



ANALYZING MOISTURE RETENTION IN A NATURAL STONE VIA HYPERSPECTRAL IMAGING SUPPORTED BY PETROGRAPHIC OBSERVATIONS FOR MICROSTRUCTURAL INSIGHT

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Abstract

Stone conservation plays a vital role in the preservation of cultural heritage, particularly in maintaining the integrity of historic structures. Since moisture content (MC) is a crucial parameter involved in most stone deterioration processes (hygric and hydric swelling, salt and ice crystallisation, mineral dissolution and biological growth), monitoring this parameter provides key insights into the conditions of the building materials. This study explores the potential of hyperspectral imaging (HSI) to estimate the thickness of the surface water layer on a natural stone sample across varying moisture saturation levels, followed by complementary petrographic analysis by thin section to understand the distribution of moisture within the stone sample throughout the drying process. The findings confirm that petrographic analysis correlates with hyperspectral-derived maps of surface moisture thickness, specifically in identifying how moisture preferentially accumulates in certain areas based on pore connectivity and distribution. This correlation provides deeper insights into the transfer of moisture in the stone sample, explaining the patterns observed at different saturation levels.

Keywords: Moisture Content, Neubrunn Sandstone, Thin Section Petrography and Deterioration Processes.

1 Introduction

Stone constructions are fundamental to built heritage and the preservation of cultural identity and historical traditions, underscoring the collective responsibility to safeguard them for future generations. However, these structures are susceptible to weathering, primarily due to moisture uptake by porous stone surfaces, leading to degradation mechanisms such as salt crystallisation, freeze-thaw cycles, biological growth, and chemical alterations that gradually compromise the structural integrity and appearance of the stone (Alves et al., 2021). Therefore, it is evident that the determination and monitoring of the moisture content (MC) in historical buildings is of key importance to prevent deterioration processes. The most widely used techniques for determining MC in stones are the gravimetric method and the calcium carbide method (Camuffo and Bertolin, 2012). Although these techniques provide reliable results, they are highly destructive. To avoid potential damage to built heritage materials, several non-destructive methods have been proposed and successfully applied to estimate the MC (Moropoulou et al., 2013). These include infrared thermography (IRT), electrical resistivity tomography (ERT), and nuclear magnetic resonance (NMR) (Capitani et al., 2012).

Recently, significant progress has been made in the study of MC using the Hyperspectral Imaging (HSI) technique. This analysis facilitates both qualitative and quantitative evaluations of the MC present at the surface of the samples under

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investigation, allowing visualization of water distribution and quantitative information on water content (Manley, 2014). Despite the promising potential of HSI for the identification and monitoring of MC in stone materials, there has been limited research in this area. Liang et al. (2012) used HSI to monitor moisture in walls, considering water absorption bands in the short-wave infrared (SWIR) range, around 1.4 μm and 1.9 μm . Kogou et al. (2025) proposed a method for in-situ monitoring of moisture and salts in historical buildings based on the combination of SWIR spectral imaging and remote Raman spectroscopy with machine learning. Recently, Chaghdo et al. (2024) explored the potential of HSI as a non-invasive technique for quantitative evaluation of MC in six different types of stone materials (five natural stones and one historical brick) at five different saturation levels. The major challenge to accurately estimating the MC of a stone material is that the acquired HSI is highly dependent on the porosity of the material, its pore size distribution, and the environmental conditions (Camuffo, 1995; Menéndez, 2016). In addition, HSI, as a surface technique, provides information only on a thin top layer of the samples (approximately 100-300 μm) (Koirala et al., 2022). In Chaghdo et al. (2024), a proxy for MC was determined that is less dependent on acquisition and environmental conditions by expressing the reflectance of a moist sample relative to that of a dry and saturated sample. Although MC estimation using HSI is promising, its limitations prevent a consistent correlation between the top surface information obtained by HSI and the bulk MC. Meanwhile, the MC estimation technique requires the spectral reflectance of dry and fully saturated samples, to estimate the MC of wet samples. To reduce the number of required parameters and improve the interpretation of the MC distribution at the surface, we explore a methodology to estimate moisture thickness maps using the absorption spectrum of water. In this paper, we evaluate the results of the moisture thickness maps by comparing them with a microscopic analysis of porosity and stone texture.

