Building and Environment 210 (2022) 108690

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Role of masonry fabric subsurface moisture on biocolonisation. A case study

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ARTICLE INFO

Keywords:
Bioreceptivity
Cultural heritage
Moisture
Non-destructive technology

ABSTRACT

High moisture is one of the main factors favouring the growth of algae and other organisms on stone surfaces. However, little is known about the specific effects of subsurface moisture on this process. Some regions will be exposed to longer periods of humidity and rainfall as a result of climate change. Understanding the role and internal dynamics of moisture in stone is therefore essential to enable development of mechanisms for controlling biological colonisation and thus preventing biodeterioration. The present case study is a preliminary investigation of the role of subsurface moisture in the biocolonisation process and was conducted on the walls of the Guard House of Stirling Castle. Moisture was measured at depth (up to 3, 11 and 30 cm) in both interior and exterior walls of the building with a portable device based on non-destructive microwave technology. Data were analysed in relation to the orientation of the walls, type of stone and biocolonisation. The subsurface moisture between 3 and 11 cm was found to play an important role in supporting colonising organisms on the building by modulating bioreceptivity.

1. Introduction

According to current scientific knowledge, more frequent and intense extreme rainfall events, together with more frequent droughts in arid and semi-arid areas, are expected to occur in the near and distant future as a result of climate change. These changing climate conditions will seriously affect historical buildings because the floors and walls of the buildings tend to be in close contact with water, and the length of time that the stone will remain damp at depth will therefore probably change [1,2]. There is already evidence that damp in natural porous stone structures in some areas will become more troublesome because of more prolonged periods of wet weather in winter associated with climate change [3].

Among the expected extreme rainfall events, the increase in wind-driven rain (WDR) [4] is a matter of concern regarding the conservation of built heritage. This type of rain impacts the building envelope and can lead to surface erosion and facilitate penetration of moisture, thus leading to biodeterioration due to the growth of mould inside the building [5,6]. Moisture input from rainfall, particularly when wind driven, has been demonstrated to travel deep in stone [5,7,8]. Predicted changes in WDR under a high emission scenario are likely to promote an increase in near-surface moisture cycles and an increase in deep-seated wetting between autumn and spring [9]. Thus, variations in moisture regimes and the movement of moisture within masonry material are expected [10]. Knowledge about such regimes is critical to understanding water resistance in building materials as information is needed to predict and manage the effects of climate change on world heritage monuments [11].

The presence and movement of moisture on masonry stone is a well-documented cause of damage to the stone [12–14] as water is a major weathering agent. Moisture is involved in both physical (migration and crystallization of soluble salts) and biological weathering processes in buildings. Although the effect of surface moisture has been studied in relation to both types of weathering [15–18], the effect of subsurface moisture has only been considered in salt weathering processes [19,20].

Moisture at the stone surface is known to be one of the main factors favouring growth of algae and other organisms [21–24], while drying of the substrate can lead to growth of spore-forming bacteria (e.g. Bacillus spp. and heat tolerant actinomycetes), in preference to Gram-negative bacteria, in temperate climates [25]. However, the role of subsurface moisture in biocolonization is not clear. Consideration of the complexity of moisture dynamics in stone is essential for understanding the

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https://doi.org/10.1016/j.buildenv.2021.108690
Received 24 September 2021; Received in revised form 25 November 2021; Accepted 14 December 2021

distribution of organisms on the stone and the associated biodeterioration mechanisms. This is especially important in the context of climate change, with models suggesting a shift towards longer periods of deep moisture in the stone of buildings, which may lead to increased cover of facades by biological colonisation, which can cause unsightly black, green or orange streaks from roof level to ground level [3].

Because of the difficulties associated with measuring subsurface moisture content, studies of subsurface moisture on masonry walls in historic buildings are scarce, and much of the current understanding is based on assumptions rather than empirical evidence from quantitative field data [7]. The gravimetric method and Karl Fischer Titration (KFT) chemical method require sampling to be carried out for measuring subsurface moisture. However, in some cases samples cannot be obtained, because of the cultural value of the building, or they cannot be obtained from the optimal positions for analysis of subsurface moisture. Most non-destructive methods available provide relative values and some, such as electrical resistivity tomography, are difficult to interpret because the measures are affected by the presence of salts [12,26]. However, a more recently developed portable non-destructive device, based on microwave technology, provides readings that are independent of salinity and allows quantification and mapping of both surface and deep moisture. The method has recently been calibrated for building stones [27] and successfully used on a granite wall and a sandstone tower [28] providing very useful information about the depth-related distribution of moisture.

