as the Equotip, Pundit or Grindosonic can provide useful additional information.

## 10.5. Conclusions

The aim of this study was to provide the first rigorous scientific assessment of the effect of lightweight, open shelters on bioclastic limestone deterioration at archaeological sites. Open lightweight shelters may be a suitable solution for the protection of archaeological sites as long as their effect on the preservation of the remains is assessed. Carefully chosen and monitored stone blocks and/or tablets in conjunction with low-cost environmental monitoring have been demonstrated in this study to provide a cost-effective and efficient methodology for shelter assessment.

This research has demonstrated that lightweight, open shelters do not exclude environmental factors of stone decay completely as they are open structures influenced by the environment outside. The periphery of the shelter and top parts of walls have a higher risk of decay as they tended to experience the most variable microclimatic conditions. On the other hand, the centre of the shelter can be affected by an increase in soiling and dust deposition due to a reduction of wind speed and increase in turbulence inside the shelter. However, this research has found that temperature and RH fluctuations inside the shelter are reduced. Therefore, the impact of decay factors, such as dry deposition of airborne pollutants, is minimised.

The research has confirmed that open shelters are effective measures to moderate microclimatic conditions not only in Mediterranean but also in temperate maritime climates. Biocolonisation and frost weathering were found to be the main causes of decay at the Bishop's Palace (Witney) whereas salt weathering seems to be an important factor in stone deterioration at Hagar Qim (Malta). The research illustrated that shelters minimise those processes. Nevertheless, the main function of lightweight,

open shelters has proven to be the reduction of temperature extremes and fluctuations creating a shade effect inside. This makes these types of shelters more effective at Mediterranean sites than in temperate maritime climates. This study has also found that, on the periphery, variable environmental conditions in Malta and high levels of RH at Witney could enhance weathering (salt crystallisation events and biocolonisation respectively).

This research has demonstrated that there is no need to study ruins directly to obtain information about deterioration of stone under lightweight, open shelters. Stone samples (blocks and tablets), provide a rapid, non-invasive method to monitor deterioration and have been found to indicate decay after only a year of exposure. Stones with low apparent density, high water absorption and high open porosity such as Chalk and Globigerina limestone, as well as fine-grained stones such as Portland, are good indicators of decay. In addition, weight and colour changes have proven to be the most consistent and useful techniques for stone decay assessment.

## APPENDIX A: CONDITION SURVEYS

### Results of the condition survey at the Bishop's Palace

<b>Periphery: horizontal surfaces on east and north sides</b>				
	<b>Type of decay</b>	<b>Severity</b>	<b>Extension</b>	<b>Degree</b>
Crack and deformation	Crack	40%	40%	3
Detachment	Delamination and peeling	20%	20%	1
	Fragmentation	40%	50%	4
Material loss	Missing part	30%	30%	3
Discoloration	Deposit	30%	30%	3
	Discoloration, staining	20%	20%	1
	Soiling	40%	40%	3
Biocolonization	Biofilm	50%	70%	5

<b>Periphery: horizontal surfaces on the south and west sides</b>				
	<b>Type of decay</b>	<b>Severity</b>	<b>Extension</b>	<b>Degree</b>
Crack and deformation	Crack	10%	10%	1
Detachment	Fragmentation	20%	30%	2
Material loss	Missing part	20%	30%	2
Discoloration	Deposit	20%	30%	2
	Discoloration, staining	10%	10%	1
	Soiling	20%	20%	1
Biocolonisation	Biofilm	20%	20%	1

<b>Vertical surfaces facing north</b>				
	<b>Type of decay</b>	<b>Severity</b>	<b>Extension</b>	<b>Degree</b>
Crack and deformation	Crack	40%	40%	3
Detachment	Delamination and peeling	20%	20%	2
	Fragmentation	40%	40%	3
Material loss	Missing part	30%	40%	3
Discoloration	Crusts	30%	40%	3
	Deposit	40%	50%	4
	Soiling	60%	70%	5
Biocolonisation	Biofilm	30%	40%	3

<b>Vertical surfaces facing east</b>				
	<b>Type of decay</b>	<b>Severity</b>	<b>Extension</b>	<b>Degree</b>
Crack and deformation	Crack	40%	40%	3
Detachment	Delamination and peeling	10%	10%	1
	Fragmentation	30%	30%	3
Material loss	Missing part	40%	50%	4
Discoloration	Crusts	50%	40%	4
	Deposit	50%	70%	5
	Discoloration, staining	20%	20%	1
	Soiling	40%	50%	4
Biocolonisation	Biofilm	30%	30%	3

Vertical surfaces facing south	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	30%	30%	3
Detachment	Delamination and peeling	30%	30%	3
	Fragmentation	50%	60%	5
Material loss	Missing part	50%	60%	5
Discoloration	Crusts	40%	40%	3
	Deposit	40%	50%	4
	Soiling	60%	60%	5
Biocolonisation	Biofilm	10%	10%	1

Vertical surfaces facing west	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	40%	20%	2
Detachment	Delamination and peeling	20%	20%	1
	Fragmentation	60%	50%	5
Material loss	Missing part	50%	60%	5
Discoloration	Crusts	40%	50%	4
	Deposit	40%	60%	4
	Soiling	50%	60%	5
Biocolonisation	Biofilm	20%	20%	1

## Results of the condition survey at Hagar Qim

Periphery: south side	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	40%	30%	3
Detachment	Disintegration	30%	30%	3
	Fragmentation	40%	40%	3
	Scaling	40%	30%	3
Material loss	Alveolisation	30%	40%	3
	Erosion	30%	40%	3
	Missing parts	30%	40%	3
Discoloration	Crusts	30%	40%	3
	Deposit	40%	40%	3
	Salt efflorescence	40%	40%	3
	Soiling	40%	40%	3
Biocolonisation	Plants	20%	30%	2
	Biofilm	40%	40%	3

Vertical surfaces facing north	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	40%	30%	3
Detachment	Disintegration	30%	30%	3
	Fragmentation	40%	40%	3
	Scaling	40%	30%	3
Material loss	Alveolisation	50%	30%	4
	Erosion	30%	30%	3
	Missing parts	30%	30%	3
Discoloration	Crusts	30%	30%	3
	Deposit	30%	40%	3
	Salt efflorescence	30%	40%	3
	Soiling	30%	30%	3
Biocolonisation	Plants	20%	10%	1
	Biofilm	20%	50%	4

Vertical surfaces facing east	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	40%	40%	3
Detachment	Disintegration	30%	30%	3
	Fragmentation	30%	40%	3
	Scaling	50%	40%	4
Material loss	Alveolisation	50%	40%	4
	Erosion	40%	40%	3
	Missing parts	30%	40%	3
Discoloration	Crusts	40%	40%	3
	Deposit	30%	40%	3
	Salt efflorescence	40%	40%	3
	Soiling	20%	30%	2
Biocolonisation	Plants	20%	10%	1
	Biofilm	40%	40%	3

Vertical surfaces facing south	Type of decay	Severity	Extension	Degree
Crack and deformation	Crack	20%	30%	3
Detachment	Disintegration	20%	40%	2
	Fragmentation	30%	40%	3
	Scaling	40%	30%	3
Material loss	Alveolisation	50%	30%	4
	Erosion	40%	40%	3
	Missing parts	30%	30%	3
Discoloration	Crusts	30%	40%	3
	Deposit	20%	40%	2
	Salt efflorescence	40%	40%	3
	Soiling	30%	40%	3
Biocolonisation	Plants	20%	10%	1
	Biofilm	30%	40%	3

<b>Vertical surfaces facing west</b>	<b>Type of decay</b>	<b>Severity</b>	<b>Extension</b>	<b>Degree</b>
Crack and deformation	Crack	30%	40%	3
Detachment	Disintegration	30%	30%	3
	Fragmentation	40%	40%	3
	Scaling	40%	30%	3
Material loss	Alveolisation	50%	30%	4
	Erosion	40%	40%	3
	Missing parts	30%	40%	3
Discoloration	Crusts	30%	40%	3
	Deposit	40%	40%	3
	Salt efflorescence	40%	40%	3
	Soiling	20%	40%	2
Biocolonisation	Plants	10%	10%	1
	Biofilm	30%	50%	4

Thesis Word Count: 72800

## BIBLIOGRAPHY

- ADAMS, J. June 1995. *RE: The Bishop's Palace (Witney). Personal communication to THOMAS, R., (URBAN ARCHAEOLOGY, ENGLISH HERITAGE). EH Report AA063432/21: English Heritage.*
- ADDISON, A. C. 2007. A Record for Posterity. *In: EPPIC, R. & CHABBI, A. (eds.) Recording, Documentation, and Information Management for the Conservation of Heritage Places. Illustrated Samples.* Los Angeles: The Getty Conservation Institute.
- AGNEW, N. 2001. Methodology, conservation criteria and performance evaluation for archaeological sites shelters. *Conservation and Management of Archaeological Sites*, 5, 7-18.
- AGNEW, N. & COFFMAN, R. 1991. Development and evaluation of the hexashelter. *In: STANLEY PRICE, N. (ed.) The conservation of the Orpheus Mosaic at Paphos, Cyprus.* Los Angeles: Getty Conservation Institute.
- AGNEW, N. & LIN, P. M. 1991. Environmental Monitoring of the Paphos Mosaics. *In: STANLEY PRICE, N. (ed.) The Conservation of the Orpheus Mosaic at Paphos, Cyprus.* Los Angeles: Getty Conservation Institute.
- AGNEW, N., MAEKAWA, S., COFFMAN, R. & MAYER, J. 1996. Evaluation of the performance of a lightweight modular site shelter. Quantitative meteorological data and protective indices for the "hexashelter". *Conservation and Management of Archaeological Sites*, 1, 136-150.
- AHMAD, A. 2011. *Characterization of natural and consolidated stones from Jordan with non-destructive ultrasonic technique and physico-mechanical methods.* Technische Universität Dortmund.
- ALLEN, J. E. 1991. Meeting to discuss final scheme design. EH Report AA063432: English Heritage.
- ALLISON, R. J. & BRISTOW, G.E. 1999. The effects of fire on rock weathering: some further considerations of laboratory experimental simulation. *Earth Surface Processes and Landforms*, 24, 707-713.

