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Thermal properties of porous stones in cultural heritage: Experimental findings and predictions using an intermingled fractal units model

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ABSTRACT

Thermal conductivity is one of the most important parameters for construction and building materials. Indeed, extensive efforts have been put in by Europe in order to decrease energy consumption at various levels. However, with regards to historical buildings, the measures of thermal performance are not simple and they, in fact, pose a wide range of error. In this paper, an intermingled fractal model has been proposed, which is capable of reproducing the porous microstructure. Moreover, by converting this model into an electrical circuit, it is capable of predicting thermal conductivity. The results are in perfect agreement with experimental ones obtained by climatic chamber.

1. Introduction

Construction and building sector is adopting new approaches in order to improve energy efficient design. Thermal insulation is an issue of remarkable novelty, not only for modern construction, but also for cultural heritage. In Europe, the building stock consumes 40% of the energy. Indeed, heating and air conditioning of settings form part of one of the principle reasons of electrical energy usage. Moreover, it symbolizes 36% of the global CO_2 emissions [1]. Europe 2020 strategy is aimed at decreasing energy consumption by 20%. This fact influences the development of new materials for improving the insulating properties of building components. However, about 35% of the residential constructions were built more than 50 years ago, about 70% are over 30 years old [2], while the annual growth trend of new construction is estimated at 1.3% [3]. Consequently, technical installations are obsolete and a number of building components are affected by ageing process.

Keeping these reasons in mind, extensive attention has to be paid to building recovery. In order to recreate thermo-hygrometric comfort, an extensive and comprehensive study must be carried out. However, it is not so simple, because in the case of conductance measure, unverifiable numerous variables (for example insufficient temperature difference between internal and external walls) force the experimental techniques to present a high level of error. This problem can be resolved carrying out experimental tests in the lab, but in case of materials from cultural heritage, this is not possible. Indeed, the number of samples, which could be taken away for various tests, is very small.

Owing to these reasons, modelling procedures aimed at predicting association between structure and properties are growing into materials science branches. One of them is represented by heat transfer.

For engineering applications like industrial or construction, the possibility of predicting thermal conductivity is of utmost importance. This property is strongly influenced by porosity. Usually, porosity is described as pore volume fraction, but this is inadequate to understand the real effects on properties. Pores can be very different from each other in size, shape, specific surface and

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Nomenclature

$\bar{c}$	Conductance
Cs	Specific conductance
D_f	Fractal dimension
k_{eff}	Effective thermal conductivity
k_f	Fluid thermal conductivity
k_{IFU}	IFU thermal conductivity
k_s	Solid thermal conductivity
IFU	Intermingled fractal units
l	Length of the piece of material
n^{th}	Iteration
n_B	Number of units B
$\bar{R}$	Resistance
$\bar{R}^1$	Resistence for first line of pattern
$\bar{R}^2$	Resistence for second line of pattern
$\bar{R}^3$	Resistence for third line of pattern
$\bar{R}_s$	Resistence of solid phase
$\bar{R}_f$	Resistence of fluid phase
R_{eff}	Total resistivity
R_f	Fluid resistivity
R_s	Solid resistivity
ε	Pore volume fraction

quantity. With Regards to this study, pore size distribution has an important influence on the thermal properties of materials. The experimental method to obtain pore size distribution is Mercury Intrusion Porosimetry Technique (MIP). The dimensions of samples used to perform these tests are very small (about 1 cm^3), and it is compatible with cultural heritage cases [4–7]. However, these data are not immediately convertible to parameters usable in analytical formulas.

During the last years, it appears relevant to the support from tools aimed at describing the microstructure of materials in geometrical and mathematical approach. One of the most used is fractal geometry. This geometry was formalised and developed in 1970s by Mandelbrot. He recognised a large number of fractal forms in organic as well as inorganic systems of nature [8]. Fractals are geometric figures characterised by fractional dimension (D_f), intricate and complex structure, geometric construction based on iteration procedure and geometric schemes that are repeated on different scales (self-similarity) [8,9].

Fractal characteristics have been recognised in various aspects of the microstructure of the materials, and they are relevant in describing and/or predicting different aspects of their macroscopic behaviour.