The present study provides a preliminary investigation of the role of subsurface moisture in biocolonisation through quantification and mapping of the horizontal and depth-related distribution of moisture in the walls of the Guard House at Stirling Castle. Using microwave-based technology, wall-scale research was carried out on each of the four facades oriented in the 4 cardinal directions, on both the inner and outer faces, which are mainly colonised by lichens (N, W and E) and algae (S). In addition, research was carried out at masonry-stone scale in both colonised and uncolonised stones with different surface finishes in order to explore the role of moisture in the bioreceptivity of the stone.

2. Material and methods

2.1. Case study

In order to identify the internal elements that determine the complex distribution of moisture in masonry, as well as its role in surface biocolonisation, the Guard house at Stirling Castle was selected as a case study (Fig. 1). The Guard house, located at the North Gate of Stirling Castle (Scotland), is a small building with basalt and sandstone blocks in the corners. It was selected for study because i) the distribution of moisture was able to be monitored along the thickness of walls with different orientations, from both outside and inside the building, ii) the walls are colonised by different types of microorganisms: algae and lichens in north-, east- and west-facing walls and only algae in the south-facing wall, and iii) each wall has colonised and uncolonised masonry, enabling analysis of the relationship between subsurface moisture and biocolonisation at wall scale and at individual masonry stone scale.

The climate in Stirling is oceanic with mild summers and cool, wet winters. Summers are the hottest in Scotland, as the area is relatively far from the cooling effects of the North Sea and the Firth of Clyde (https://www.metoffice.gov.uk/).

2.2. Moisture measurements

Moisture was measured three days during the October–November 2018 period in selected areas of 180 × 150 cm^2 surface on each wall from both the interior and the exterior of the building in order to analyse the relationship between subsurface moisture and biocolonisation on the different walls. A portable measuring device based on non-destructive microwave technology (MOIST350B), which has the advantage of detecting moisture independently from salinity, was used. The MOIST350B device (hf sensor, Leipzig, DE) produces microwave fields of varying geometry sensitive at different depths, and measurements are made via contact between the sensor head and the stone surface. Based on a reflection principle, the attenuation of microwaves passing through the damp material is measured. Three sensing heads enabling penetration to depths up to 3, 11 and 30 cm were used. The sensors have been found to calibrate well over a range of water contents for building stones

Fig. 1. The Guard house of Stirling Castle (Scotland).

[27]. In order to compare results from the three sensors the device MIC (moisture index comparable) mode was used. Measurements were made with a 15 cm grid/point spacing for the 3 and 11 cm sensors and with 30 cm grid/point spacing for the 30 cm sensor. Thus, 132 data points were obtained with the 3 and 11 cm sensors, and 42 data points with the 30 cm sensor. Data, expressed as dimensionless numbers between 0 and 4000 related to the reflection coefficient, were analysed using MOISTANALYZE 3.2 software, which provides spatial representations of the moisture index across the masonry walls. Moreover, the distributional characteristics of the group of data in quartiles were considered by processing data as box and whisker pots. The high number of measures together with this data processing allow to overcome some of the disadvantages of this technique due to wall surface irregularities.

In order to examine the role of subsurface moisture in the bioreceptivity, both colonised and uncolonised masonry stones were selected (two colonised and two uncolonised) in both east-facing and west-facing walls. As bioreceptivity is strongly influenced by roughness, one of the uncolonised stones selected had a smooth surface, while the other had a rough surface (on each east and west facade). Twenty measurements were taken on each stone with the 3 and 11 cm sensors and 30 measurements were made with the 30 cm sensor.

