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Comparison between traditional laboratory tests, permeability measurements and CT-based fluid flow modelling for cultural heritage applications

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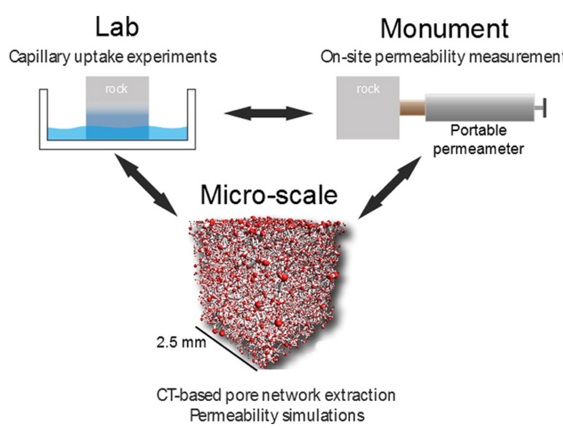
HIGHLIGHTS

- Measurements of capillary absorption are compared to in-situ permeability.
- We obtain pore size distribution and connectivity by using micro-CT.
- These properties explain correlation between permeability and capillarity.
- Correlation between both methods is good to excellent.
- Permeability measurements could be a good alternative to capillarity measurement.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we examine the possibility to use on-site permeability measurements for cultural heritage applications as an alternative for traditional laboratory tests such as determination of the capillary absorption coefficient. These on-site measurements, performed with a portable air permeameter, were correlated with the pore network properties of eight sandstones and one granular limestone that are discussed in this paper. The network properties of the 9 materials tested in this study were obtained from micro-computed tomography (μCT) and compared to measurements and calculations of permeability and the capillary absorption rate of the stones under investigation, in order to find the correlation between pore network characteristics and fluid management characteristics of these sandstones. Results show a good correlation between capillary absorption, permeability and network properties, opening the possibility of using on-site permeability measurements as a standard method in cultural heritage applications.

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1. Introduction

The determination of the capillary absorption coefficient of natural stones according to European standard EN 1925 is standardised on blocks of around 5 cm^3. While this is convenient for the characterisation of stones prior to their use in construction, this is not so much the case for historical buildings. When assessing the quality of a building stone in a historical monument, determination of the capillary absorption coefficient often is one of the standard tests. By comparing the coefficient of the weathered rock to that of the same or similar unweathered stones, the internal deterioration of the material can be estimated. Also for the validation of the effect of consolidation or hydrophobation (Manoudis et al., 2009; Tsakalof et al., 2007) of natural stones, the capillary absorption coefficient is an important measure (Cnudde, 2005; Peruzzi et al., 2003).

However, ancient buildings and monuments are precious, meaning that it is often difficult to acquire a large volume of sample material for petrophysical testing. In this case, tests should be done on smaller samples, inflicting as little damage as possible to the structure. European standard *EN 15801: Conservation of cultural property Test methods Determination of water absorption by capillarity* (2010) describes a method for the determination of the capillary absorption coefficient by performing measurements on samples of at least 10 mm^3, in roughly the same way as the large-scale test. Although this is an adequate method for many materials, absorption in porous sandstones like the Bentheimer sandstone is often too fast to be measured by weighing at different intervals.

In this paper, we aim to correlate traditional fluid flow parameters such as the capillary absorption coefficient to the stone's permeability, a value that is usually not determined in weathering studies of buildings and monuments. The absolute permeability of a medium is described as a measure of the ability of this porous medium to allow fluids (liquid and gas) to pass through it. Permeability has different units, depending on the specific field in geology it is used in, although the official SI unit for permeability is m2. When dealing with reservoir rocks and fluid transport modelling, a more practical unit is used: the *darcy* (d) or *millidarcy* (md). A medium that has a permeability of 1 darcy permits a flow of 1 cm^3 per second, of a fluid with a viscosity of 1 mPa·s under a pressure gradient of 1 atm/cm across an area of 1 cm^2. This corresponds to about 10–12 m^2 or 1 μm^2. The definition of permeability (κ) is further expressed by Darcy's law:

$$\kappa = \nu \frac{\mu \cdot \Delta x}{\Delta P}.$$

In this equation, v is the velocity of fluid flow in m/s through the medium, μ is the viscosity of the fluid that is flowing in Pa·s, ΔP is the applied pressure drop over the medium in Pa and Δx is the thickness over which permeability is measured in m. Rocks with a high permeability generally have a high porosity and a high connectivity between the pores and permeability is mainly hindered by narrow pore throats. Comparably, high porosity and good connectivity through large throats also gives rise to high capillary absorption coefficients, with the difference that narrow capillary tubes provide more capillary suction (Hall and Hoff, 2002), and therefore increase the maximum rise height of fluids by capillarity (Karoglou et al., 2005). Since similar stone properties are responsible for both processes, in-situ permeability measurements directly on a building or outcrop might be directly correlated to laboratory measurements of the capillary absorption coefficient, since both parameters tell us something on how fast a fluid can flow through a building stone.