The analysis of porosimetric data has facilitated in studying the association between porosity and permeability for a tortuous and fractal tubular bundle [10]. Moreover, pore volume fraction, fractal dimension for pore size distribution and tortuosity fractal dimension have significant effect on the multiphase flow through unsaturated porous media [11]. Fractal models have also been proposed in order to study the spontaneous imbibition process in different rock types, fibrous materials, and silica glass [12,13]; the heterogeneity of the Geysers rocks, which can be determined quantitatively using fractal dimension [14]; the contributions of water and gas to the diffusion transportation in unsaturated building materials involving geometry parameters of unsaturated building materials [15]; the hygrometric behaviour of a porous material such as mortar [16]; the mechanical properties of vesicular basalt used in prehistoric buildings [17] and porous ceramics obtained by pore-forming agent [18]; the surface wear resistance of chemically and thermally stabilised earth-based materials [19].

Regarding heat transfer, several papers have provided different fractal model and analytical formulas to calculate thermal conductivity value. Indeed, Huai et al. generated several types of fractals to simulate the microstructures of porous media as well as to reproduce heat conduction by the finite volume method [20] and lattice Boltzmann method [21,22]; Singh et al. formalised an artificial neural networks procedure aimed at predicting effective thermal conductivity of porous systems filled with different liquids [23]; whereas Pia et al. studied the effects of microstructure on lightweight concrete prepared from clay, cement, and wood aggregates [24]. Xiao et al. [25] proposed a model distinctly related to the thermal conductivities of the base fluids having average diameter, concentration and fractal dimension of nano-particle. A good agreement between the proposed model predictions and experimental data was found. Zhou et al. [26] adopted the fractal theory to establish a geometrical model of the aquifer, which facilitates in the analysis of the heat transfer mechanism in an irregular configuration, and derives a correlation of the overall thermal conductivity from the thermal resistance structure.

Recently, in order to reproduce the pore size distribution of materials, an Intermingled Fractal Units model (IFU) has been proposed. It is capable of predicting several properties like permeability, sorptivity, mechanical properties and thermal conductivity [27–30]. The validation of IFU is in progress. Currently, data models are in good agreement with experimental ones for different kinds of materials: traditional and advanced ceramics, cement and concrete [24,31]. This peculiarity is owing to the capacity of reproducing morphological aspects of microstructures and converting them into physical-mathematical language.

In this paper, IFU procedure has been proposed in order to predict thermal conductivity of natural stone often used in cultural heritage in the urban area of Cagliari. In this model, it is possible to control the properties of the materials in several points of building's masonry or in several conditions (humidity, temperature, low or high weathering) by taking very small samples. IFU calculated values have been compared with experimental data obtained by climatic chamber using samples with large dimension.

2. Intermingled fractal units (IFU) model

IFU model is based on mixing of fractal units' base, specifically two types (A and B) of Sierpinski carpets. It is obtained by repeatedly removing squares from an initial square of unit side-length. Even though the number of iteration increases, geometrical structure remains fine, highly intricate and detailed at all scales [8,9]. Fig. 1 shows Sierpinski carpet with three pores and its geometrical construction procedure (iteration $i = 0–3$).

The number of iterations defines the porosimetric range. Indeed, iteration by iteration, new class of pores with different rays is created. For every unit A, n_B units B are used,

$$n_B = \frac{(A_{Ap} - \varepsilon \times A_A)}{(\varepsilon \times A_B - A_{Bp})} \quad (1)$$

Where A_A, A_B, A_{Ap} and A_{Bp} respectively represent the total area and the area of the pores belonging to units A and B which make up the IFU (Fig. 2).

For increasing the simulating power of this model, during iteration process, it is not possible to involve all the filled squares, so every iteration could have different configuration based on *iterated square* and *solid forever* square [18]. Moreover, for settling pore volume fraction, a filled surface could be inserted. After mixing, fractal figures generate a porous microstructure very close to real one. IFU model must be converted into electrical pattern, wherein resistances are connected in series and parallel. So, considering electrical and thermal equivalence, thermal conductivity value could be calculated (Fig. 2).