3. Results

Maps were constructed to show the distribution of surface (3 cm depth) and subsurface (11 and 30 cm depth) moisture in west, north, east and south-facing interior and exterior faces of the walls, on each of the three different measurement days (Fig. 2). High moisture content is indicated in blue, and low moisture content in yellow. On the outer face of the walls, the moisture content did not vary with height, but there were differences at all depths on the north, east and west facades depending on the type of stone. In all of these cases, the moisture content was lower in sandstone than in basalt. In each wall, the moisture content remained constant with depth in sandstone, but varied with depth in the basalt. It should be noted that the sensors measure down to a particular depth, not *at* a particular depth, and they are therefore influenced by near-surface water contents [28]. Surface moisture (to 3 cm) was therefore lower than subsurface moisture in basalt, with most of the moisture located between 3 and 11 cm, as the moisture index to a depth of 30 cm was lower than the moisture index to 11 cm. This trend was independent of the orientation of the wall and was repeated on the three measurement days. In the inner face of walls, there was also no difference in relation to height, and subsurface moisture was greater than surface moisture, independently of the orientation.

Although these types of graphics are useful for visualising the spatial distribution of water in the wall and comparing variations at a single point, comparison of the whole wall is difficult as it includes numerous points and two different materials affected in different ways by moisture. Thus, although the microwave-device readings on the sandstone were quite constant, they varied widely on the basalt. These differences can lead to misinterpretation of the data. For a more accurate analysis of the differences in moisture contents of the walls at various depths and to evaluate the behaviour of masonry systems, the data for basalt were displayed in box-and-whisker plots, which include the spread and centre of the data set. The box-and-whisker plots for moisture content in each wall measured from respectively outside and inside, on the three different days are shown in Fig. 3. Similar results were obtained on all three days. The surface moisture content was lower than subsurface content (measured with the 11 cm and 30 cm sensors) in both the inner and outer faces of the four walls, but both were similar in the four inner faces and in the four outer faces. Most of the subsurface moisture was located at a depth of between 3 and 11 cm in the outer face of the north, east and west walls but in the outer face of the south wall and in all the inner faces subsurface moisture was distributed between 3 and 30 cm as

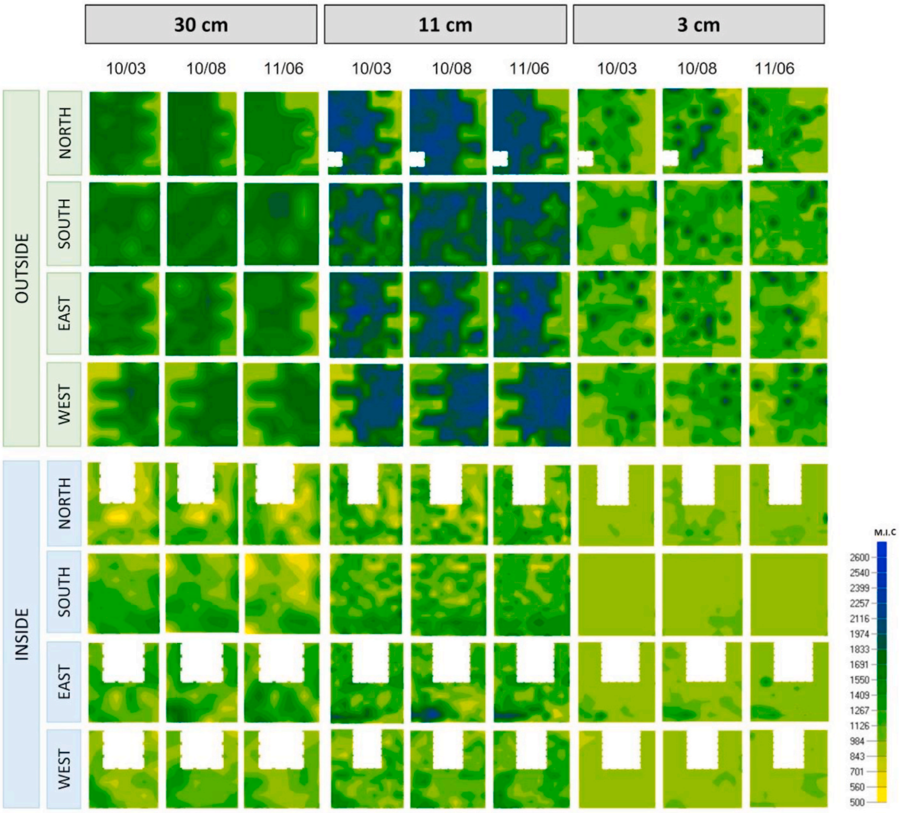

Fig. 2. Maps of moisture distribution to depths of 3, 11 and 30 cm in the exterior and interior faces of the four walls of the Guard House of Stirling Castle, measured on three different days. M.I.C: moisture index comparable.

