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Predicting water permeability in sedimentary rocks from capillary imbibition and pore structure

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ABSTRACT

In this paper, absolute water permeability is estimated from capillary imbibition and pore structure for 15 sedimentary rock types. They present a wide range of petrographic characteristics that provide degrees of connectivity, porosities, pore size distributions, water absorption coefficients by capillarity and water permeabilities. A statistical analysis shows strong correlations among the petrophysical parameters of the studied rocks. Several fundamental properties are fitted into different linear and multiple expressions where water permeability is expressed as a generalized function of the properties. Some practical aspects of these correlations are highlighted in order to use capillary imbibition tests to estimate permeability. The permeability–porosity relation is discussed in the context of the influence of pore connectivity and wettability. As a consequence, we propose a generalized model for permeability that includes information about water fluid rate (water absorption coefficient by capillarity), water properties (density and viscosity), wetting (interfacial tension and contact angle) and pore structure (pore radius and porosity). Its application is examined in terms of the type of pores that contribute to water transport and wettability. The results indicate that the threshold pore radius, in which water percolates through rock, achieves the best description of the pore system. The proposed equation is compared against Carman–Kozeny's and Katz–Thompson's equations. The proposed equation achieves very accurate predictions of the water permeability in the range of 0.01 to 1000 mD.

1. Introduction

Water transport in porous rocks has been widely studied in several fields of research and technological applications, such as engineering geology, soil physics, building materials, ground water, geothermal reservoir engineering, secondary and enhanced oil recovery (EOR), and unconventional hydrocarbon resource assessment for further production, among others. Water transport can be carried out in different ways depending on the water saturation of the rocks. We can distinguish between saturated water flow, which is described by the permeability, and unsaturated water flow, which can be defined through the capillary flow.

Permeability measures a material's ability to transmit fluids into a saturated material under a pressure gradient. It can be referred to in different ways depending upon the field. Thus, depending on the fluid composition, a distinction must be established among intrinsic or absolute permeability (laminar flow of a single nonreactive fluid), effective permeability (flow of one fluid in the presence of another fluid, when the fluids are immiscible), and relative permeability (ratio of effective and absolute permeability) (Schön, 2011). Intrinsic permeability depends only on the pore structure of the material and has units with dimensions of area (m^2, in SI units). In the oil industry, the Darcy (D) or, more commonly, the milliDarcy (mD) are typical units. Hydraulic conductivity is usually referred to as permeability or the 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 and is widely used in hydrogeology. Between the two properties, the following conversion can be used (the correct equation implements density and viscosity of water and gravity): 1D $\sim 10^{-12}$ m^2–10^{-5} m/s (for pure water at 20 °C). In this paper, we study the water intrinsic permeability, k, which for convenience will be called water permeability, using mD as the measurement units.

Capillary flow is the most common water transport mechanism in soils and rocks when they are in contact with the atmosphere. The spontaneous capillary imbibition is characterized through the water absorption coefficient by capillarity, C, which is referred to as the variation of water weight per unit of the square root of time and sample area,

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and sample sorptivity, S, which describes the height variation of water in the rock sample. The units of C are $[ML^{-2}\,T^{-1/2}]$, whereas S presents the units $[LT^{-1/2}]$. Capillarity absorption of a liquid depends on the pore microstructure (pore radius and porosity) and on the intrinsic properties of the liquid: density, viscosity, wettability and surface tension.

As we previously mentioned, permeability is a fundamental property to be quantified, and it can be directly obtained in the field or in the laboratory. However, permeability measurements may entail some important problems that include obtaining core samples, the experimental time demanded and costly equipment requirements. For that reason, several models and empirical equations have been developed in order to estimate permeability from pore structure parameters of rocks, including connected porosity, pore size, specific surface area or tortuosity. Probably the simplest model for single-phase permeability was proposed by Kozeny (1927) and later modified by Carman (1937). The Carman–Kozeny model, one of the most widely accepted derivations of permeability and its relationship to permeable medium properties, was developed by comparing Darcy's law with the Hagen–Poiseuille's law for steady laminar flow of an incompressible fluid through a bundle of circular capillary tubes (Panda and Lake, 1994). Moreover, Katz and Thompson's model (1986) used percolation theory to develop a relationship between permeability and the critical pore diameter of sedimentary rocks.

Some models predict permeability from other petrophysical properties, such as electrical resistivity (Archie, 1942), ultrasonic wave velocities (Alam et al., 2011), electromagnetic wave velocities (dielectric constants) (Hubbard and Rubin, 2000) or critical and irreducible water saturation (Leverett, 1940; Brooks and Corey, 1964). In many situations, these practical and interesting relations between permeability and petrophysical properties are an indirect estimation rather than a fluid transport parameter. In this case, permeability estimations will be more realistic in terms of fluid-rock interactions.

