Experimental relationship between water permeability and capillarity imbibition in porous rocks

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INTRODUCTION

The movement of fluid through porous systems in rocks has been widely studied in several fields of research such as ground water, petroleum engineering, engineering geology, soil physics and building materials.

Permeability measures the material's ability to transmit fluids and can be termed in different ways depending on the field. Permeability depends only on the pore structure of the material and has units with dimensions of area (m^2). A practical unit for permeability is the darcy (D), or more commonly the millidarcy (mD). Hydraulic conductivity is usually referred to permeability or coefficient of permeability and it is related to intrinsic permeability (pore structure) and to the properties of the fluid. Hydraulic conductivity has units with dimensions of length per time or speed. Thus, for pure water at 20 ºC, 1D is $\sim 10^{-12} m^2$ or $\sim 10^{-5}$ m/s.

Capillary flow is the most common water transport mechanism in porous building rocks, since they tend to be unsaturated water. This parameter is essentially equivalent to the sorptivity parameter physics in soil and building and depends on pore structure and to the properties of the fluid.

Some experimental and limited studies showed that the capillary absorption coefficient is related to the square root of the permeability for homogeneous and porous materials (Benavente et al., 2007; Casteleyn et al., 2010). Consequently, further research into a wider range of rock types is needed in order to corroborate this relationship. Permeability measurements require more sophisticated procedures than the capillary imbibition test. Additionally, in rocks with low porosity values, mass flow rate in a steady-state regime is too low and, thus, the time required for measurements is too long. Moreover, the characterisation of a wider range of rock types with different permeability values may request the use of different equipment (Galvañ et al., 2014). The aim of this paper is to estimate empirically water permeability from capillary imbibition and pore structure for a wide range of rock types with different petrographic characteristics. One important and practical significance of this study regards the direct relationship found between both permeability and capillary imbibition to pore structure.

MATERIAL AND METHODS

In this study, 15 porous stones have been chosen for their different petrophysical and petrographic characteristics (Figure 1).

fig.1. Image of the studied samples. C: biocalcarenites. T: travertines and tufas. L: limestones. S: sandstones.

These stones are used as building materials or they are found in the Spanish built heritage. The stones tested correspond to four groups of sedimentary rocks with different kind of pores: biocalcarenites (C), travertines and tufas (T), limestones (L) and sandstones (S). According to the Lucia's petrophysical classification of porosity in sedimentary rocks (Lucia, 2007), biocalcarenites, limestones and sandstones present interparticle (intergranular and intercrystalline) porosity, whereas travertines and tufas have both interparticle and vuggy porosity. In particular, T14 presents touching-vug porosity whereas T13 shows non-touching-vug porosity, and T15 displays very large pores and touching-vug porosity.

Water transport was characterized by means of liquid water permeability (saturated flow) and capillary imbibition (unsaturated flow). Permeability tests were carried out in a triaxial device with an automatic pressure system using the steady-state method (see details in Benavente et al. 2007 and Galvañ et al., 2014). The water absorption by capillarity was carried out using a continuous data-recording device due to the high absorption rates of samples. The non-continuous standard method does not permit an accurate calculation of capillary absorption coefficients, C, for $C > 10$ kg/m^{2}h$^{0.5}$ ($C > \sim 150$ g/m^{2}s$^{0.5}$) (Benavente et al. 2007). The open porosity, ϕ_o, was calculated using the vacuum water saturation test (UNE-EN 1936:2007). Pore structure was described in terms of porosity and pore size distribution (quantified by the mean pore size, r_M,). The connected porosity, ϕ_{Hg}, and mean pore size, r_M, were obtained by Autopore IV 9500 Micromeritics mercury intrusion porosimetry (MIP). The pore size interval ranges from 0.003 to 200 μm.

RESULTS AND DISCUSSION

Table 1 shows open and connected porosities, mean pore radius, coefficient of capillary imbibition and water permeability. The studied porous building rocks have a wide range of petrophysical and petrographic characteristics, which are conditioned by rock structure, pore size and pore connectivity of vuggy porosity. In general, porous rocks with larger pores and high porosity values present the highest transport coefficient values.

Acording to Hölting's (1989) classification for the permeability, eight varieties of the studied building stones (C1, C2, C4, C6, L11, T12, T13, T14) are classified as very low permeability rocks, other four (C3, C5, L10, S7) are low permeable and the last three (L10, L11, L15) are permeable.

palabras clave: Permeabilidad, Capilaridad, Porosidad,	*key words:* Permeability, Capillarity, Porosity

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Figure 2 shows a good relation between water permeability and capillarity for the most of the studied rocks. However, T15 and T14 samples are not well fitted to this relation due to their pore structure. T15 is a tufa and presents well connected large pores (r > 1 mm) meanwhile T14 shows touching-vug porosity. Both kinds of pores contribute to increase the saturated water transport (permeability) but not to unsaturated flow (capillarity), since capillary forces produced in the interface aire-water-pore surface are not enough to overcome gravitational forces. The estimation of water permeability from pore structure and capillarity coefficient is carried out by means of a stepwise multiple regression analysis. Thus, permeability is expressed as a generalized function of several fundamental properties. Variables are logarithmic transformed in order to include more terms. T15 and T14 are not included in the multiple correlations due to presence of touching-vug porosity. Thus, water permeability, k (mD), is taken as a dependent variable, while both open, log ϕ_O (%), and connected, ϕ_{Hg} (%), porosity, mean pore radius, r_M (μm) and capillary absorption coefficient, C (kg/(m^2·h$^{0.5}$)) are considered as independent variables.