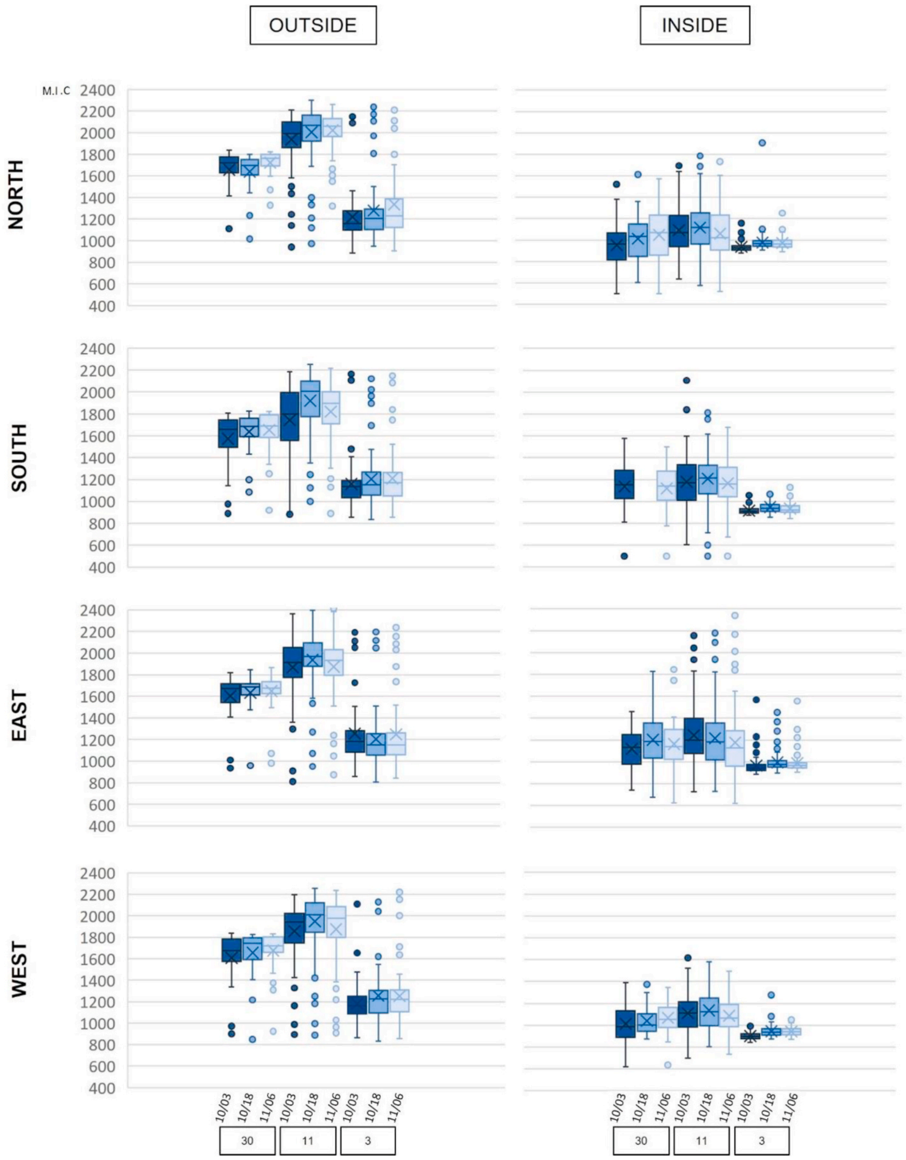

Fig. 3. Box-and-whisker plots of moisture contents for interior and exterior faces of each wall (north, south, east and west) at different depths (3, 11 and 30 cm) and on the three measurement days. M.I.C: moisture index comparable.

in those cases the moisture indexes to 11 cm and to 30 cm are similar.

