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Predicting capillary absorption of porous stones by a procedure based on an intermingled fractal units model

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ABSTRACT

This study presents an intermingled fractal model capable of simulating the porous microstructure of natural stones used in historical buildings. The developed model is aimed at predicting, by an analytical approach, the sorptivity of these materials. To verify the actual ability of the proposed method to predict stone sorptivity, in this study the intermingled fractal units model was applied to eight types of natural stones. The results are in very good agreement with sorptivity values obtained by experimental tests on the investigated stones. Compared to other analytical formulas proposed in the literature for predicting the sorptivity of porous materials, the newly proposed method better matches with the experimental results, and this can be attributed to that fact it takes into consideration the whole pore size distribution of the analyzed material, rather than the average pore radius only. Thanks to the proposed method, the sorptivity of natural stones used in historical buildings can be calculated from their pore size distribution determined by MIP, which, contrary to standard tests for sorptivity determination, only requires small and irregular samples.

1. Introduction

In porous building materials, such as concrete, brick, mortar and stone, water sorptivity (i.e., water capillary absorption rate) is a key parameter, which describes the amount of water that penetrates into the material per unit surface area per square root of time. Since water is responsible for many weathering processes that affect porous building materials, such as salt-crystallization cycles (Scherer, 2004), freezing-thawing cycles (Martínez-Martínez, Benavente, Gomez-Heras, Marco-Castaño, & García-del-Cura, 2013), dissolution of soluble fractions (Franzoni & Sassoni, 2011), swelling of clays (Wangler & Scherer, 2008), reduction of mechanical properties (Gentilini, Franzoni, Bandini, & Nobile, 2012), the important role of sorptivity in evaluating materials durability is evident. Moreover, as a consequence of microstructural modifications induced by the above mentioned weathering processes, water absorption and sorptivity progressively increase with increasing weathering level (Franzoni, Sassoni, Scherer, & Naidu, 2013; Tuğrul, 2004), so that materials durability is progressively further threatened by high sorptivity, which becomes a consequence of degradation, in addition to being its cause. In the field of cultural heritage conservation, surface treatments for consolidation and protection are usually applied to improve materials durability (Amoroso & Fassina, 1983). These treatments have the effect of either partly occluding pores or altering

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materials hydrophilic behavior (Sassoni, Franzoni, Pigino, Scherer, & Naidu, 2013; Scherer & Wheeler, 2009), in both cases resulting in a reduction in sorptivity and hence in an increase in durability. However, sorptivity alteration after consolidating/protective treatments is a delicate aspect, as the exchange of liquid water and water vapor between the material and the environment should not be completely blocked after the treatment, because durability issues may arise in case water is trapped behind a treated, impermeable layer (Sassoni, Naidu, & Scherer, 2011; Scherer & Wheeler, 2009). In any case, sorptivity measurement is a fundamental test for evaluating the efficacy and the compatibility of conservation treatments, as specifically recommended in Italian Guideline NORMAL 20/85 for stone ("Recommendation NORMAL 20/85, Conservazione dei materiali lapidei: Manutenzione ordinaria e straordinaria," 1985).

According to European Standard EN 15801 ("European Standard 15801, conservation of cultural property – test methods – determination of water absorption by capillarity, 2010," 2010), water sorptivity test on stone must be performed on regular samples (prisms or cylinders). Although easy to perform in the laboratory on new samples, this test can hardly be carried out on samples collected from heritage buildings, subjected to specific regulations for cultural heritage safeguard. As a matter of fact, suitable prismatic or cylindrical samples can basically never be withdrawn from historical buildings, where small and irregular samples are available, if ever (Sandrolini, Franzoni, Sassoni, & Diotallevi, 2011). Although not large enough for sorptivity measurement, stone samples withdrawn from historical buildings and monuments are generally suitable for mercury intrusion porosimetry (MIP), where small fragments (about 1 g) with irregular shape are currently used. Therefore, the development of methods for indirectly evaluating sorptivity on the basis of MIP curves would be highly useful. Some analytical formulas have been proposed in the literature (Raimondo, Dondi, Gardini, Guarini, & Mazzanti, 2009; Scherer & Wheeler, 2009) to correlate sorptivity with properties of both liquid (density, surface tension, contact angle with material, viscosity) and material (open porosity, average pore radius, tortuosity), but sorptivity values calculated by these formulas generally differ from the actual experimental values by even an order of magnitude (Raimondo et al., 2009). Such difference is largely owing to the fact that, in these formulas, material microstructure is simply described in terms of total open porosity, average pore size and tortuosity. While these parameters can effectively describe a simple system composed of a singular capillary (for which the cited formulas were actually developed), they can only provide a rough description of complex systems such as real natural stones, where pores with different and varying size are present. For example, larger pores absorb water faster than thinner pores (as they offer less frictional resistance) but water can rise higher in thinner pores (Scherer & Wheeler, 2009), hence taking into account only the average pore size leads to a very rough estimation of material microstructure and, consequently, sorptivity. Therefore, the need for alternative methods for describing material microstructure and predicting sorptivity comes out. In this paper, a novel methodology based on fractal geometry is proposed. The development of "fractal geometry" dates back to XIX century, however its true acknowledgment and formalization started in the 1970s owing to Mandelbrot (2004). A geometrical structure, in its simplest version, is considered fractal when there is an identical recurring theme on whatever scale it is observed. The fractal dimension, D_f, is the main (although not the only) parameter which represents the fractal geometrical structure in a given context and it can be expressed in different ways. The remarkable versatility of the models that can be developed starting from these concepts has led fractal geometry to play an increasing role within materials science. For example, Winslow (1985) described an X-ray scattering technique for measuring the dimension of a fractal surface and demonstrated that the surface of hydrated cement paste is fractal in character and has a large fractal dimension. Livingston (2000) presented a fractal model to describe nucleation and growth for the hydration of tricalcium silicate. In Arandigoyen and Alvarez (2007), microstructure of blended mortars is studied taking into account porosity, pore size distribution and surface fractal dimension, while Diamond and Bonen (1993) showed that pore systems of concrete may exhibit fractal characteristics. In Xu and Dong (2004) the characteristics of the soil–water system, hydraulic conductivity and soil–water diffusivity of unsaturated soils are derived and expressed by only two parameters, the fractal dimension and the air-entry value, which can be evaluated from the fractal model for the pore-size distribution. Shi, Xiao, Pan, and Yuan (2006) presented a series of fractal models developed to investigate the effect of wettability on liquid water and gas permeation of gas diffusion layers, while Zheng, Xu, Yang, and Yu (2013) proposed a fractal model for gaseous leak rate through the contacting surfaces under non-isothermal condition based on the Darcy law and diffusion theory.

This study proposes a model based on fractal geometry for the representation of the microstructure of natural stones. On the basis of this model, a procedure was developed capable of predicting the stone sorptivity. The proposed model is characterized by a close correlation with microstructure and it can also model non-fractal configurations, which is particularly important since not all microstructures present in nature can be considered as fractal. This is an advantage since fractals are geometries analytically known, which can be led back to mathematical expressions. In order to evaluate the effectiveness of the fractal model and of the procedure proposed, this study took into consideration eight kinds of natural stones. The sorptivity values obtained by applying the proposed method were compared, on the one hand, to the values obtained experimentally and, on the other hand, to the values obtained by applying the two different formulas (reported in Raimondo et al. (2009) and Scherer and Wheeler (2009)).

2. Materials and characterization techniques

Eight stone types with varying porosity were selected. Labels, names, provenance and description of the stones are reported in Table 1.