Study of the impact of microstructure on the thermal properties of porous materials used in civil engineering

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Abstract. This work focuses on studying the impact of porosity and fluid saturation on the thermal conductivity of calcarenite rocks. The porosity of these porous materials is measured using the water porosity technique, and thermal conductivity is measured using thermal conductivity scanning (TCS). Models for predicting the thermal properties of rocks have been established. The results obtained show that thermal conductivity values increase considerably in the saturated state compared to the dry state. Comparison of the experimental results and theoretical predictions shows that the thermal conductivity values lie between the two theoretical limits, with values closer to the parallel model, indicating that water saturation promotes heat transfer through the solid matrix.

Keywords: Porous materials, calcarenite rocks, thermal conductivity, porosity, modelling, TCS.

1 Introduction

Many natural materials such as rocks and soils, and artificial materials such as cements and ceramics, can be considered porous media. These materials are used in many fields such as rock mechanics, civil engineering, geophysics, and biology.
A porous material in its natural state is a three-phase heterogeneous medium composed of a solid phase, a liquid phase, and a gaseous phase [1-3]. It is composed of an assembly of grains or solid particles separated by voids called pores, which may or may not be saturated by one or more fluids.
Porosity and thermal conductivity play an important role, influencing the exchanges between fluid and rock, as well as the characterization of porous materials [3, 4]. Studying the

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relationship between them helps to understand how the microstructure and the pore network come into play. This also allows for a better definition of the porosity of a porous material.
Several authors have examined the impact of microstructure on the thermal properties of porous materials. Rahmouni et al. [3] studied the relationship between porosity and thermal conductivity in dry and saturated calcarenite rocks to analyze their thermal behavior and anisotropy. The microscopic structure, thermal and mechanical properties of sandstones under the influence of temperature, were investigated by Xiao et al. [5]. Janssen and Van De Walle [6] studied the interactive influence of different pore structure factors on the thermal conductivity of porous building with micrometer and nanometer sized pores. The impact of mineral composition, density, porosity, and other factors on the thermal properties of rocks of different lithologies was analyzed by Xiong et al. [7]. According to Suft et al. [8], rocks are characterized by significant thermal heterogeneity, and their thermal behavior is linked to their microstructure and mineral composition.
The aim of this work is to study the impact of microstructure on the thermal conductivity of calcarenite rocks in order to understand the relationship between the thermal properties and microstructure of porous materials. We measured the porosity of these materials using water porosimetry and thermal conductivity using the TCS technique. The experimental results obtained are compared with the predictions of theoretical models of thermal conductivity.

2 Materials and Methods

2.1 Studied materials

The capital of Morocco, Rabat, is rich in historical and architectural heritage, with important monuments that are mainly built from calcarenite, a coarse limestone rock. Calcareous sandstone is characterized by high and variable porosity (18 to 47%) [1, 3]. Chemical analyses conducted on several samples of calcarenites show that the main component of these samples is calcium carbonate ($CaCO_3$) [9]. Its content varies between 50 and 57% with a small percentage of silica (SiO_2) in the form of quartz grains [3]. Ten rock samples were cored in size 7 × 7 × 7 cm³ for porosity and thermal conductivity measurements.

2.2 Porosity

The total water porosity is defined as the porosity accessible to water under vacuum. The measurement of total water porosity was carried out according to the techniques defined by the RILEM standard, which stipulates that the sample be imbibed in the absence of air. The samples previously dried in an oven at 60°C until a constant weight, are placed in a crystallizing dish connected to a vane pump that allows for a primary vacuum. In parallel, in a second crystallizing dish connected to the first, distilled water is degassed using a water aspirator for 24 hours. Next, the interconnection between the crystallizers is opened, and the imbibition of the test tubes gradually occurs from their base. The vacuum is then broken, and the test tubes are left submerged for 24 hours at atmospheric pressure.
The value of porosity ϕ, is then obtained by the triple weighing method. Knowing the dry weight of the specimen W_d measured before the experiment and its soaked weight W_1, we can access the porous volume occupied by water (W_1- W_d). The total volume of the sample is obtained by subtracting the hydrostatic weight of the specimen W_2 from the imbibed weight W_1 ($V_t \equiv W_1$ - W_2). The porosity of the sample is then expressed as:

$$\phi = \frac{W_1 - W_d}{W_1 - W_2} \times 100 \qquad (1)$$

2.3 Thermal conductivity scanning (TCS)

The TCS technique is mainly used to avoid the effect of thermal contact resistances. It is based on the variation of the surface temperature of the sample following a controlled heat input. The experimental equipment comes in the form of a mobile unit, consisting of two sensors and a heat source. They measure the temperature of the sample before and after heating. Since the distance and speed remain fixed, we can then relate the temperature increase at point x, θ(x), to the thermal conductivity of the sample [10]:

$$\theta(x) = \frac{q}{2\pi x\lambda} \qquad (2)$$

with q the source power, x the distance source - sensor, and λ the conductivity.
To determine the thermal conductivity value, it is simply aligned with a standard λ_{std} = 1.35 W/ (m K). The thermal conductivity will be determined from equation (3) [10]:

$$\lambda(x) = \lambda_{std}\frac{\theta_{std}}{\theta(x)} \qquad (3)$$

The preparation of the samples is quite simple. We just put a thin layer of black paint so that the heat is absorbed evenly. The device can measure conductivities from 0.2 to 70 W/ (m K) with a small margin of error. Next, the temperature and conductivity measurements are done directly by computer.

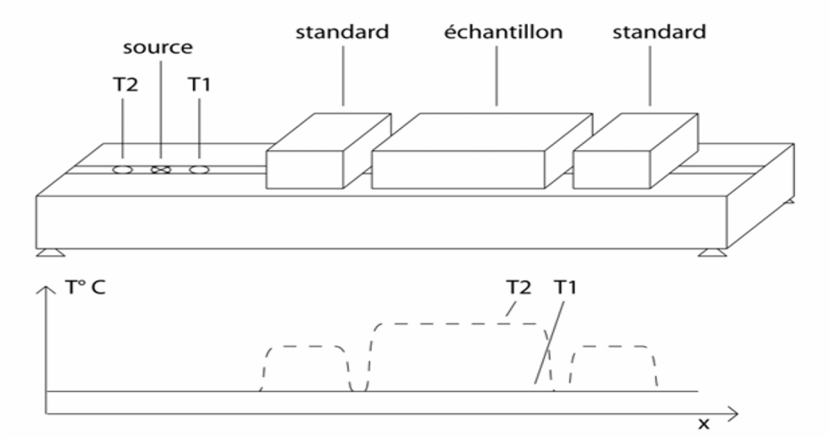

Fig 1. TCS measurement principle.

2.4 Thermal conductivity modeling

The porous media is considered as a juxtaposition of alternating solid and fluid layers, characterized respectively by their thermal conductivities λ_s and λ_f. In this work, analytical models were used to calculate the apparent thermal conductivity of the medium.
The series and parallel models are based on the hypothesis of unidimensional heat flow and were obtained by electrical analogy. In these models, the internal structure of the heterogeneous material is assumed to consist of layers perpendicular (series model) and parallel (parallel model) to the heat flow.
In series model, the medium is considered to be a succession of alternating solid and fluid layers arranged perpendicular to the direction of heat flow. The corresponding thermal conductivity λ_{per} is [11]:

$$\lambda_{per} = \frac{1}{\frac{(1-\phi)}{\lambda_s} + \frac{\phi}{\lambda_f}} \quad (4)$$

In the parallel model, heat flows through both layers in parallel. In this case, the thermal conductivity is expressed as follows [11]:

$$\lambda_{para} = (1 - \phi)\lambda_s + \phi\,\lambda_f \quad (5)$$

3 Results and discussion

Based on measurements performed on different, it can be seen that all samples have a difference in porosity. The porosity value of these samples varies between 19.62% and 35.83%. The average porosity is 29.54% (Fig. 2).