Various experimental and limited studies have shown that the capillary absorption coefficient is related to the square root of the permeability (Scherer, 2004; Benavente et al., 2007; Cueto et al., 2009; Casteleyn et al., 2010; Hall and Hoff, 2012; Espinosa-Marzal and Scherer, 2013). The theoretical relationships between both transport parameters have been characterized through Hagen–Poiseuille's equation, which can be written as

$$q = \frac{dv}{dt} = \frac{\pi r^4}{8\eta}\frac{\Delta P}{L}, \tag{1}$$

where q is the volumetric flow rate, v is the volumetric uptake, t is the time, r is the tube radius, η is the viscosity of the fluid ($1.003 \cdot 10^{-3}$ Pa · s for water at 20 °C), ΔP is the pressure drop, and L is the length of the tube.

Principal advantages for predicting permeability from capillarity are provided through consideration of both scientific and technical meaning. Permeability measurements require more sophisticated procedures than the capillary imbibition test, such that the estimation of water permeability from capillary imbibition also presents a practical interest. Until now, however, the majority of the few permeability and capillarity relationships have been developed for homogeneous and porous materials. Consequently, further research into a wider range of rock types is needed in order to corroborate this relationship.

The aim of this paper is to estimate water permeability from capillary imbibition and pore structure for a wide range of sedimentary rock types with different petrographic characteristics. For this purpose, first, a statistical analysis is carried out in order to empirically establish correlations between these parameters. The results are discussed in the context of the influence of pore connectivity and wettability. Second, a generalized model capable of predicting permeability in sedimentary rocks of distinct lithofacies is proposed based on the statistical analysis. The generalized model is compared against other models, and their applications are discussed in terms of the type of rock porosity. Finally, some practical aspects of this study are highlighted in order to use the capillary imbibition test to estimate permeability.

2. Experimental procedure

2.1. Materials

In this study, 15 samples of porous stones have been chosen for their different petrophysical and petrographic characteristics (Fig. 1). These stones are used as building materials or are found in the Spanish-built heritage. The tested stones correspond to four groups of sedimentary rocks with different pore types: biocalcarenites (C), sandstones (S), limestones (L) and travertines and carbonate tufas (T).

2.1.1. Biocalcarenites

The studied biocalcarenites are carbonate sandstones with calcite cement, variable amounts of terrigenous components and fossils (mainly foraminifera) and intergranular porosity. C1, C2, C3 and C4 are well-sorted biocalcarenites that contain foraminifera and quartz, feldspar, mica and dolomite grains (Benavente, 2003; Benavente et al., 2004, 2008). C5 shows bioclasts larger than the rest of the studied biocalcarenites, and it is constituted by bryozoans, red algae, molluscs and echinoderms. Other detrital components are quartz, dolostones and feldspars (Benavente, 2003). C6 is composed of foraminifera, quartz, feldspars and mica grains (Benavente, 2003).

2.1.2. Sandstone

S7 is a well-sorted sandstone, mainly composed of monocrystalline quartz grains. S7 presents intergranular porosity (Benavente, 2003).

2.1.3. Limestones

The analysed limestones show a wide range of sizes and types of allochems. These limestones mainly have interparticle porosity. L8 and L9 are detrital limestones (biocalcirrudites) composed of large allochem grains (mainly bivalves, bryozoans and red algae) (Benavente, 2003). L10 is a biomicrite composed of oriented fragments of fossils (mainly ostracods and molluscs), which, consequently, provide a structural anisotropy to the rock. L11 is an oolitic limestone (oosparite) where oolites are densely packed and poorly sorted (Martínez-Martínez et al., 2013).

2.1.4. Travertines and tufas

The studied travertines and tufas present different structural (mesofeatures) and textural (microfeatures) characteristics. In this investigation, such meso- and micro-features are described in accordance with García-del-Cura et al. (2012) classification. Thus, T12 presents banded and massive structures with low porosity values (mainly intercrystalline porosity) and some unconnected bugs perpendicular to the banded structure. T13 shows a porous banded structure with fenestral and vug macroporosity, which provides a structural anisotropy. T13 also has intergranular (related to small pisoids) and intercrystalline porosity. T14 presents banded and massive structures with low porosity values (mainly intercrystalline porosity). It shows some separated fenestral and vug macroporosity, so these macropores are interconnected only through intercrystalline porosity. T15 can be classified as homogeneous tufa. It is a very porous limestone with predominant microcrystalline calcite formed over rushes and reeds (accretional microcrystalline fringe cement). T15 shows intercrystalline porosity linked to microcrystalline fringe cements. Macroporosity is also abundant and is formed by plant casts, which have a diameter larger than 0.5 cm.

Lucia's petrophysical classification of porosity in carbonate rocks is applied to the studied sedimentary rocks. This classification was modified after Choquette and Pray's (1970) classification to include pore connectivity. Lucia showed that pore space located between grains (intergranular porosity) and between crystals (intercrystalline