In order to analyse each whole wall, the moisture distribution in each wall from the outer to the inner face on only one day is represented in Fig. 4. The distribution of moisture on the whole wall was similar for west, north and east walls; however, on the south wall, in addition to the previously mentioned wider distribution of subsurface moisture, the moisture content to 30 cm in the inner and outer faces was similar while in the other walls the moisture content to 30 cm in the outer face was greater than in the inner face.

The moisture indexes for the October 3, 2018 day at 30, 11 and 3 cm depth for each of the four selected stones in the east and west walls are shown in Fig. 5. The results for the other two days are similar. As in the case of the walls, the subsurface moisture content was higher than the surface moisture content, being highest to a depth of 11 cm.

In both walls, at all depths, the moisture content of the uncolonised smooth stones was sufficient to enable biocolonisation, as they were higher than or similar to those in the colonised stones, while those of the rough uncolonised stones were lower.

4. Discussion

The use of a portable measuring device based on non-destructive microwave technology made it possible to determine differences in the moisture content of both types of stone in the walls of the Guard House of Stirling Castle. The moisture content was lower in sandstone than in basalt and remained constant with depth, while it varied with depth in the basalt. Orr et al. [28] found that moisture affects the various materials in walls and structures in different ways, reporting porosity-related differences in the moisture content of granite and mortar joints in walls and sandstone and mortar joints in pinnacles. Because basalt and sandstone are very different in terms of porosity (0.1–1.0% in basalt and 5–25% in sandstone) [29], the different relationships between stone and moisture are not surprising. However, the different dielectric permittivity of both materials (8 for basalt and 6 for sandstone), should be also considered as it is related with the attenuation of microwaves passing through the material. Thus, not direct comparison on the moisture content in both rocks can be made but it is possible to assert that moisture variations with depth are more pronounced in basalt than in sandstone in the four walls studied. Because of