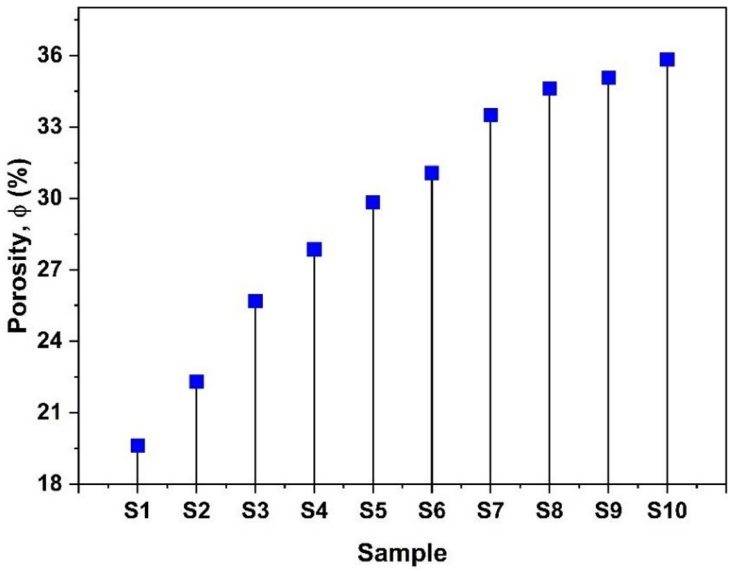

Fig 2. Results of total water porosity expressed in % for the 10 calcarenite samples.

Thermal conductivity values were measured for ten samples in dry and saturated conditions, in perpendicular (λ_{per}) and parallel (λ_{para}) directions. In the dry state, the values of λ_{per} vary between 0.87 W/(m.K) and 1.227 W/(m.K), while those of λ_{para} range from 0.768 to 1.185 W/(m.K), with respective averages of approximately 1.009 and 0.933 W(/m.K). In the saturated samples, the values of λ_{per} range from 1.673 to 1.905 W/(m.K), and those of λ_{para} between 1.667 W/(m.K) and 1.989 W/(m.K), with respective averages of 1.745 W/(m.K) and 1.783 W/(m.K). These results show that the thermal conductivity values increase significantly in saturated conditions compared to the dry state.

In addition, the samples show marked variability, with sample 1 showing the highest conductivities under all conditions, while sample 10 records the lowest values. This confirms that saturation significantly influences thermal conductivity, and that the direction of measurement (perpendicular or parallel) must also be taken into account.

Fig. 3 illustrates a comparison between the experimental thermal conductivity values of dry calcarenite rocks, measured in perpendicular and parallel directions, and the theoretical

predictions of the series and parallel models. In this state, the fluid is air, representing the natural condition of the material in its dry state. This allows for the comparison of experimental results with theoretical models to evaluate the effect of porosity on thermal conductivity under dry conditions. The results obtained confirm that heat transfer takes place in both the solid and gas phases. The large deviation from the series model suggests that conduction through the solid matrix remains dominant even at higher porosities, while the parallel model provides an upper limit for dense materials.
According to Fig. 3, we observe that as porosity increases, thermal conductivity in the perpendicular and parallel directions decreases. This result is interpreted as the insulating effect of air-filled pores, which interrupt the solid conduction paths within the solid matrix.
Furthermore, anisotropy is limited in the perpendicular and parallel thermal conductivity of these rocks. This indicates that the distribution and orientation of pores exert a similar influence on heat flow in both measured directions, resulting in almost isotropic thermal behavior despite the sedimentary calcarenite.