- AOKI, H. & MATSUKURA, Y. 2007. A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. *Earth Surface Processes and Landforms* 32, 1759–1769.
- ARNOLD, A. & ZEHNDER, K. 1991. Monitoring Wall Paintings Affected by Soluble Salts. In: CATHER, S. (ed.) *The Conservation of wall paintings: proceedings of a symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute*. London: The Getty Conservation Institute.
- ASLAN, Z. 1997. Protective Structures for the Conservation and Presentation of Archaeological Sites. *Journal of Conservation and Museum Studies*, 3.
- ASLAN, Z. 2001. Designing protective structures at archaeological sites. Criteria and environmental design methodology for a proposed structure at Lot's Basilica, Jordan. *Conservation and Management of Archaeological Sites*, 5, 73-85.
- ASLAN, Z. 2003. Assessing the efficiency of protective structures for in situ conservation and presentation of mosaics on archaeological sites: a planning and design methodology for architects and site managers. In: BLANC, P. & CHANERIAUX, F. (eds.) *Les mosaïques: conserver pour présenter? VIIème conférence du Comité international pour la conservation des mosaïques (Arles, 1999)*. Musée archéologique de Saint-Romain-en-Gal: Éditions du Musée de l'Arles et de la Provence antiques.
- ASLAN, Z. 2007. *The design of protective structures for the conservation and preservation of archaeological sites*. PhD, University College London (University of London).
- AVRAMI, E., BARROW, J., JEROME, P. & TAYLOR, M. R. 2001. Protective shelters for archaeological sites in southwest USA. A colloquium held at Tumacacori, Arizona. 9-12 January, 2001. *Conservation and Management of Archaeological Sites*, 5, 3-6.
- BELL, F. G. 1993. Durability of carbonate rocks as building Stone with comments on its preservation. *Environmental Geology*, 21, 187-200.

- BERTAUX, J. P., GOUTAL, M., MECHLING, J. M., MEISTERSHEIM, P. & CREVOISIER, J. P. 1998. The Gallo-Roman sanctuary at Grand, France II. The protection and development of the amphitheatre. *Conservation and Management of Archaeological Sites*, 2, 217-228.
- BIESKE, K. & VANDAHL, C. 2008. A Study about Colour-Difference Thresholds. *Lux et Color Vespremiensis*. Veszprem: Virtual Environments and Imaging Technology Laboratory.
- BOLTON, D. 1980. The computation of equivalent potential temperature. *Monthly Weather Review*, 108, 1046-1053.
- BONAZZA, A., SABBIONI, C., MESSINA, P., GUARALDI, C. & DE NUNTIIS, P. 2009. Climate change impact: Mapping thermal stress on Carrara marble in Europe. *Science of the Total Environment*, 4506–4512.
- BRIMBLECOMBE, P. 2011. Environment and Architectural Stone. In: SIEGESMUND, S. & SNETHLAGE, R. (eds.) *Stone in Architecture: Properties, Durability*. 4th ed. Berlin: Springer.
- BRIMBLECOMBE, P., GROSSI, C. M. & HARRIS, I. 2006. Climate change critical to cultural heritage. *Proceedings of the International Conference on Heritage, Weathering and Conservation (Madrid, 2006)*, 1, 387-393.
- BUCCELLATI, G. & BONETTI, S. 2003. Conservation at the Core of Archaeological Strategy: The Case of Ancient Urkesh at Tell Mozan. *The Getty Conservation Institute Newsletter*, 18, 18-21.
- BUILDING RESEARCH ESTABLISHMENT 2001. BRE British Stone List. <http://projects.bre.co.uk/ConDiv/stonelist/portbedbase.html> [Accessed May 2015].
- BUTLIN, R. N., COOTE, A. T., DEVENISH, M., HUGHES, I. S. C., HUTCHENS, C. M., IRWIN, J. G., LLOYD, G. O., MASSEY, S. W., WEBB, A. H. & YATES, T. J. S. 1992. Preliminary Results from the Analysis of Stone Tablets from the National Materials Exposure Programme (NMEP). *Atmospheric Environment*, 26B, 189-198.

- BUTLIN, R. N., YATES, T. J. S., COOTE, A. T., LLOYD, G. O. & MASSEY, S. W. 1993. The first phase of the National Materials Exposure Programme 1987-1991 (Revised October 1993). Building Research Establishment.
- BUTLIN, R. N., YATES, T. J. S., MURRAY, M. & ASHALL, G. 1995. The United Kingdom National Materials Exposure Programme. *Water, Air and Soil Pollution*, 85, 2655-2660.
- CACACE, C., D'AGOSTINO, S., FERRONI, A. M. & LAURENTI, M. C. 2006. La vulnerabilità archeologica: efficienza e adeguatezza delle coperture di protezione. In: LAURENTI, M. C. (ed.) *Le Coperture delle Aree Archeologiche. Museo Aperto*. Roma: Gangemi Editore.
- CAMUFFO, D. 1986. Deterioration Processes of Historical Monuments. *Studies in Environmental Science*, 30, 189-221.
- CAMUFFO, D. 1997. Perspectives on Risks to Architectural Heritage. In: BAER, N. S. & SNETHLAGE, R. (eds.) *Saving Our Architectural Heritage. The Conservation of Historic Stone Structures*. Chichester: John Wiley & Sons.
- CAMUFFO, D. 1998. *Microclimate for Cultural Heritage*, Amsterdam, Elsevier Science.
- CAMUFFO, D. 2013. *Microclimate for Cultural Heritage. Conservation and Restoration of Indoor and Outdoor Monuments*, New York, Elsevier.
- CAMUFFO, D., BRIMBLECOMBE, P., VAN GRIEKEN, R., BUSSE, H. J., STURATO, G., VALENTINO, A., BERNANDI, A., BLADES, N., SHOOTER, D., DE BOCK, L., GYSELS, K., WIESER, M. & KIM, O. 1999. Indoor air quality at the Correr Museum, Venice, Italy. *The Science of the Total Environment*, 236, 135-152.
- CAMUFFO, D. & GIORIO, R. 2003. Quantitative Evaluation of Water Deposited by Dew on Monuments. *Boundary-Layer Meteorology*, 107, 655-672.
- CANADIAN ASSOCIATION FOR CONSERVATION OF CULTURAL PROPERTY & CANADIAN ASSOCIATION OF PROFESSIONAL CONSERVATORS 2000. *Code of Ethics and Guidance for Practice*, Ottawa, Canadian Association for Conservation of Cultural Property and Canadian Association of Professional Conservators.

- CANNAROZZI, A., MIRANDA, S. D. & UBERTINI, F. 2000. Il tema delle coperture visto da uno strutturista. *Arkos: i grandi restauri*, Coperture per aree e strutture archeologiche: repertorio di casi esemplificativi, 8-9.
- CARCANGIU G., CASTI, M., DESOGUS, G., MELONI, P. & RICCIU, R. 2014. Microclimatic monitoring of a semi-confined archaeological site affected by salt crystallisation. *Journal of Cultural Heritage*, 16, 113-18.
- CARROLL, S. 1998. Temporary protection of a tel site excavation in central Turkey. *Conservation and Management of Archaeological Sites*, 2, 155-162.
- CARTER, N. E. A. & VILES, H. 2003. Experimental investigations into interactions between moisture, rock surface temperatures and an epilithic lichen cover in the bioprotection of limestone. *Building and Environment*, 38, 1225-1234.
- CASSAR, J. 2002. Deterioration of the Globigerina Limestone of the Maltese Islands. In: SIEGESMUND, S., WEISS, T. & VOLLBRECH, A. (eds.) *Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies*. London: The Geological Society of London.
- CASSAR, J. 2004. Composition and property data in Malta's building stone for the construction of a database. In: PRIKRYL, R. & SIEGL, P. (eds.) *Architectural and sculptural stone in cultural heritage*. The Karolinum Press.
- CASSAR, J. 2007a. Malta: buildings, materials and deterioration. *STONE. Newsletter on stone decay*, 3-4.
- CASSAR, J. 2007b. Malta's prehistoric temples: conservation issues. *STONE. Newsletter on stone decay*, 3-7.
- CASSAR, J. 2010. The use of limestone in a historic context - the experience of Malta. In: SMITH, B. J., GÓMEZ-HERAS, M., VILES, H. A. & CASSAR, J. (eds.) *Limestone in the Built Environment: Present-Day Challenges for the Preservation of the Past*. London: Geological Society.
- CASSAR, J., GALEA, M., GRIMA, R., STROUD, K. & TORPIANO, A. 2011. Shelters over the Megalithic Temples of Malta: debate, design and implementation. *Environmental Earth Sciences*, 63, 1849-1860.