Table 2 displays the equations of regression results. Eq. (i) represents the classical permeability–porosity relations to characterise flow units in petroleum industry. This statistical relation is recommended for different samples of similar rocks through a reservoir but not for different kind of rocks as we are here preformed. Eq. (ii), and also in Figure 2, displays an interesting relationship between both transport coefficients for the most of the studied rocks. Eq. (iii) includes porosity to Eq. (ii) and the goodness of fit is slightly increased. Since open and connected porosities have similar values, the expression of Eq. (iii) will be equivalent by using any of the studied porosities (ϕ_{Hg} or ϕ_O). Eqs. (ii) and (iii) are recommended from the practical point of view since C and ϕ_O are easy, cheap, clean and fast to be obtained in the lab. Eq. (iv) contains pore structure parameters obtained from mercury porosimetry technique (MIP).

This empirical equation presents a poor fit and therefore is not recommended for estimating water permeability. In literature, MIP is successfully used to estimate rock permeability through capillary pressure curves but not to be used in an empirical equation (see examples in Schön, 2011). Finally, Eq. (v) considers all the petrophysical variables reaching the best goodness of fit.

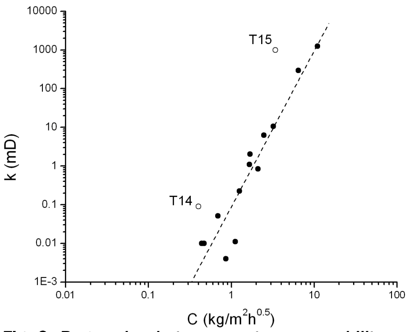

***Fig. 2:** Regression between water permeability and capillarity imbibition for the studied porous building rocks.*

CONCLUSIONS

Using linear regression analysis, we expressed permeability as a generalized function of several fundamental properties. We recommend permeability predictions from capillarity imbibition since present an excellent correlation and it is easy and fast of testing. Statistical correlations were only preformed to the rocks with interparticle porosity. Consequently in samples with very large pore fraction and/or touching-vug porosity, the predictive permeability equations from capillarity imbibition cannot be used.

ACKNOWLEDGMENTS

This research was financed by the Spanish Ministry of Science and Innovation (CGL2011-25162). A pre-doctoral research fellowship was awarded to C. Pla for this project.

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Rock	ϕ_O (%)	ϕ_{Hg} (%)	r_M (μm)	C (kg/m2h0.5)	k (mD)
C1	16.29	14.31	0.08	0.86	0.004
C2	20.61	15.65	0.33	1.25	0.226
C3	22.03	18.83	1.48	2.48	6.27
C4	16.70	14.18	0.15	1.12	0.011
C5	23.52	21.79	0.46	3.20	10.59
C6	26.72	26.02	0.35	2.10	0.839
S7	13.11	14.18	0.15	1.68	2.02
L8	20.35	17.79	28.69	6.47	293.31
L9	19.01	16.32	34.18	10.94	1251.33
L10	12.00	10.80	9.21	1.65	1.09
L11	8.62	6.36	0.09	0.69	0.051
T12	7.04	3.51	0.06	0.44	0.010
T13	12.54	7.31	0.15	0.47	0.010
T14	8.46	9.00	0.29	0.40	0.090
T15	28.04	12.34	16.62	3.39	990.95

***Table 1.** Open, ϕ_O, and connected, ϕ_{Hg}, porosity, mean pore radius, r_M, capillary absorption coefficient, C, and water permeability, k, of the studied porous building rocks.*

Eq.	Logarithmic expression	Regression coefficient, R
i	$\log k = -6.373 + 5.157 \cdot \log \phi_{Hg}$	0.5109
ii	$\log k = -1.054 + 4.0268 \cdot \log C$	0.9527
iii	$\log k = 1.2651 + 4.5873 \cdot \log C - 2.0371 \cdot \log \phi_{Hg}$	0.9646
iv	$\log k = -0.5336 + 0.4912 \cdot \log r_M + 0.2882 \cdot \log \phi_{Hg}$	0.2853
v	$\log k = 0.645 + 4.1603 \cdot \log C + 0.1997 \cdot \log r_M - 1.5064 \cdot \log \phi_{Hg}$	0.9700

***Table 2:** Empirical relationships between permeability, k (mD), connected porosity, ϕ_{Hg} (%), mean pore radius (μm) and capillary absorption coefficient, C (kg/(m^2·h$^{0.5}$)).*