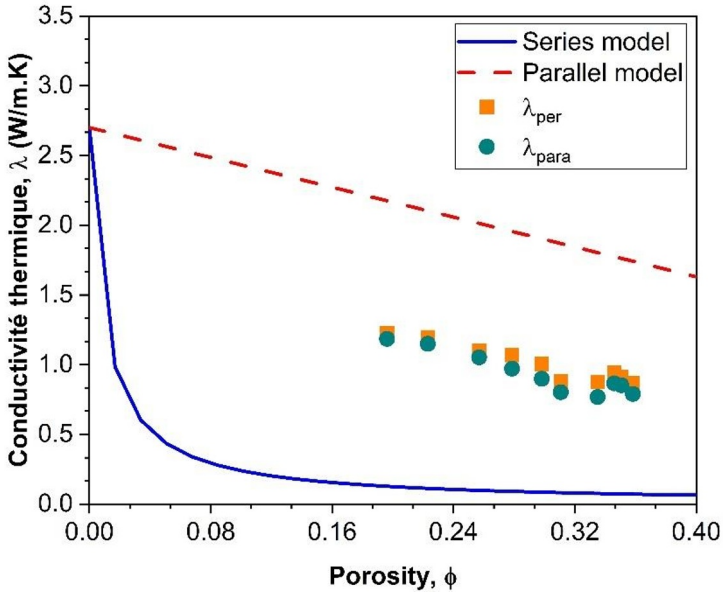

Fig 3. Comparisons of thermal conductivity measurements as a function of porosity with series and parallel models for dry samples ($\lambda_s = 2{,}7\ W/m.K$, thermal conductivity of calcite (solid matrix); $\lambda_f = 0{,}026\ W/m.K$, thermal conductivity of air).

The comparison between experimental measurements of the thermal conductivity of saturated calcarenites (perpendicular and parallel directions) and theoretical predictions from series and parallel models is shown in Fig. 4. In this state, water was used as the fluid, as the material is frequently exposed to rain in real conditions, which justifies the study of its thermal behavior when saturated. This use also allows for a comparison between theory and experiment by analyzing the impact of water filling the pores on thermal conductivity.
The results obtained show that the thermal conductivity values are located between the two theoretical limits, with values closer to the parallel model, indicating that water saturation favors heat transfer through the solid matrix and reduces the insulating effect of the pores compared to dry samples. In this state, porosity has a less limiting effect than in the dry state, because water reduces the insulating effect in the pores.

A low anisotropy in the thermal conductivity of saturated samples is due to the small difference between perpendicular conductivity and parallel conductivity.

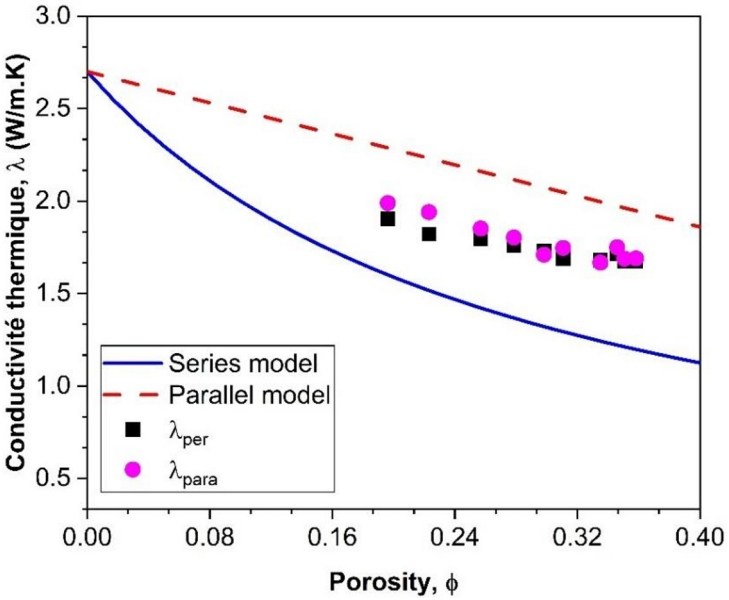

Fig 4. Comparisons of thermal conductivity measurements as a function of porosity with series and parallel models for saturated samples ($\lambda_s = 2{,}7\ W/m.K$, thermal conductivity of calcite (solid matrix); $\lambda_f = 0{,}6\ W/m.K$, thermal conductivity of water).

4 Conclusions

This study presents an in-depth analysis of the impact of microstructure on the thermal properties of calcarenite rocks used in civil engineering. In dry state, thermal conductivity decreases with increasing porosity due to the insulating effect of air-filled pores. Water saturation affects thermal conductivity by improving heat transfer through the pore network. Comparison of experimental thermal conductivity values with theoretical predictions shows that, for dry rocks, the large deviation from the series model suggests that conduction through the solid matrix remains dominant even at higher porosities, while saturated rocks tend toward the parallel model, and calcarenite rock shows low thermal anisotropy.

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