- CASSAR, J. & VANNUCCI, S. 1999. Petrographical and chemical research on the stone of the Megalithic Temples. *International Experts Group meeting on the Conservation of Malta's Megalithic Temples*. Malta, 24-27 May 1999.
- CASSAR, M., BRIMBLECOMBE, P., NIXON, T., PRICE, C., SABBIONI, C., SAIZ JIMENEZ, C. & VAN BALEN, K. 2001. Technological Requirements for Solutions in the Conservation and Protection of Historic Monuments and Archaeological Remains, working paper for the STOA Unit. *In*: CASSAR, M. (ed.). Luxembourg: European Parliament.
- CENTRO REGIONALE PER LA PROGETTAZIONE E IL RESTAURO E PER LE SCIENZE NATURALI ED APPLICATE AI BENI CULTURALI 2007. *Progetto di Recupero e Conservazione della Villa Romana del Casale di Piazza Armerina*, Palermo, Regione Siciliana, Assessorato dei Beni Culturali ed Ambientali e della Pubblica Istruzione, Dipartimento dei Beni Culturali ed Ambientali ed Educazione Permanente.
- CITTERIO, M. & GIANI, E. 2006a. Clima e microclima. *Le Coperture delle Aree Archeologiche. Museo Aperto*, 159-178.
- CITTERIO, M. & GIANI, E. 2006b. I modelli di simulazione per la previsione del microclima. *In*: LAURENTI, M. (ed.) *Le coperture delle aree archeologiche. Museo aperto*. Roma: Gengemi Editore.
- CITTERIO, M. & GIANI, E. 2006c. A microclimatic study for the design of new shelters for the archaeological site of Castellammare di Stabia- Naples. *In*: FORT, R., BUERGO, M. A. D., GOMEZ-HERAS, M. & VAZQUEZ-CALVO, C. (eds.) *Proceedings of the International Conference on Heritage, Weathering and Conservation (Madrid, 2006)*. London: Taylor & Francis.
- CONSIGLIO NAZIONALE DELLE RICERCHE & ISTITUTO DI SCIENZE DELL'ATMOSFERA E DEL CLIMA 2006. Environmental Monitoring at Hagar Qim and Mnajdra Temples. Results and Recommendations on the microenvironmental impact of the shelters for the Temples. Heritage Malta.

- CONSIGLIO NAZIONALE DELLE RICERCHE & ISTITUTO DI SCIENZE DELL'ATMOSFERA E DEL CLIMA 2006. Environmental Monitoring at Hagar Qim and Mnajdra Temples. Final Report. Heritage Malta.
- COOKE, R. U. 1979. Laboratory simulation of salt weathering processes in arid environments. *Earth Surface Processes*, 4, 347-359.
- COOKS, J. 1983. Geomorphic response to rock strength and elasticity. *Zeitschrift für Geomorphologie, NF*, 27, 483-493.
- COOMBES, M. 2011. Rock warming and drying under simulated intertidal conditions, part I: experimental procedures and comparisons with field data. *Earth Surface Processes and Landforms*, 36, 2114-2121.
- COOTE, A. T., YATES, T., CHAKRABARTI, S., BIGLAND, D. J., RIDAL, J. P. & BUTLIN, R. N. 1991. Evolution of decay to stone tablets: Part 1 - after exposure for 1 and 2 years. *Convention on Long-Range Transboundary Air Pollution. UN/ECE International Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments*. Watford: Building Research Establishment.
- CRISPIM, C. A., GAYLARDE, P. M. & GAYLARDE, C. C. 2003. Algal and Cyanobacterial Biofilms on Calcareous Historic Buildings. *Current Microbiology*, 46, 79-82.
- CROSBY, A. 2007. Rapid Assessment. In: EPPIC, R. & CHABBI, A. (eds.) *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Illustrated Samples*. Los Angeles: The Getty Conservation Institute.
- CUTLER, N. A., VILES, H. A., AHMAD, S., MCCABE, S. & SMITH, B. J. 2013. Algal 'greening' and the conservation of stone heritage structures. *Science of the Total Environment*, 442, 152-164.
- CHAROLA, A. E. 2000. Salts in the deterioration of Porous Materials: An Overview. *Journal of the American Institute for Conservation*, 39, 327-343.
- CHAROLA, A. E., PÜHRINGER, J. & STEIGER, M. 2007. Gypsum: a review of its role in the deterioration of building materials. *Environmental Geology*, 52, 339-352.
- CHEVALIER, P. 1953. Erosion or corrosion? *Proceedings of International Speleological Conference*. Paris.

- CHRISTARAS, B. 1996. Non destructive methods for investigation of some mechanical properties of natural stones in the protection of monuments. *Bulletin of the International Association of Engineering Geology*, 54, 59-63.
- D'ALCONZO, P. 2002. *Pinturæ Excisæ. Conservazione e Restauro dei Dipinti Ercolanesi e Pompeiani tra VIII e XIX secolo*, Roma, "L'Erma" di Bretschneider.
- DEMAS, M. 2001. Annotated bibliography on protective shelters for archaeological sites. *Conservation and Management of Archaeological Sites*, 5, 91-105.
- DEMAS, M. 2003. *Conservation and Management of Archaeological Sites. A Select Annotated Bibliography*, Los Angeles, The Getty Conservation Institute.
- DEMAS, M. 2013. Protective Shelters for Archaeological Sites. In: ROBY, T. & DEMAS, M. (eds.) *Mosaics In Situ. An Overview of Literature on Conservation of Mosaics In Situ*. Los Angeles: The Getty Conservation Institute.
- DIANA, G., CASSAR., J. & ZAMMIT, G. 2014. Physical characteristics of Globigerina Limestone using ultrasonic and thermographic methods. *Quarterly Journal of Engineering Geology and Hydrogeology*.
- DOEHNE, E. 1991. Evaluation of tesserae from the Paphos mosaics. In: STANLEY PRICE, N. (ed.) *The conservation of the Orpheus Mosaic at Paphos, Cyprus*. Los Angeles: Getty Conservation Institute.
- DOEHNE, E. & PRICE, C. A. 2010. *Stone Conservation. An Overview of Current Research*, Los Angeles, Getty Conservation Institute.
- EDWARDS, C., CORFIELD, M., KNIGHT, B., TEUTONICO, J. M. & ADAMS, J. 2003. The investigation and conservation of 4th century mosaics at Brading Roman villa, Isle of Wight, England. In: MICHAELIDES, D. (ed.) *Mosaics make a site: the conservation in situ of mosaics on archaeological sites. Proceedings of the VIth conference of the International Committee for the Conservation of Mosaics, Nicosia, Cyprus, 1996*. Rome, Italy: ICCM.
- EKLUND, J. A., ZHANG, H., VILES, H. & CURTEIS, T. 2013. Using Handheld Moisture Meters on Limestone: Factors Affecting Performance and Guidelines for Best

- Practice. *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration*, 7, 207–224.
- ESHØJ, B. & PADFIELD, T. 1993. The use of porous building materials to provide a stable relative humidity. *Preprints of the ICOM-CC (International Council of Museums - Conservation Committee) Conference*. Washington DC.
- EUROPEAN CONFEDERATION OF CONSERVATOR-RESTORERS' ORGANISATIONS. 2003. *Professional Guidelines* [Online]. Brussels: European Confederation of Conservator-Restorers' Organisations (ECCO). Available: <http://www.ecco-eu.org/about-e.c.c.o./professional-guidelines.html> [Accessed November 2013].
- FANOOD, M. R. 2012. The Debate on the Need for a Protective Shelter over the Mausoleum of Cyrus the Great. *Journal of Architectural Conservation*, 18, 53-70.
- FARRUGIA, S. & SCHEMBRI, J. A. 2008. Wind funnelling underneath the Hagar Qim protective shelter. *Malta Archaeological Review*, 9, 51-59.
- FEILDEN, B. M. 2003. Causes of Decay in Materials and Structure. *Conservation of Historic Buildings*. 3 ed. Oxford: Architectural Press.
- FERRONI, A. M. & LAURENTI, M. C. 2006. Coperture in protezione. Studi pregressi e ricerche in corso. In: LAURENTI, M. C. (ed.) *Le coperture delle aree archeologiche*. Museo aperto. Rome: Gangemi Editore.
- FIERO, K. 2001. Preserving dirt-walled structures in Mesa Verde National Park. *Conservation and Management of Archaeological Sites*, 5, 55-62.
- FLATT, R. J., GIRARDET, F. J. & WEIDMANN, D. C. 1997. In situ Conservation of the Roman Mosaics at the Villa of Boscéaz (Orbe, Switzerland): Diagnosis of Risks Involved. In: VANDIVER, P. B., DRUZIK, J. R., MERKEL, J. F. & STEWART, J. (eds.) *Materials Issues in Art and Archaeology V: symposium held December 3-5, 1996, Boston, Massachusetts, USA*. Pittsburgh: Materials Research Society.
- FORM TL INGENIEURE FÜR TRAGWERK UND LEICHTBAU GMBH 2007. Preliminary membrane forces and membrane evaluation. Internal report (project number 5447): Heritage Malta.