2 Experimental Dataset and Method

2.1 Dataset

In this work, we prepared a hyperspectral dataset from Neubrunn stone (German sandstone). This stone is part of a larger group of stones from the Upper Triassic, also known as Weisser Mainsandstein. The stone sample is a cube with dimensions of 6×6×6 cm^3 . Following the standard NBN EN 1936:2007 procedure, the sample was fully saturated (100%) under a vacuum for 48 hours to ensure homogeneous moisture distribution. After full saturation, the sample's MC was gradually reduced using an oven at 60°C, producing samples with different saturation levels (90%, 75%, 50%, and 25%), which were left wrapped in foil for 48 hours to equilibrate before capturing the hyperspectral image. In this work, we used a Snapscan SWIR hyperspectral camera manufactured by Imec to acquire hyperspectral images of the prepared samples. The Snapscan SWIR camera operates from 1100 to 1670 nm, capturing over 100 spectral bands with a spectral resolution of approximately 5 nm. The spatial resolution of the image is approximately 0.5 mm. In addition to the hyperspectral dataset, a 30 μm thin section, as shown in Figure 1, was produced from this stone type, and a petrographic examination was performed to highlight the type of pores present.



Figure 1: General view of the thin section of Neubrunn sandstone

(single shot taken using a light table and a camera, dimension of the thin section: $3.5 \times 2.5 \text{ cm}^2$)

2.2 Methodology

In this work, we assume that the moist stone sample can be modelled as a two-layer mixture consisting of stone grains and water. We further assume that water is a non-diffusely reflecting material, whereas the stone grains reflect the incident light diffusely. In this mixing scenario, the thickness of the water layer (z) on top of the stone grains can be related to the spectral reflectance of the moist stone sample (R) using a simple physical model presented in (Koirala et al., 2022).

$$R = R' e^{-2az} \quad (1)$$

where R' is the spectral reflectance of the dry stone sample and a is the absorption spectrum of water. Estimating the thickness (z) of the water layer from the spectral reflectance of the moist stone sample then boils down to inverting equation (1); that is, by minimizing the expression $\|R - R' e^{-2az}\|$, subject to the constraint, $z \geq 0$.

3 Results and Discussion

This section presents the results of the hyperspectral-derived moisture thickness maps, along with the petrographic analysis conducted on a thin section of the stone sample Neubrunn.

Figure 2 displays an optical microscopy image of the thin section from Neubrunn stone, highlighting the internal microstructural features responsible for moisture retention. The petrographic analysis under a polarizing microscope provides essential insights into the internal pore structure of the Neubrunn sandstone. The intergranular pores, visible in yellow, are the primary contributors to the stone's effective porosity. These pores are critical for moisture retention and movement within the stone. Additionally, the analysis reveals a second category of pores, intragranular pores, located within the grains themselves, such as feldspar and rock fragments. While these pores contribute to porosity, their role in moisture retention is limited compared to the intergranular pores. The distinction between these two types of pores is vital in understanding how moisture behaves in Neubrunn sandstone. The intergranular pores serve as the primary pathways for moisture movement, whereas the intragranular pores have a secondary influence on moisture distribution.



Figure 2: Detail view showing the general appearance of Neubrunn stone under a polarizing microscope (single polarized light). The intergranular pores are visible in yellow in the picture. Quartz grains (nonporous) appear white. Feldspar grains and rock fragments appear in light grey.

The spatial distribution and retention of moisture within the stone sample at various saturation levels (100%, 90%, 75%, 50%, and 25%) are illustrated in Figure 3 through moisture thickness maps. To interpret these observations, the pore network of the stone is conceptually simplified as a system of cylindrical capillaries. Based on this conceptualization and assuming equilibrium conditions, capillary forces, which are strongest in the smallest capillaries, govern the sequence of pore saturation. At low moisture content, moisture is expected to occupy the smallest pores and pore throats first, with progressively larger pores becoming saturated as the overall moisture content increases.

This can be observed in the moisture thickness maps. At the dry state, the stone contains negligible moisture. As the moisture content increases to 25%, moisture begins to distribute more uniformly throughout the material, primarily occupying the finer intergranular pores, in accordance with the predicted behaviour of capillary-driven moisture retention. This suggests that the primary moisture retention mechanism is based on the connectivity and distribution of these pores. As the MC rises to 50%, and more pronounced at 75%, the moisture content is higher in certain laminae, following the stone's bedding. This is likely due to subtle variations in the stone's pore network between layers. Some layers within the stone consist of a network of finer pores (probably because the sand grains are slightly smaller), which become fully saturated at lower moisture contents. In contrast, other layers contain slightly larger pores that do not reach full saturation at these moisture levels. This observation is consistent with the behaviour at 100% saturation, where it is ensured that all pores are filled. At this point, the moisture thickness of the layers exhibits an inverted pattern. The layers that previously had higher moisture thickness at intermediate moisture contents (50%–75%) show little to no further increase, as these pores were already filled at lower overall moisture contents and do not absorb additional water as the moisture content increases. Conversely, the layers with lower moisture thickness at intermediate moisture contents exhibit a marked increase in moisture content at 100% saturation. These layers contain the largest pores, which only fill at full saturation. Given that these larger pores have the capacity to hold a greater volume of water when filled, they correspond to the layers with the highest moisture thickness at 100% saturation.