Furthermore, the obtained measurements and results can be corroborated by using fluid flow modelling directly on 3D μCT image data (Mostaghimi et al., 2013) or on pore network models extracted from these images (Bultreys et al., 2015; Dong and Blunt, 2009). By studying the pore network of the investigated materials, we aim to link differences in structure and connectivity of their pore network to differences in the capillary absorption coefficient. Furthermore, this data will be used to explain the correlation between capillary absorption and permeability in the investigated samples. By understanding these relations, both the water management and weathering behaviour of stones could be predicted in the future, without having to analyse a large quantity of samples. The materials that were used in this paper were selected on their homogeneity, as this should minimize the chance of large-scale features being left out μCT analysis by subsampling prior to this analysis. A first group of materials were three varieties of the Bentheimer sandstone: the red Bentheim variety and two types of the Gildehaus variety, called the 'regular' and the 'porous' variety (Dubelaar and Nijland, 2015). As the names suggest, the main difference between these two types is the slightly higher porosity in the porous variety compared to traditional Bentheimer sandstone. Since the mineralogy of the three Bentheimer varieties is very similar, being mostly quartz, differences in water management properties can be addressed solely to the differences in pore network characteristics and not to chemical variations. Besides the Bentheimer sandstones, several other stones were included in the test, in order to understand the relations in a more general way. These materials are the French Vosges sandstone (De Boever et al., 2015), German Oberkirchner (Nijland et al., 2003) and Leistadter sandstones, and a few Belgian building stones: a glauconite-rich sandstone called fieldstone (Cnudde et al., 2012), the ferruginous sandstone of Diest (Cnudde et al., 2011), and Maastricht limestone (Cnudde, 2005).

This paper starts with a discussion on experimental results of capillary absorption and in-situ air permeability. Subsequently, μCT scans performed on small sub-samples of the analysed stones will be presented, followed by fluid flow simulations and characterisation of the pore network on these 3D datasets. Before making any conclusions, an estimation of the representativeness of these small μCT sub-volumes will be shown, to evaluate if the obtained characteristics and simulations are representative for larger rock volumes. Results of capillary absorption, permeability measurements and the μCT-based methods are then discussed and compared, to assess the degree of correlation between the three types of measurements. Based on these conclusions, the possibility of using μCT-based permeability simulations and in-situ air permeability measurements in cultural heritage applications is discussed.

2. Methods

2.1. Microscopic experiments and analysis

For all materials, except the Vosges sandstone, a sample with a diameter of approximately 5 mm was scanned using UGCT's HECTOR setup (Masschaele et al., 2013). An X-ray tube accelerating voltage of 100 kV and an X-ray source output power of 9 W in the case of the Bentheimers and 10 W in all other cases except the Vosges sandstone were used and 2400 projections with 1 second exposure time were taken. This resulted in datasets with a reconstructed voxel size of around 5 μm. This resolution does not provide enough detail for correct analysis of the Vosges sandstone, and therefore a smaller sample was used to acquire a μCT scan at higher resolution. This was done at the newly developed Medusa setup at UGCT, and a spatial resolution of 0.86 μm was reached by acquiring 2800 projections at an exposure time of 1.5 s per projection, a tube accelerating voltage of 90 kV and an output power of 1 W. All volumes were segmented into binary datasets representing the pore space and solid matrix using hysteresis thresholding in Octopus Analysis (Brabant et al., 2011).Several properties of a pore network can be considered important for the water flow characteristics of a stone. To determine the properties of the pore system, geometrical pore network models (PNMs) were extracted from each CT scan (Dong and Blunt, 2009). In these representations of the pore space, each pore body is presented as a sphere which is connected to other pores by tubes (Fig. 1). These spheres and tubes are typically called nodes and links. Besides