- FRANCESCHETTI, G., GASPARRI, F. & SANTOPUOLI, N. 2000. Classificazione degli interventi di copertura e creazione di una banca dati. *Arkos: i grandi restauri*, Coperture per aree e strutture archeologiche: repertorio di casi esemplificativi, 16-18.
- GALDIES, C. 2011. The Climate of Malta: statistics, trends and analysis 1951-2010. Valletta: National Statistics Office.
- GALEA, M. July 2014 2014. *RE: Hagar Qim (personal communication)*.
- GETTY CONSERVATION INSTITUTE 2009. Conservation of Mosaics in Situ. 2011.
- GETTY CONSERVATION INSTITUTE & INSTITUTO HONDUREÑO DE ANTROPOLOGÍA E HISTORIA 2006. The Hieroglyphic Stairway of Copán, Honduras. Study Results and Conservation Proposals. A project report. Los Angeles and Tegucigalpa: Getty Conservation Institute and Instituto Hondureño de Antropología e Historia.
- GOMEZ-HERAS, M. & FORT, R. 2007. Patterns of halite (NaCl) crystallisation in building stone conditioned by laboratory heating regimes. *Environmental Geology*, 52, 259-267.
- GOUDIE, A. S., ALLISON, R. J. & MCLAREN, S. J. 1992. The Relations between modulus of elasticity and temperature in the context of the experimental simulation of rock weathering by fire. *Earth Surface Processes and Landforms*, 17, 605-615.
- GOUDIE, A. S. & VILES, H. A. 2000. The Thermal Degradation of Marble. *Acta Universitatis Carolinae, Geographica*, XXXV, Supplementum, 7–16.
- GROSSI, C. M. & BRIMBLECOMBE, P. 2002. The effect of atmospheric pollution on building materials. *Journal of Physique Archives IV France*, 12, 197-210.
- GROSSI, C. M., BRIMBLECOMBE, P., MENÉNDEZ, B., BENAVENTE, D., HARRIS, I. & DÉQUÉ, M. 2011. Climatology of salt transitions and implications for stone weathering. *Science of the Total Environment*, 409, 2577–2585.
- GROSSI, C. M., ESBERT, R. M., DIAZ-PACHE, F. & ALONSO, F. J. 2003. Soiling of buildings in urban environments. *Building and Environment*, 38, 147-159.

- GYSELS, K., DELALIEUX, F., DEUTSCH, F., VAN GRIEKEN, R., CAMUFFO, D., BERNARDI, A., STURARO, G., BUSSE, H. J. & WIESER, M. 2004. Indoor environment and conservation in the Royal Museum of Fine Arts, Antwerp, Belgium. *Journal of Cultural Heritage*, 5, 221-230.
- HALSEY, D. P., MITCHELL, D. J. & DEWS, S. J. 1998. Influence of climatically induced cycles in physical weathering. *Quarterly Journal of Engineering Geology*, 31, 359-367.
- HANCOCK, J. M. 1975. The Petrology of the Chalk. *Proceedings of the Geologists' Association*, 86, 499-535.
- HARGREAVES, P. R., LEIDI, A., GRUBB, H. J., HOWE, M. T. & MUGGLESTONE, M. A. 2000. Local and seasonal variations in atmospheric nitrogen dioxide levels at Rothamsted, UK, and relationships with meteorological conditions. *Atmospheric Environment*, 34, 843-853.
- HEBBELINCK, S., HENDRICKX, A. H., MOLLAERT, M. & HAASE, J. 2001. New ideas on the use of systematically constructed tension structures to cover historical and archaeological sites. *Transactions on the Built Environment*, 55, 29-38.
- HEINRICHS, K. & FITZNER, B. 2007. Stone monuments of the Nemrud Dag sanctuary/Turkey – petrographical investigation and diagnosis of weathering damage. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, 158, 519-548.
- HISTORIC BUILDINGS AND MONUMENTS COMMISSION FOR ENGLAND 1988. The Palace of the Bishops of Winchester at Witney, Oxfordshire. Preservation of the Archaeological Remains and Examination of Options for Display. EH Report P1 CDS (12 088 REP/1 MACH/2): English Heritage.
- HISTORIC BUILDINGS AND MONUMENTS COMMISSION FOR ENGLAND 1992. Maintenance Manual for the West Oxfordshire District Council, Miscellaneous Specifications. EH Report AA 63432/21: English Heritage.
- HONEYBORNE, D. B. 1998. Weathering and decay of masonry. In: ASHURST, J. & DIMES, F. G. (eds.) *Conservation of buildings & decorative stone*. Oxford: Butterworth-Heinemann.

- HORSFIELD, B. & OXFORDSHIRE GEOLOGY TRUST 2011. Strategic Stone Study. A Building Stone Atlas of Oxfordshire. *In*: LOTT, G. & BRITISH GEOLOGICAL SURVEY (eds.). English Heritage.
- HUBBART, J., LINK, T., CAMPBELL, C. & COBOS, D. 2005. Evaluation of a low-cost temperature measurement system for environmental applications. *Hydrological Processes*, 19, 1517-1523.
- IBENHOLT, H. 2003. Les ruines de la cathédrale de Hamar (Norvège) et leur protection. *Vestiges archéologiques en milieu extrême: table ronde internationale* Paris: Monum, Éditions du Patrimoine.
- ICCROM & CENTRO DI CONSERVAZIONE ARCHEOLOGICA 1986. *La Conservazione sullo Scavo Archeologico. Atti del Convegno (Cipro, 1983)*, Roma, ICCROM.
- ICOMOS INTERNATIONAL SCIENTIFIC COMMITTEE FOR STONE ISCS 2008. *ICOMOS-ISCS: Illustrated glossary on stone deterioration patterns = Glossaire illustré sur les formes d'altération de la pierre*, Paris, ICOMOS.
- INGHAM, J. P. 2005. Predicting the frost resistance of building stone. *Quarterly Journal of Engineering Geology and Hydrogeology*, 38, 387-399.
- INKPEN, R. 1995. Errors in measuring the percentage dry weight change of stone tablets. *Earth Surface Processes and Landforms*, 20, 783-793.
- INKPEN, R., COOKE, R. U. & VILES, H. 1994. Processes and Rates of Urban Limestone Weathering. *In*: ROBINSON, D. A. & WILLIAMS, R. B. G. (eds.) *Rock Weathering and Landform Evolution*. Chichester: John Wiley and Sons Ltd.
- INKPEN, R. & MAY, E. 2006. Stone. *In*: MAY, E. & JONES, M. (eds.) *Conservation Science. Heritage Materials*. Cambridge: RSC Publishing.
- INTERNATIONAL COMMITTEE FOR THE MANAGEMENT OF ARCHAEOLOGICAL HERITAGE 1990. Charter for the Protection and Management of the Archaeological Heritage. Lausanne: International Council for Monuments and Sites (ICOMOS).
- JAYNES, S. M. & COOKE, R. U. 1987. Stone Weathering in Southeast England. *Atmospheric Environment*, 21, 1601-1622.