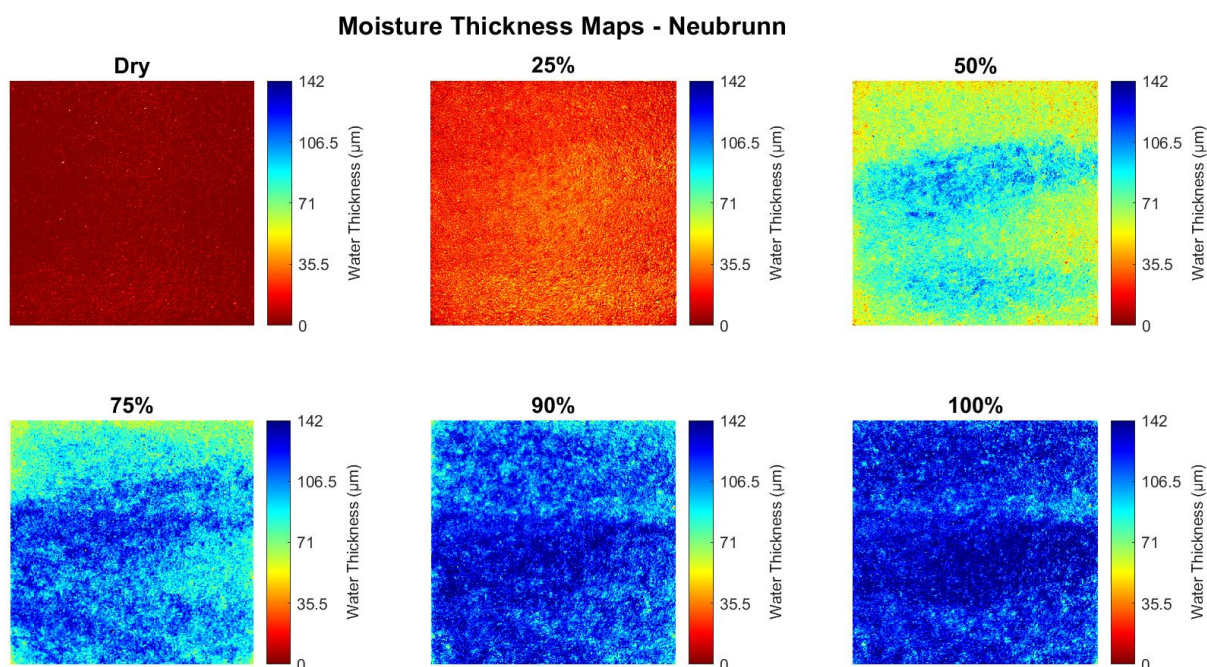


Figure 3: Moisture Thickness Maps of Neubrunn stone at varying saturation levels.

While the moisture thickness maps reveal the actual distribution of moisture, the petrographic analysis provides crucial context for interpreting these results. It helps explain why certain laminae absorb moisture more readily than others and how the pore network influences moisture retention across different saturation levels. The close correlation between the moisture maps and petrographic data highlights the primary role of intergranular pores in moisture distribution for Neubrunn sandstone.

4 Conclusion

In conclusion, this study critically examined the potential of hyperspectral imaging to estimate moisture thickness maps in Neubrunn sandstone and paired these findings with petrographic analysis for robust interpretation. The moisture maps revealed distinct distribution patterns across saturation levels, indicating that variations in pore structure significantly influence the spatial retention of water on the stone's surface. Complementary petrographic analysis provided a microstructural perspective that validated the mapping results by linking observed moisture trends to the stone's intricate pore distribution. This correlation reinforces the potential of hyperspectral imaging as a possible non-destructive tool for visualizing moisture transference and estimating moisture content within stone materials.

Acknowledgements: This research was funded by the Belgium Science Policy (Belspo) within the framework of BRAIN-be 2.0, Belgian Research Action through Interdisciplinary Networks: project B2/212/P2/CLIMPACTH. Bikram Koirala is a postdoctoral fellow of the Research Foundation Flanders, Belgium (FWO: 1250824N-7028).

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