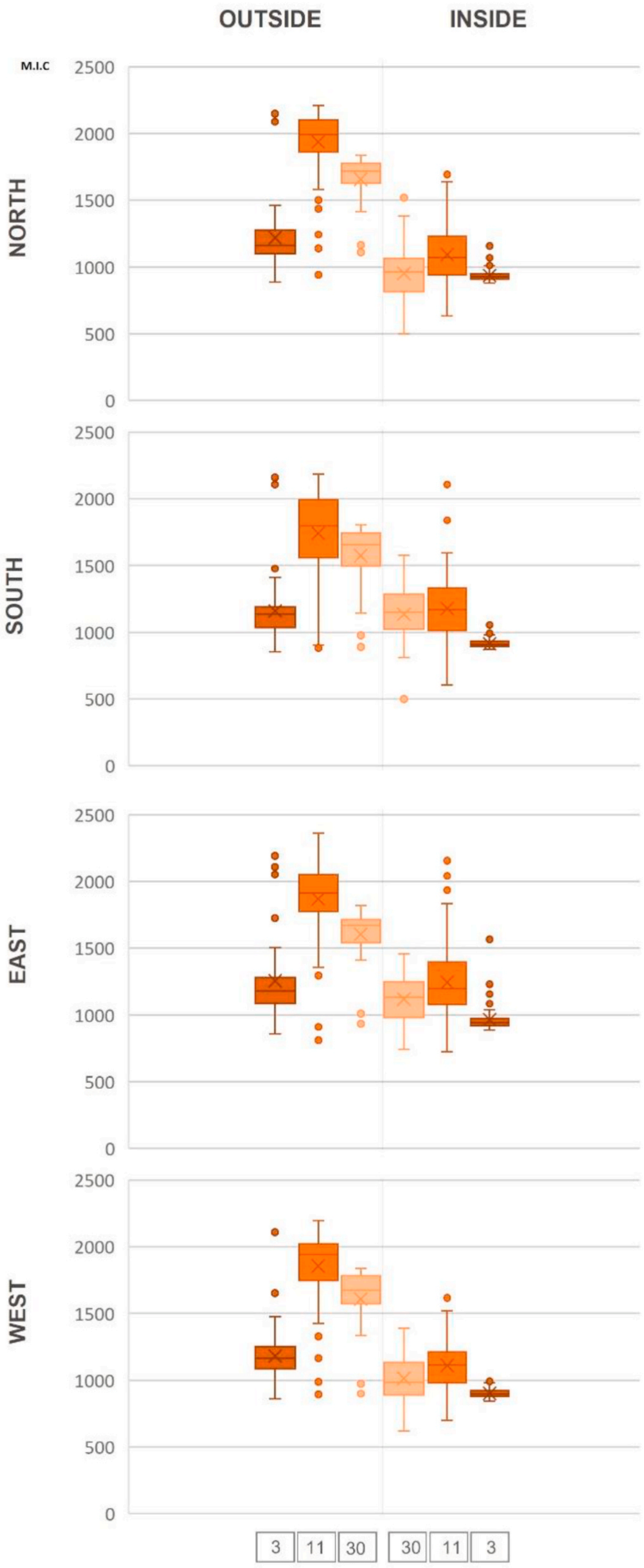

Fig. 4. Box-and-whisker plots of moisture contents measured on 3/10/20 for the exterior-interior transect of each wall. M.I.C: moisture index comparable.

the impossibility of comparing rocks, only basalt moisture data have been processed (Figs. 3–5).

4.1. Moisture distribution at different depth levels

The moisture was heterogeneously distributed along the thickness of the walls. Subsurface moisture content (3–30 cm depth) was higher than surface moisture (0–3 cm) in the four walls studied. Most of the subsurface moisture was located between 3 and 11 cm in the outer walls, except in the south wall where subsurface water was more widely distributed, as in all of the inner faces (3–30 cm depth). Cutler et al. [30] also established the location of the dampest area at 3–11 cm depth in the outer face of walls by using 2D electrical resistivity tomography, in a study of depth-related distribution of moisture in four walls in different buildings. Sass and Viles [31] also related an apparent zone of enhanced moisture at a depth of 5–15 cm below the surface exposed to rainfall on building walls. However, other authors have reported higher surface moisture content than subsurface moisture content, e.g. in the Lukianos monument, analysed by Ince et al. [32] using non-destructive techniques to determine moisture penetration.

The observed differences between surface (0–3 cm) and subsurface (3–30 cm) moisture contents are consistent with the usual wetting-drying cycles in walls: surface wetting is regularly followed by drying, depending on the weather conditions, while interior wetting requires the accumulation of surface moisture to penetrate at depth and dries out much more slowly [33], following seasonal cycling [3]. McAllister et al. [7] highlighted differences in moisture cycling between near-surface (5–10 mm) and deeper regions within the stone (sandstone), and Srinivasan et al. [34] demonstrated experimentally that although the inner mass of a limestone block remained damp after being exposed to simulated wetting with a water spray, the surfaces of the blocks may dry out due to simulated environmental conditions of airflow and intermittent thermal cycles. However, the external atmospheric conditions only determine evaporation from the wall surface under conditions of high surface water content and for a lower moisture content on a wall surface, the evaporation rate is often limited by the internal moisture [35].

Nevertheless, there are some reported cases, e.g. of the basement of a medieval town hall [36], where the moisture content inside masonry walls (to a depth of 60–80 cm) is much higher than in the subsurface area. Damp occurs in basement walls as a result of the capillary action of water from the ground, as indicated by the decrease in moisture content with increasing height. Height-related differences in moisture content are common in historical buildings [37–39] where walls are often not well isolated from the ground. Rising damp occurs at both the stone surface and inside, and because the inner mass dries out slowly, moisture can accumulate at deeper levels than when rainfall is the only source of water. As there was no height-related distribution of moisture in any of the inner and outer faces of the four walls in the Guard House of Stirling Castle and most of the moisture was located at the subsurface level, the ground can be ruled out as a source of water accumulating in the wall, and rainfall is probably the only source of water in the stone. Moreover, the maximum amount of subsurface moisture on the inner face of the wall was similar to the surface moisture on the outer face of the wall. This indicates a strong hygrothermal interaction between the exterior and interior via the transfer of heat and moisture to the walls due to the lack of adequate air space, insulation or vapour retarders, as is common in historical buildings in Europe [5]. The interaction between exterior and interior walls is quite worrying in the case of strong wind driven rain as it causes a significant increase in moisture content inside walls or stone block surfaces [5,7].

