An Experimental Approach for the Characterisation of Rigid Porous Media and Unsaturated Conductivity Relations

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Abstract. A laboratory procedure for the characterisation of rigid, porous media is developed and tested. The overall objective of the characterisation is to provide a basis for the choice of a relevant unsaturated conductivity relation. With the proposed procedure, the porous materials are characterised through hydraulic conductivity measurements, saturation-pressure measurements, porosity measurements and air entry pressure measurements. The measurements were conducted using water and a selected non-aqueous phase liquid (\(n\)-decane), and two types of homogeneous, rigid porous media of different origin (fritted glass samples with guaranteed homogeneity by the manufacturer, and chalk). The laboratory method successfully characterised the fritted glass samples as homogeneous on basis of calculated tortuosity values, measured bubble pressures and measured pore-size density curves. The contact angle between the liquid and the solid had negligible impact when comparing the drainage of water with the drainage of \(n\)-decane, and also when comparing \(n\)-decane drainage in dry porous media with \(n\)-decane drainage in media where a film of water separated the \(n\)-decane from the pore wall. Also, the differences in saturated conductivities between \(n\)-decane and water in both samples of chalk and fritted glass were well predicted on basis of differences in density and viscosity of the liquids. The laboratory procedure was furthermore used for characterisation of the pore space available for non-aqueous liquid flow in partially water-saturated porous media. The \(n\)-decane conductivities in the fritted glass samples partially saturated with water were considerably lower than the \(n\)-decane conductivities in the dry fritted glass samples.

Keywords: pore-size density, unsaturated conductivity, effective porosity, tortuosity, non-aqueous phase liquid

1. Introduction and Objectives

In problems related to the prediction of the fate of hazardous chemicals that are released in soil, various assumptions need to be made regarding the soil structure. Some soil types (e.g., sand and kaolinite) can in many respects be assumed to behave like a rigid, porous medium. The quantification of unsaturated porous medium flow is generally based on the non-linear Richard’s equation, which combines Darcy’s law and the equation of continuity and yields for the 1D-case:

\[
\frac{\partial S}{\partial t} = -\frac{\partial}{\partial \varepsilon} K(S) \left( \frac{1}{\rho g} \frac{\partial P}{\partial \varepsilon} + 1 \right)
\]

(1)
where \( S \) is the water saturation (volume water per pore volume), \( t \) is time, \( z \) is the vertical spatial coordinate (with origin at the soil surface and positive downwards), \( \rho \) is the water density, \( g \) is the mass gravity and \( P \) is the capillary pressure that is defined as \( P = P_{nw} - P_w \), where \( P_{nw} \) is the non-wetting phase (air) pressure and \( P_w \) is the wetting phase (water) pressure immediately adjacent to the interface. In the following we use the air pressure (i.e., the atmospheric pressure) as a reference point, implying that \( P_{nw} = 0 \) and \( P = -P_w \). The porous medium properties are in Eq. (1) accounted for through the unsaturated hydraulic conductivity function that yields the conductivity of the medium as a function of the water saturation, \( K(S) \). The water saturation \( S \) is in turn a function of the capillary pressure \( P \), which commonly is expressed through the retention function, \( S(P) \). The unsaturated hydraulic conductivity function and the retention function are generally non-linear and their determination for a specific porous medium requires some type of experimental investigation of that medium.

Direct measurements of the unsaturated hydraulic conductivity function are time-consuming and expensive [11]. However, several models, so called statistical models, have been developed for determination of the relative conductivity function \( K_r(S) \), on basis of the more easily measured retention function, \( S(P) \) [3, 5, 20, 22, 26]. The relative conductivities (usually defined as the ratio of the unsaturated conductivity at a fixed saturation and the saturated conductivity; \( 0 < K_r < 1 \) can then be scaled by one measured conductivity value (usually the saturated conductivity) to yield the unsaturated hydraulic conductivity function \( K(S) \). This procedure is based on the assumption that the porous medium may be regarded as a set of interconnected pores, which are randomly distributed in the sample and characterised by their length scale, the “pore radius” \( r \). Moreover, a modified version of Poiseuille’s formula, taking for instance tortuosity into account (see Appendix I, Eqs. (I-1) and (I-2)), is assumed to be valid at the level of the single pore, and the soil retention curve is considered analogous to the pore radii distribution function [21]. Thus, even though these models are often considered macroscopic, they are postulated at the pore scale.

It has been shown that the statistical models often fail to adequately describe retention- (and consequently conductivity-) functions in porous media with a heterogeneous pore structure, and a flexible retention function was developed for these media, resulting in a predicted conductivity function which was distinctly different from the classical unimodal description [9, 27]. Especially, a secondary pore structure or a macropore can result in large model prediction errors close to saturation which is unfortunate since, as mentioned above, the saturated hydraulic conductivity is often used as a matching value. In order to adequately describe the retention function and predict the conductivity function, it is thus necessary to characterise the pore structure of the medium, and especially identify macro pores, cracks and heterogeneities.

This paper reports on a laboratory procedure for the characterisation of rigid, porous media. The overall objective of the characterisation is to provide a basis for the choice of a relevant unsaturated conductivity relation. The laboratory procedure is therefore designed to enable the identification of the three following categories of porous media: (I) homogeneous media containing a primary pore system which is drained at intermediate pressure heads, (II) media containing a secondary (structural) pore system caused by aggregation or microchannels, and (III) media containing macropores or cracks, which typically occupy a negligible volume of the total sample volume and may be drained at low pressure heads. The specific objective of this study was to investigate whether the accuracy of the laboratory method is sufficiently high to provide conclusive evidence regarding the homogeneity of the tested samples (using the above definition of homogeneity). Furthermore, the developed laboratory procedure could be useful for the measurement of non-aqueous liquid (NAPL) conductivities at different degrees of porous medium hydration, enabling the quantification of the effective pore space available for NAPL flow.

In the present study, the measurement accuracy is tested for the case of the flow of water and a typical NAPL (\( n \)-decane) through two types of homogeneous, rigid porous media of different origin (fritted glass samples with guaranteed homogeneity by the manufacturer, and chalk). Since the liquid properties and the interactions between the liquid phase and the solid phase must be taken into account in the characterisation, the effects of such interactions between \( n \)-decane and water are also investigated.

2. Theory and Evaluation Methodologies

A mean pore radius of the materials is calculated in two different ways based on two independent sets of