- JEROME, P. 1995. Proposed permanent shelter for Building 5 at the Bronze Age site of Palaikastro, Crete. *Conservation and Management of Archaeological Sites*, 1, 35-42.
- KEMPT, A. W., FOSTER, D., MILLS, S. R., WORSSAM, B. C., HORTON, A., AMBROSE, K., BREWSTER, J., LAWRENCE, D. J. D., MOORLOCK, B. S. P., RIDGWAY, J. M., SUMBLER, M. G., WILSON, D., WYATT, R. J., COPPACK, POOLE, E. G. & WILLIAMS, B. J. 1982. *Witney Sheet 236*, 1:50000 Southampton: Ordnance Survey of Great Britain.
- KENDALL, C. P. & ENGLISH HERITAGE SOUTH EAST LOCAL OFFICE. 1992. *RE: Personal communication*. Type to J.E. ALLEN & CENTRAL ARCHITECTURAL PRACTICE (ENGLISH HERITAGE).
- KOESTLER, R. J., WARSCHEID, T. & NIETO, F. 1997. Biodeterioration: Risk Factors and Their Management. *In: BAER, N. S. & SNETHLAGE, R. (eds.) Saving Our Architectural Heritage. The Conservation of Historic Stone Surfaces*. Chichester: John Wiley & Sons.
- KOIT HIGH-TECH GMBH KONSTRUKTIVE MEMBRANENE (UK) LTD. 1993. *RE: Private communication*. Type to ENGLISH HERITAGE.
- KOTLÍK, P. & HEIDINGSFELD, V. 2002. Monitoring of stone sculptures and reliefs in Bethlehem near Kuks (Eastern Bohemia, Czech Republic). *In: PŘIKRYL, P. & VILES, H. A. (eds.) Understanding and Managing Stone Decay. Proceedings of the International Conference Stone Weathering and Atmospheric Pollution Network (SWAPNET 2001)*. Prague: The Karolinum Press.
- KROCHMAL, D. & KALINA, A. 1997. A Method of Nitrogen Dioxide and Sulphur Dioxide Determination in Ambient Air by Use of Passive Samplers and Ion Chromatography. *Atmospheric Environment*, 31, 3473-3479.
- LAURENTI, M. 2000. Strategie operative attuali per la conservazione delle aree archeologiche. *Arkos: i grandi restauri*, Coperture per aree e strutture archeologiche: repertorio di casi esemplificativi, 6.
- LAURENTI, M. C. 2001. Research project on protective shelters for archaeological areas in Italy. *Conservation and Management of Archaeological Sites*, 5, 109-115.

- LAURENTI, M. C. 2003. On-site protection of mosaics: covering and protecting archaeological remains. *In: MICHAELIDES, D. (ed.) Mosaics make a site: the conservation in situ of mosaics on archaeological sites. Proceedings of the VIth conference of the International Committee for the Conservation of Mosaics, Nicosia, Cyprus, 1996.* Rome, Italy: ICCM.
- LAYCOCK, E. A., SPENCE K., JEFFERSON, D. P., HETHERINGTON, S., MARTIN B. & WOODS, C. 2008. Testing the durability of limestone for cathedral façade restoration. *Environmental Geology*, 56, 521-528.
- LEARY, E. 1983. The building limestones of the British Isles. *Building Research Establishment Report*. London.
- LEISEN, H. 2002. Contour scaling: the disfiguring disease of Angkor Wat reliefs. *Museum International*, 54, 85-92.
- LETELLIER, R. 2007. *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding principles*, Los Angeles, The Getty Conservation Institute.
- LIPFERT, F. W. 1989. Atmospheric damage to calcareous stones: comparison and reconciliation of recent experimental findings *Atmospheric Environment*, 23, 415-429.
- LIVINGSTONE, R. A. 1992. Graphical methods for examining the effects of acid rain and sulfur dioxide on carbonate stones. *In: DELGADO RODRIGUES, J., HENRIQUES, F. & TELMO, J. F. (eds.) 7th International Congress on Deterioration and Conservation of Stone.* Lisbon, Portugal.
- LLOP, E., ÁLVARO, I., GÓMEZ-BOLCA, A., HERNÁNDEZ MARINÉ, M. & SAMMUT, S. 2013. Biological crusts contribute to the protection of Neolithic Heritage in the Mediterranean region. *In: ROGERIO-CANDELERIA, M. A., LAZZARI, M. & CANO, E. (eds.) Science and Technology for the Conservation of Cultural Heritage.* Santiago de Compostela: Taylor & Francis.
- MAEKAWA, S. 2006. Comparison of Shelters' Performance at Joya de Cerén, El Salvador. *In: FORT, R., BUERGO, M. A. D., GOMEZ-HERAS, M. & VAZQUEZ-*

- CALVO, C. (eds.) *Proceedings of the International Conference on Heritage, Weathering and Conservation (Madrid, 2006)*. London: Taylor & Francis.
- MCCABE, S., BRIMBLECOMBE, P., SMITH, B. J., MCALLISTER, D., SRINIVASAN, S. & BASHEER, P. A. M. 2013. The use and meanings of 'time of wetness' in understanding building stone decay. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46, 469-476.
- MERELLO, P., GARCÍA-DIEGO, F. J. & ZARZO, M. 2013. Evaluation of corrective measures implemented for the preventive conservation of fresco paintings in Ariadne's house (Pompeii, Italy). *Chemistry Central Journal* 7.
- MET OFFICE. 2013. *Southern England: climate* [Online]. <http://www.metoffice.gov.uk/climate/uk/so/>. [Accessed January 2015].
- MICHAELIDES, D. & SAVVIDES, N. 2008. Lessons not learned: the shelters at Kourion, Cyprus. In: ABED, A. B., DEMAS, M. & ROBY, T. (eds.) *9th Conference of the International Committee for the conservation of mosaics (Tunisia, 2005). Lessons learned: reflecting on the theory and practice of mosaics conservation*. Los Angeles: The Getty Conservation Institute.
- MILLER A.Z., SANMARTÍN P., PEREIRA-PARDO L., DIONÍSIO A., SAIZ-JIMENEZ C., MACEDO M.F. & PRIETO B. 2012. Bioreceptivity of building stones: a review. *Science of the Total Environment*, 426, 1-12.
- MINISTERO PER I BENI E LE ATTIVITÀ CULTURALI & ISTITUTO CENTRALE PER IL RESTAURO 2006. *Le Coperture delle aree archeologiche. Museo aperto*, Roma, Gangemi Editore.
- MIRWALD, P. W. & BRÜGGERHOFF, S. 1997. Requirements For Accelerated and Field Testing. *Saving our Architectural Heritage: The Conservation of Historic Stone Structures*, 255-268.
- MOL, L. 2014. Investigations into the relationship between changes in internal moisture regimes and rock surface deterioration in cavernous sandstone features. *Earth Surface Processes and Landforms*, 39, 914-927.

- MOL, L. & VILES, H. 2013. Exposing drying patterns: using electrical resistivity tomography to monitor capillary rise in sandstone under varying drying conditions *Environmental Earth Sciences*, 68, 1647-1659.
- MOLLAERT, M., DE LAET, L., VERDONCK, A., LOMBARDI, S., BECCARELLI, P. & ZANELLI, A. 2011. Textile shelters for archaeological or heritage areas: design references. In: BREBBIA, C. A. & BINDA, L. (eds.) *Structural Studies, Repairs and Maintenance of Heritage Architecture XII*. Poole: WIT Press.
- MOROPOULOU, A. & BISBIKOU, K. G. 1995. Environmental Monitoring and Damage Assessment at the Ancient Sanctuary of Demeter in Eleusis, Greece. *Materials Research Society Symposium Proceedings*, 352, 745-757.
- MOROPOULOU, A., KOUI, M., TSIOURVA, T., KOURTELI, C. & PAPASOTIRIOU, D. 1996. Macro- and micro- non destructive tests for environmental impact assessment on architectural surfaces. *Materials Research Society Symposium Proceedings*, 462, 343-349.
- MORTIMORE, R. N., STONE, K. J., LAWRENCE, J. & DUPERRÉ, A. 2004. Chalk physical properties and cliff instability. In: MORTIMORE, R. N. & DUPERRÉ, A. (eds.) *Coastal Chalk Cliff Instability*. London: Geological Society Engineering Geology Special Publication.
- MOSES, C. 2000. Field rock block exposure trials. *Zeitschrift für Geomorphologie Supplementband*, 120, 33-50.
- MOSES, C., ROBINSON, D. & BARLOW, J. 2014. Methods for measuring rock surface weathering and erosion: A critical review. *Earth-Science Reviews* 135, 141–161.
- MOSES, C. A. Year. Methods for investigating stone decay mechanisms in polluted and 'clean' environments, Northern Ireland. In: SMITH, B. J. & WARKE, P. A., eds. *Stone Weathering and Atmospheric Pollution Network Conference, 19-20 May 1995 1996* Belfast. Donhead, 212-227.
- NATALI, I., TOMASIN, P., BECHERINI, F., A., BERNARDI, A., CIANTELLI, C., FAVARO, M., FAVONI, O., FORRAT PÉREZ, V. J., OLTEANU, I. D., ROMERO SANCHEZ, M. D., VIVARELLI, A. & BONAZZA, A. 2015. Innovative consolidating products for stone

materials: field exposure tests as a valid approach for assessing durability. *Heritage Science* 3, 1-13.

NEGUER, J. 2004. Vulnerability assessment and Conservation Management Maintenance planning of in-situ exposed mosaics. In: MELI, G. (ed.) *Apparati musivi antichi nell'area del Mediterraneo: conservazione programmata e recupero: contributi analitici alla Carta del Rischio: atti del I Convegno internazionale di studi: La Materia e i segni della storia, Piazza Armerina, 9-13 Aprile 2003*. Palermo: Centro regionale per la progettazione e il restauro.