Although guidelines for conducting moisture measurement on walls suggests study of the moisture distribution along the thickness of at least one inner and one outer wall [36], to our knowledge studies addressing the distribution of moisture along the thickness of walls are scarce. Our findings are consistent with the distribution model presented by Hola

Fig. 5. Box-and-whisker plots of moisture contents measured on October 3, 2018 to depths of 3, 11 and 30 cm in masonry stones in the east and west walls. M.I.C: moisture index comparable.

[36] for exterior walls when the air moisture and temperature on both sides of the wall are different. In those cases, as in the present study, the difference between surface and deep moisture in the exterior face of the wall is greater than in the inner face (Fig. 4). However, although this is true for the four walls, the difference in moisture content to 3 cm and to 30 cm in the exterior face of the south wall is less than in the other three orientations. The moisture content inside the wall is therefore lower than in the other walls but as already pointed out, the moisture is more homogenously distributed between 3 and 30 cm. Thus, moisture in the exterior south wall behaves similarly to that in interior walls. This suggests a more stable environment in the exterior of this wall which may be due to the proximity to that part of the building and a natural rocky outcrop.

Subdivision of surface or near-surface, subsurface and deeper moisture content seems to be arbitrary or dependent on the measurement device used. Thus, for instance, while McAllister et al. [7] consider near-surface to be between 5 and 10 mm, Ince et al. [32] consider surface moisture to a depth of 40 mm and subsurface moisture to a depth of 300 mm, and Vecchiattini [40] considers subsurface moisture as between 2 and 4 cm. These differences hamper comparison of the findings of different studies and highlight the need to standardize the depths.

4.2. *Role of moisture in the distribution of biocolonisation*

Various studies have analysed the influence of water (vapour or liquid) on the spatial distribution of biocolonisation on monuments, but only considering the effect of surface water. Caneva et al. [15] demonstrated significant correlations between lithobiont growth and incident rainfall in several buildings in Rome and the surrounding areas. Traversetti et al. [16] demonstrated the important role of rainfall, specifically wind-driven rain, on biological growth in the archaeological site of Pompeii. Cutler et al. [41] studied the effect of humidity on the distribution of algal biofilms and although they did not find a direct link, they indicated a possible relationship between the temporal distribution of humidity and transient wetting events in the process of biofilm development. Ortega-Morales et al. [42] observed the effect of relative humidity and substrate moisture content on the development and biodiversity of biofilms both outside and inside Mayan monuments in Uxmal (Mexico). In addition, Gorbushina [43] and Charola et al. [44] showed that phototrophic biofilms usually appear in humid patches caused by rainfall on the walls.

Mould growth is the most common process related with the presence of water on the surface of indoor walls. Available water is the most important factor for fungi growth on building materials [45] being capable of growing when the water activity on building materials is approximately 0.7 [46]. Sedlbauer [47] stipulates as a risk limit for mould fungus infestation a lasting surface humidity of more than 80% over a prolonged period of time. The expected increase of high indoor relative humidity consequence of climate change leads to project an increase of the mould presence [48].

In the present study, the external and internal surface moisture contents (up to 3 cm depth) were the same on all four walls, but with differences in subsurface moisture. The depth and amount of subsurface moisture appear to be related to the distribution of colonising organisms on the building as although three of the walls were colonised by lichens, the wall with a different distribution of subsurface water (south wall) was only colonised just by green algae. The moisture content was lower at between 3 and 11 cm depth in the south wall than in the other three walls and is almost similar to that at 30 cm depth (i.e. there is less subsurface moisture and it is located deeper). We considered two possible explanations for this finding: a) the moisture content between 3 and 11 cm depth is lower because the developed biofilm retains more water than lichens (as sub-aerial green algae are known to be highly effective at sequestering moisture), and b) the algal biofilm needs a greater supply of moisture, which it obtains from the subsurface zone when there is no water on the surface deposited by rain, thus contributing to the outflow of moisture from the wall.