NEGUER, J. & ALEF, Y. 2008. Rapid Assessment of Shelters over Mosaics: Initial Results from Israel. *9th Conference of the International Committee for the conservation of mosaics (Tunisia, 2005). Lessons learned: reflecting on the theory and practice of mosaics conservation.*, 193-204.

NICHOLSON, D. T. 2001. Pore Properties as Indicators of Breakdown Mechanisms in Experimentally Weathered Limestones. *Earth Surface Processes and Landforms*, 819-838.

NICHOLSON, D. T. 2002. Quantification of rock breakdown for experimental weathering studies. In: PŘIKRYL, P. & VILES, H. A. (eds.) *Understanding and Managing Stone Decay. Proceedings of the International Conference Stone Weathering and Atmospheric Pollution Network (SWAPNET 2001)*. Prague: The Karolinum Press.

NISHIURA, T. & ARANYANARK, C. 2002. Are Buddha Statues in Remains Living Heritage for Local Buddhist People? - Case Study on the Conservation of the Giant Buddha Statutue at Sukhothai Historical Park in Thailand *Strategies for the World's Cultural Heritage. Preservation in a globalised world: principles, practices and perspectives. Proceedings of the 13th International Scientific Symposium*. Madrid: ICOMOS

ODGERS, D., HENRY, A. & ENGLISH HERITAGE 2012. *Practical Building Conservation: Stone*, Farnham, Ashgate.

- ORTEGA-MORALES, O., GUEZENNE, J., HERNANDEZ-DUQUE, G., GAYLARDE, C. C. & GAYLARDE, P. M. 2000. Phototrophic Biofilms on Ancient Mayan Buildings in Yucatan, Mexico. *Current Microbiology*, 40, 81-85.
- ÖSTERREICHISCHES ARCHÄOLOGISCHES INSTITUT 2002. *Ein Dach für Ephesos: der Schutzbau für das Hanghaus 2 = A roof for Ephesos: the shelter for Terrace House 2 = Efes için bir çatı: yamaç ev 2 koruma binası*, Wien, Austria, Österreichisches archäologisches Institut.
- OXFORDSHIRE HISTORIC ENVIRONMENT RECORD. *Site of Bishop of Winchester's Palace* [Online]. Oxfordshire County Council. Available: <http://publicapps.oxfordshire.gov.uk> [Accessed July 2014].
- PALMER, T. J. 2008. Limestone petrography and durability in English Jurassic Freestones. In: DOYLE, P., HUGHES, T. G. & THOMAS, I. (eds.) *England's Heritage in Stone*. York: English Stone Forum.
- PALUMBO, G. 2001. Sheltering an archaeological structure in Petra. A case-study of criteria, concepts, and implementation. *Conservation and Management of Archaeological Sites*, 5, 35-44.
- PARANDOWSKA, E. 2003. Conservation of Mosaics from the Early Roman Villa at Kom el Dikka, Alexandria. In: BLANC, P. & CHANERIAUX, F. (eds.) *Les mosaïques: conserver pour présenter? VIIème conférence du Comité international pour la conservation des mosaïques (Arles, 1999)*. Musée archéologique de Saint-Romain-en-Gal: Éditions du Musée de l'Arles et de la Provence antiques.
- PEDLEY, H. M., HOUSE, M. R. & WAUGH, B. 1976. The Geology of Malta and Gozo. *Proceedings of the Geologists' Association*, 87, 325-341.
- PESARESI, P. & RIZZI, G. 2007. New and existing forms of protective shelter at Herculaneum: towards improving the continuous care of the site. *Conservation and Management of Archaeological Sites*, 8, 237-252.
- PESAVA, P., AKSU, R., TOPRAK, S., HORVATH, H. & SEIDL, S. 1999. Dry deposition of particles to building surfaces and soiling. *The Science of the Total Environment*, 235, 25-35.

- PINNA, D. 2014. Biofilms and lichens on stone monuments: do they damage or protect? *Frontiers in Microbiology*, 5, 1-3.
- PINNA, D. & SALVADORI, O. 2008. Processes of biodeterioration: general mechanisms. In: CANEVA, G., PIA NUGARI, M. & SALVADORI, O. (eds.) *Plant biology for cultural heritage*. Los Angeles: The Getty Conservation Institute.
- PIO, C. A., RAMOS, M. M. & DUARTE, A. C. 1997. Atmospheric aerosol and soiling of external surfaces in an urban environment. *Atmospheric Environment*, 32, 1979-1989.
- PIQUÉ, F., NEGUER, J. & LUCHERIN, B. 2003. The role of maintenance in the conservation of mosaics in situ: Comparative field-testing methodology. In: BLANC, P. & CHANERIAUX, F. (eds.) *Les mosaïques: conserver pour présenter? VIIème conférence du Comité international pour la conservation des mosaïques (Arles, 1999)*. Musée archéologique de Saint-Romain-en-Gal: Éditions du Musée de l'Arles et de la Provence Antiques.
- PRICK A. 1997. Critical degree of saturation as a threshold moisture level in frost weathering of limestones *Permafrost and Periglacial Processes* 8, 91–99.
- PŘIKRYL, R. 2013. Durability assessment of natural stone. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46, 377–390.
- PROIETTI, A., LECCESE F., CACIOTTA, M., MORRESI, F., SANTAMARIA, U. & MALOMO, C. 2014. A New Dusts Sensor for Cultural Heritage Applications Based on Image Processing. *Sensors*, 14, 9813-9832.
- RANELLUCCI, S. 1996. *Strutture Protettive e Conservazione dei Siti Archeologici*, Pescara, Carsa Edizioni.
- RIVERO WEBER, L. (ed.) 2011. *Memorias y lineamientos del taller sobre implementación de cubiertas arquitectónicas en contextos arqueológicos*, Mexico, DF.: Fomento Cultural Banamex.
- RIZZI, G. 2008. Sheltering the mosaics of Piazza Armerina: issues of conservation and presentation. *Heritage, Conservation & Archaeology*.

- ROBINSON, D. & MOSES, C. 2011. Rock Surface and Weathering: Process and Form. *In: GREGORY, K. J. & GOUDIE, A. S. (eds.) The SAGE Handbook of Geomorphology.* London: SAGE Publications.
- ROBY, T. 2006. The Conservation of Mosaics in Situ: Preserving Context and Integrity. *In: ABED, A. B. (ed.) Stories in Stone. Conserving Mosaics of Roman Africa. Masterpieces from the National Museums of Tunisia.* Los Angeles: The Getty Conservation Institute.
- RODRIGUEZ-NAVARRO, C. & DOEHNE, E. 1999. Salt weathering: influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms*, 24, 191-209.
- ROSINA, E., ZANELLI, A., BECCARELLI, P., GARGANOT, M. & ROMOLI, E. 2011. New Procedures and Materials for Improving Protection of Archaeological Areas. *Materials Evaluation*, 69, 979-989.
- ROSS, K. D., HART, D. & BUTLIN, R. N. Year. Durability tests for natural building stone. *In: BAKER, J. M., DAVIES, H., MAJUMDAR, A. J. & NIXON, P. J., eds. Durability of Building Materials and Components. Proceedings of the 5th International Conference, 1991 Brighton, UK, 7-9 November 1990.* Chapman and Hall Ltd., 100-115.
- ROTHERT, E., EGGERS, T., CASSAR, J., RUEDRICH, J., FITZNER, B. & SIEGESMUND, S. 2007. Stone properties and weathering induced by salt crystallization of Maltese Globigerina Limestone. *In: PRIKRYL, R. & SMITH, B. J. (eds.) Building Stone Decay: From Diagnosis to Conservation.* Geological Society, London, Special Publications.
- ROVANÍKOVÁ, P. 2007. Environmental pollution effects on other building materials. *In: MONCMANOVÁ, A. (ed.) Environmental deterioration of materials.* Southampton: WIT press.
- SABBIONI, C., BRIMBLECOMBE, P. & CASSAR, M. 2010. *The Atlas of Climate Change Impact on European Cultural Heritage. Scientific Analysis and Management Strategies*, London, Anthem Press.