Cutler et al. [30] and Smith et al. [49] demonstrated that algal biofilms are capable of reducing the input of moisture, by determining the relationship between algal cover and drier conditions at depth. However, the reduction in the input of moisture in the wall by sequestering moisture has been considered a positive feed-back role for algal colonisation in facilitating greater moisture retention at depth [3]. Under these conditions of surface biosealing, it is possible that water can reach deeper areas in the wall, as observed here. In this respect, future studies should investigate differences in surface biosealing by lichens and sub-aerial biofilms.

Considering that algal biofilms are less tolerant of dry conditions than lichens, differences in the amount and distribution of moisture in the south wall may be related to the transmission of moisture from deep inside the wall to meet the water demand from algal biofilm under conditions of low relative humidity. Migration of moisture from depth within walls to surface is more effective when the hydraulic connection between near-surface and deeper regions of the wall is not disrupted [7]. Retention of water by algal biofilms can reduce evaporative loss of water from into the wall, thus preventing disruption of hydraulic connections and facilitating the uptake of deep moisture by the biofilm. In this respect, the amount of moisture measured from the interior of the building up to a depth of 30 cm on the south wall was similar to that measured up to a depth of 30 cm from the exterior of the wall, which may indicate a better hydraulic connection between the interior and exterior of the building.

The surfaces of the Guard House walls were not completely biocolonised. This was particularly evident in those walls mainly colonised by lichens where some pieces of masonry were colonised, and others were not. As the environmental conditions were the same on each wall, biocolonisation will be determined by differences in the bioreceptivity (susceptibility to be biocolonised [50,51]) of each piece. Bioreceptivity, in turn, is determined by intrinsic substrate properties, their dynamics and their relationships with external factors. Among these, open porosity, capillary water content and roughness are the most important intrinsic factors in relation to colonisation by phototrophs [52–54]. In the present study, with the aim of determining the role of subsurface moisture in bioreceptivity, the amount and distribution of moisture at depth was examined in colonised and uncolonised pieces of masonry with rough and smooth surfaces on east and west walls. Similar observations were made in all walls regarding surface and subsurface moisture contents, with lowest values at the surface and highest values at a depth of 11 cm (in both walls). Analysis of differences in moisture content at all depths showed that in both walls, smooth uncolonised stones have enough moisture to allow biocolonisation as the moisture contents were higher than in the colonised stones. However, in both walls, the moisture content of rough uncolonised stones was lower than that of the colonised stones.

Laboratory experiments demonstrated that properties determining the movement of water inside stone, such as open porosity, capillary water content and surface roughness are closely related to the bioreceptivity of the construction material [52,53,55,56]. However, the present study is the first to consider the combined effect of bioreceptivity of stone and roughness in real situations. On the walls under study, taking only the moisture content (surface and subsurface) into account, the smooth uncolonised pieces should have been colonised as the moisture content was higher than in colonised pieces; in these cases, the smooth texture of the surface is the limiting factor. However, when surface conditions are appropriate, biocolonisation only occurs when the moisture content is high enough. Thus, the moisture content of stone is the main factor determining bioreceptivity but is regulated by surface roughness.

5. Conclusions

The findings of the present study demonstrate the role of subsurface moisture in the building envelope in determining biocolonisation. The data reveal that subsurface moisture is, together with surface moisture, an important factor to be taken into account when managing biological colonisation of buildings. Both the depth and amount of subsurface moisture seem to be responsible for the distribution of colonising organisms.

The relationship between moisture and biocolonisation of buildings stones must be studied by analysing moisture content to a depth of 30 cm, as long as non-destructive technology can be applied. This indicates the need to redefine the term “interface” in terms of depth in biodeterioration studies.

Taking into account the expected increase in the frequency of extreme events in the present context of climate change and the subsequent increase in the moisture content of building materials, increased bioreceptivity, biocolonisation and biodeterioration of cultural heritage should be expected.

CRediT authorship contribution statement

B. Prieto: Writing – original draft, Conceptualization, Methodology, Investigation. **M.E. Young:** Writing – review & editing, Methodology, Investigation, Conceptualization. **A. Turmel:** Conceptualization, Investigation. **E. Fuentes:** Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was partly financed through project CGL2016-79778-R (AEI/FEDER, UE) and Xunta de Galicia (ED431 2018/32). E. Fuentes was financially supported by a PhD Fellowship-Contract MICINN-FPI (BES-2017-079927).

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