- SAIZ JIMENEZ, C. 2003. Organic Pollutants in the Built Environment and Their Effect on the Microorganisms. *In: BRIMBLECOMBE, P. (ed.) Effects of Air Pollution on the Built Environment*. Imperial College Press.
- SALVATORE, M. 2004. Le coperture nelle aree archeologiche: status quaestionis e prospettive. *In: MELI, G. (ed.) Apparati musivi antichi nell'area del Mediterraneo: conservazione programmata e recupero. Contributi analitici alla Carta del Rischio. Atti del I convegno internazionale di studi: La materia e i segni della storia, Piazza Armerina, 9-13 Aprile 2003*. Palermo: Centro regionale per la progettazione e il restauro.
- SANTORO, S. & SANTOPUOLI, N. 2000. La protezione delle aree archeologiche: ricerca e prassi operativa. *Arkos: i grandi restauri, Coperture per aree e strutture archeologiche: repertorio di casi esemplificativi*, 3-5.
- SCHAFFER, R. J. 1932. *The weathering of natural building stones*, London, Her Majesty's Stationery Office
- SCHMID, M. 1998. Protective shelters at the archaeological sites of Mallia (Crete) and Kalavassos-Tenta (Cyprus). *Conservation and Management of Archaeological Sites*, 2, 143-153.
- SGARBI, V. 2007. Linee guida per la progettazione. *In: MELI, G. (ed.) Progetto di recupero e conservazione della Villa Romana del Casale di Piazza Armerina*. Palermo: Dipartimento beni culturali ed ambientali ed educazione permanente.
- SIEDEL, H., SIEGFRIED, S. & STERFLINGER, K. 2011. Characterisation of Stone Deterioration on Buildings. *In: SIEGSMUND, S. & SNETHLAGE, R. (eds.) Stone in Architecture: Properties, Durability*. 4th ed. Berlin: Springer.
- SIEGSMUND, S. & DÜRRAST, H. 2011. Physical and Mechanical Properties of Rocks. *Stone in Architecture: Properties, Durability*, 97-225.
- SIEGSMUND, S., PIRSKAWETZ, S., FRANK WEISE, F., PLAGGE, R. & RIEFFEL, Y. 2012. Winter Inter shelters for marble sculptures of the Schlossbrücke Berlin: Climatic constraints. *12th International Congress on the Deterioration and Conservation of Stone*. Columbia University, New York.

- SIKKA, S. 2007. Recording, Documentation, and Information Management for the Conservation of Heritage Places. Illustrated Samples. *In: EPPIC, R. & CHABBI, A. (eds.) Recording, Documentation, and Information Management for the Conservation of Heritage Places. Illustrated Samples.* Los Angeles: The Getty Conservation Institute.
- SMITH, B. J., GOMEZ-HERAS, M. & MCCABE, S. 2008. Understanding the decay of stone-built cultural heritage. *Progress in Physical Geography* 32, 439-461.
- SMITH, B. J., GÓMEZ-HERAS, M. & VILES, H. A. 2010a. Underlying issues on the selection, use and conservation of building limestone. *In: B. J. SMITH, M. GÓMEZ-HERAS, H. A. VILES & CASSAR, J. (eds.) Limestone in the Built Environment: Present-Day Challenges for the Preservation of the Past.* London: The Geological Society. Special Publications.
- SMITH, B. J., GOMEZ-HERAS, M., VILES, H. A. & CASSAR, J. (eds.) 2010b. *Limestones in the Built Environment: Present-day challenges for the preservation of the past,* London: Geological Society.
- SMITH, B. J., MCCABE, S., MCALLISTER, D., ADAMSON, C., VILES, H. A. & CURRAN, J. M. 2011. A commentary on climate change, stone decay dynamics and the 'greening' of natural stone buildings: new perspectives on 'deep wetting'. *Environmental Earth Sciences*, 63, 1691–1700.
- SMITH, B. J., SRINIVASAN, S., GOMEZ-HERAS, M., BASHEER, P. A. M. & VILES, H. A. 2001. Near-surface temperature cycling of stone and its implications for scales of surface deterioration. *Geomorphology*, 130, 76-82.
- SMITH, B. J., TÖRÖK, A., MCALISTER, J. J. & MEGARRY, Y. 2003. Observations on the factors influencing stability of building stones following contour scaling: a case study of oolitic limestones from Budapest, Hungary. *Building and Environment*, 38, 1173 – 1183.
- SMITH, B. J., WARKE, P. A. & CURRAN, J. M. 2004. Implications of climate change and increased "time-of-wetness" for the soiling and decay of sandstone structures in Belfast, Northern Ireland. *In: PRIKRYL, R. (ed.) Dimension Stone 2004: New*

*Perspectives for a Traditional Building Material*. London: Taylor & Francis Group.

SOPRINTENDENZA ARCHEOLOGICA PER LE PROVINCE DI NAPOLI E CASERTA 1992. *Alla ricerca di Iside: analisi, studi e restauri dell'Isola pompeiana nel Museo di Napoli*, Roma, Arti.

STANLEY-PRICE, N. & PONTI, G. 2003. Protective enclosures for mosaic floors: a review of Piazza Armerina, Sicily, after forty years. In: MICHAELIDES, D. (ed.) *Mosaics make a site: the conservation in situ of mosaics on archaeological sites. Proceedings of the VIth conference of the International Committee for the Conservation of Mosaics, Nicosia, Cyprus, 1996*. Rome, Italy: ICCM.

STANLEY-PRICE, N. P. & JOKILEHTO, J. 2001. The decision to shelter archaeological sites. Three case-studies from Sicily. *Conservation and Management of Archaeological Sites*, 5, 19-34.

STEFANIS, N. A., THEOULAKIS, P. & PILINIS, C. 2009. Dry deposition effect of marine aerosol to the building stone of the medieval city of Rhodes, Greece. *Building and Environment*, 44, 260-270.

STEIGER, M. 2003. Salts and crusts. In: BRIMBLECOMBE, P. (ed.) *Effects of Air Pollution on the Built Environment*. Imperial College Press.

STEIGER, M., CHAROLA, A. E. & STERFLINGER, K. 2011. Weathering and Deterioration. In: SIEGISMUND, S. & SNETHLAGE, R. (eds.) *Stone in Architecture: Properties, Durability*. 4th ed. Berlin: Springer.

STERNBERG, T., VILES, H. & CATHERSIDES, A. 2011. Evaluating the role of ivy (*Hedera helix*) in moderating wall surface microclimates and contributing to the bioprotection of historic buildings. *Building and Environment*, 46, 293-297.

STEWART, J. 2008. Rapid Assessment of Shelters over Mosaics: Methodology and Initial Results from England. *9th Conference of the International Committee for the Conservation of Mosaics (Tunisia, 2005). Lessons learned: reflecting on the theory and practice of mosaics conservation*, 182-190.

- STEWART, J., JULIEN, S. & STANIFORTH, S. 2004. An integrated monitoring strategy at Chedworth Roman villa (Gloucestershire). *Preserving archaeological remains in situ?: proceedings of the 2nd conference, 12-14 September 2001*, 179-187.
- STEWART, J., NEGUER, J. & DEMAS, M. 2006. Assessing the Protective Function of Shelters over Mosaics. *The Getty Conservation Institute Newsletter*. Los Angeles: The Getty Conservation Institute.
- STEWART, J., STANIFORTH, S. & BERRY, J. 2003. Chedworth Roman Villa: a methodology for the monitoring of in situ mosaics. In: BLANC, P. & CHANERIAUX, F. (eds.) *Les mosaïques, conserver pour présenter? VIIe conférence générale du Comité international pour la conservation des mosaïques (Arles, 1999)*. Musée archéologique de Saint-Romain-en-Gal: Éditions du Musée de l'Arles et de la Provence antiques.
- STROUD, K. 2010. Hagar Qim & Mnjdra Prehistoric Temples (Qrendi). In: HERITAGE MALTA (ed.) *Malta Insight Heritage Guides*. Sta Venera: Midsea Books.
- STUART, B. 2007. *Analytical Techniques in Materials Conservation*, Chichester, John Wiley & Sons.
- TEUTONICO, J. M. 2001. Protective shelters for archaeological sites in the southwest USA. Conclusions and recommendations. *Conservation and Management of Archaeological Sites*, 5, 87-90.
- THEOULAKIS, P. 1993. Microclimatic monitoring at the temple of Apollo Epikourios at Bassai, Greece. In: THIEL, M. J. (ed.) *Conservation of Stone and Other Materials. Proceedings of the International RILEM/UNESCO Congress (Paris, 1993)*. London: E & FN Spon.
- THOMPSON, T. D. & TAYLOR, M. R. 2001. Establishment of conservation, design and construction criteria for protective shelters at Fort Selden State Monument, New Mexico. *Conservation and Management of Archaeological Sites*, 5, 45-54.
- THORNBUSH, M. & VILES, H. 2004. Integrated digital photography and image processing for the quantification of colouration on soiled limestone surfaces in Oxford, England. *Journal of Cultural Heritage*, 5, 285-290.

- TIDBLAD, J., KUCERA, V., MIKHAILOV, A. A., HENRIKSEN, J., KREISLOVA, K., YATES, T., STOCKLE, B. & SCHREINER, M. 2001. UN ECE ICP Materials: Dose-response functions on dry and wet acid deposition effects after 8 years of exposure. *Water Air and Soil Pollution*, 130, 1457-1462.
- TÖRÖK, A. 2002a. The influence of wall orientation and lithology on the weathering of ooidal limestone in Budapest, Hungary. In: PRIKRYL, R. & VILES, H. (eds.) *Understanding and managing stone decay*. Prague: Karolinum Press.
- TÖRÖK, A. 2002b. Oolitic limestone in a polluted atmospheric environment in Budapest: weathering phenomena and alterations in physical properties. In: SIEGISMUND, S., WEISS, T. & VOLLBRECH, A. (eds.) *Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies*. London: Geological Society.
- TÖRÖK, A. & PŘIKRYL, R. 2010. Current methods and future trends in testing, durability analyses and provenance studies of natural stones used in historical monuments. *Engineering Geology*, 115, 139–142.
- TORRACA, G. 2009. *Lectures on Materials Science for Architectural Conservation*, Los Angeles, The Getty Conservation Institute.
- TRINGHAM, S. & STEWART, J. 2008. Protective Shelters over Archaeological Sites: A Review of Assessment Initiatives. *9th Conference of the International Committee for the conservation of mosaics (Tunisia, 2005). Lessons learned: reflecting on the theory and practice of mosaics conservation*, 204-214.
- TRUDGILL, S. T. 1975. Measurement of erosional weight-loss of rock tablets. *British Geomorphological Research Groups Technical Bulletin*, 17, 13-19.
- TRUDGILL, S. T. 1977. Problems in the estimation of short-term variations in limestone erosion processes *Earth Surface Processes* 2, 251-256.
- TRUDGILL, S. T. & VILES, H. A. 1998. Field and laboratory approaches to limestone weathering. *Quarterly Journal of Engineering Geology*, 31, 333-341.
- TRUDGILL, S. T., VILES, H. A., INKPEN, R., MOSES, C., GOSLING, W., YATES, T., COLLIER, P., SMITH, D. I. & COOKE, R. U. 2001. Twenty-year weathering remeasurements

- at St Paul's Cathedral, London. *Earth Surface Processes and Landforms*, 26, 1129-1142.
- VAN TILBURG, J. A., AREVALO PAKARATI, C. & HOME, A. 2007. Mapping Features. In: EPPIC, R. & CHABBI, A. (eds.) *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Illustrated Samples*. Los Angeles: The Getty Conservation Institute.
- VILES, H. 1990. The early stages of building stone decay in an urban environment. *Atmospheric Environment*, 24A, 229-232.
- VILES, H. 1996. Monitoring the effects of the Oxford Transport Strategy on building stone decay and soiling. In: RIEDERER, J. (ed.) *8th International Congress on Deterioration and Conservation of Stone*. Berlin: Möller Druck.
- VILES, H. 2003. Conceptual modeling of the impacts of climate change on karst geomorphology in the UK and Ireland. *Journal for Nature Conservation*, 11, 59–66.
- VILES, H. 2005. Microclimate and weathering in the central Namib Desert, Namibia. *Geomorphology*, 67, 189-209.
- VILES, H. 2012. Greening Stone Conservation: Exploring the Protective Role of Plants and Microbes. *12th International Congress on the Deterioration and Conservation of Stone*. New York.
- VILES, H. 2013. Durability and conservation of stone: coping with complexity. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46, 367-375.
- VILES, H. & GORBUSHINA, A. 2003. Soiling and microbial colonisation on urban roadside limestone: a three year study in Oxford, England. *Building and Environment*, 38, 1217-1224.
- VILES, H., GOUDIE, A., GRAB, S. & LALLEY, J. 2011. The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. *Earth Surface processes and Landforms*, 320–333.
- VILES, H. A., CAMUFFO, D., FITZ, S., FITZNER, B., LINDQVIST, O., LIVINGTON, R. A., MARAVELAKI, P. N. V., SABBIONI, C. & WARSCHEID, T. 1997. Group Report:

- What Is the State of Our Knowledge of the Mechanisms of Deterioration and How Good Are Our Estimates of Rates of Deterioration? In: BAER, N. S. & SNETHLAGE, R. (eds.) *Saving Our Architectural Heritage. The Conservation of Historic Stone Structures*. Chichester: John Wiley & Sons.
- VILES, H. A. & GOUDIE, A. S. 2007. Rapid salt weathering in the coastal Namib desert: Implications for landscape development. *Geomorphology*, 85, 49–62.
- VILES, H. A., TAYLOR, M. P., YATES, T. J. S. & MASSEY, S. W. 2002. Soiling and decay of NMEP limestone tablets. *Science of the Total Environment*, 292, 215-229.
- VILLARI, G. 2004. La musealizzazione di un sito archeologico. In: MELI, G. (ed.) *Apparati musivi antichi nell'area del Mediterraneo: conservazione programmata e recupero. Contributi analitici alla Carta del Rischio. Atti del I convegno internazionale di studi: La materia e i segni della storia, Piazza Armerina, 9-13 Aprile 2003*. Palermo: Centro regionale per la progettazione e il restauro.
- WAINWRIGHT, G. J. 1984. Assessment of Importance. EH Report AA63432/1: English Heritage.
- WARKE, P. A. 2007. Complex weathering in drylands: Implications of 'stress' history for rock debris breakdown and sediment release. *Geomorphology*, 85, 30-48.
- WATT, D. & COLSTON, B. 2000. Investigating the effects of humidity and salt crystallisation on medieval masonry. *Building and Environment*, 35, 737–749.
- WATT, D. & SWALLOW, P. 1996. Causes of deterioration and decay. *Surveying Historic Buildings*. Shaftesbury: Donhead.
- WEBB, A. H., BAWDEN, R. J., BUSBY, A. K. & HOPKINS, J. N. 1992. Studies on the effects of air pollutions on limestone degradation in Great Britain. *Atmospheric Environment*, 26B, 165-181.
- WEIDMANN, D. 2008. Orbe-Bosceaz (Canton de Vaud, Suisse) 1995-2005: 30 ans de réflexions sur la conservation d'anciennes et de nouvelles mosaïques. In: ABED, A. B., DEMAS, M. & ROBY, T. (eds.) *9th Conference of the International Committee for the conservation of mosaics (Tunisia, 2005). Lessons learned:*

*reflecting on the theory and practice of mosaics conservation*. Los Angeles: The Getty Conservation Institute.

- WEIDMANN, D., FLATT, R., FÉLIX, C., GIRARDET, F. & GLAUSER, A. 2003. Analyse des altérations et déformations de mosaïques à Orbe-Boscéaz (Canton de Vaud, Suisse). In: MICHAELIDES, D. (ed.) *Mosaics make a site: the conservation in situ of mosaics on archaeological sites. Proceedings of the VIth conference of the International Committee for the Conservation of Mosaics, Nicosia, Cyprus, 1996*. Rome: ICCM.
- WEIDMANN, D. & GIRARDET, F. 2005. Contrôle climatique de mosaïques in situ sous abris. *Proceedings of the VIIIth Conference of the International Committee for the Conservation of Mosaics (ICCM). Wall and Floor Mosaics: Conservation, Maintenance, Presentation (Thessaloniki, 2002)*. Thessaloniki: Europaiko Kentro Vyzantinon kai Metavyzantinon Mnemeion.
- WEISS, T., SIEGESMUND, S., KIRCHNER, D. & SIPPEL, J. 2004. Insolation weathering and hygric dilatation: two competitive factors in stone degradation. *Environmental Geology*, 46, 402–413.
- WEST OXFORDSHIRE DISTRICT COUNCIL 2014. 2014 Air Quality Progress Report for West Oxfordshire District Council.
- WOOLFITT, C. 2007. Preventive conservation of ruins: reconstruction, reburial and enclosure. In: ASHURST, J. (ed.) *Conservation of Ruins*. Amsterdam: Butterworth-Heinemann.
- WUNDERER, E. 2002. Climatologic considerations for the shelter construction. In: KRINZINGER, F. (ed.) *A Roof for Ephesos. The shelter for terrace house 2*. Wien, Austria: Österreichisches archäologisches Institut.
- YAKA ÇETIN, F. & İPEKOĞLU B. 2013. Impact of transparency in the design of protective structures for conservation of archaeological remains. *Journal of Cultural Heritage*, 14, e21-e24.
- YATES, T. 2007. Results fom the 2005-2006 trend exposure programme. Corrosion attack on limestone after 1 year of exposure. *Convention on Long-Range Transboundary Air Pollution. UN/ECE International Co-operative Programme on*

*Effects on Materials, including Historic and Cultural Monuments.* Watford: Building Research Establishment.

YAVUZ, H., DEMIRDAG, S. & CARAN, S. 2010. Thermal effect on the physical properties of carbonate rocks. *International Journal of Rock Mechanics and Mining Sciences*, 47, 94-103.

ZANARDINI, E., ABBRUSCATO, P., GHEDINI, N., REALINI, M. & SORLINI, C. 2000. Influence of atmospheric pollutants on the biodeterioration of stone. *International Biodeterioration & Biodegradation*, 45, 35-42.

ZANELLI, A. 2015. Architectural fabric structures in the refurbishment of archaeological and cultural heritage areas. In: LLORENS DE, J. I. (ed.) *Fabric Structures in Architecture*. Oxford: Elsevier.

ZANELLI, A., ROSINA, E., BECCARELLI, P., MAFFEI, R. & CARRA, G. 2013. Innovative solutions for ultra-lightweight textile shelters covering archaeological sites. In: CRUZ, P. (ed.) *Structures and Architecture: New concepts, applications and challenges*. London: CRC Press.