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Saturated hydraulic conductivity and structural properties of clay-sand systems

Conductivité hydraulique en saturé et propriétés structurales de systèmes argile-sable

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INTRODUCTION

Many investigations about the flow properties of soils and clays have shown that hydraulic conductivity (K) is a factor dependent on both chemical composition and electrolyte concentration of the percolating solution, as well as the structural state of the soil. The amount and type of clays and their exchangeable cations and anions, besides the presence of binding agents, also contribute in determining the hydraulic conductivity of the soil (Reeve et al. 1954; Quirk and Schofield 1955; Brooks et al. 1956; Levy et al. 1988; Frenkel and Levy 1992).

The main mechanisms responsible for the reduction in the soil hydraulic conductivity are: (i) dispersion and migration of colloid particles with subsequent lodging in the conducting pores, and (ii) the swelling of clays, which occurs at high exchangeable sodium percentage (ESP) and salt concentration above 0.01 N (Felhender et al. 1974; Frenkel et al. 1978; Pupinsky and Shainberg 1979; Shainberg et al. 1981; Keren and Singer 1988). Whenever such phenomena occur the hydraulic conductivity is no longer a constant factor but changes with time due to particle arrangement during the flow process, and non-linear relationships between effluent volume and time are observed. As a consequence Darcy's law which characterizes steady or stationary flow processes (Hillel 1971) cannot be applied to calculate soil hydraulic conductivity. In an earlier paper Aringhieri and Capurro (1994) proposed an empirical model to describe the flow of solutions having different SAR (Sodium Adsorption Ratio) and electrolyte concentration, through soil columns under the above conditions, i.e., in the presence of structural modifications of the substrate during the percolating process. The basic equations of this model are the following:

$$dQ/dt = (dQ/dt)_{t=0} e^{-at} \quad (1)$$

$$Q = (A DH/La) K_{sat}^{\circ} (1 - e^{-at}) \quad (2)$$

$$Q' = (A DH/L) K_{sat}^{\circ} e^{-at} \quad (3)$$

$$\ln Q' = \ln (A DH/L) K_{sat}^{\circ} - at \quad (4)$$

where Q represents the volume (cm^3) of solution vertically flowing through a soil column (L cm length with a cross sectional area of A cm^2); Q' its derived function; DH (cm) the constant hydraulic head; K_{sat}° (cm/h) the initial hydraulic conductivity; t (h) the time, and a (h^{-1}) the rate constant of the flow process. This latter parameter being linked to the speed by which structural modifications (i.e. swelling or colloidal dispersion) can occur during the percolation. Considering now Eq.4, a plot of $\ln Q'$ against t produces a straight line of negative slope equal to a , and intercept equal to $\ln (A DH K_{sat}^{\circ} / L)$. It is therefore possible to calculate the values for K_{sat}° and a as parameters characterizing the flow of solutions through soil columns under saturated conditions. Moreover, Eq. 3 results in the Darcy's equation when considering a short range of time or in the absence of structural modifications. The proposed model could therefore quantitatively characterize the flow process when non-linear relationships (non-Darcy behavior) are observed. The present work was then undertaken to validate the model by applying it to different clay-sand systems (Illite and Kaolin) at low electrolyte concentrations, and to evaluate their relative flow properties as essential components of the soil.

MATERIALS AND METHODS

Clay Minerals

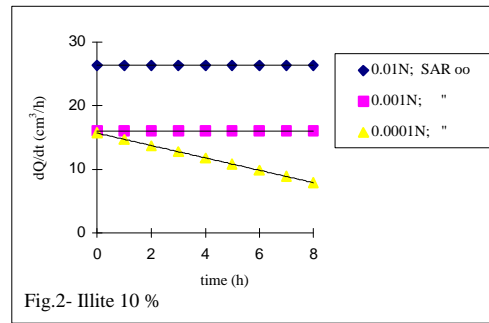
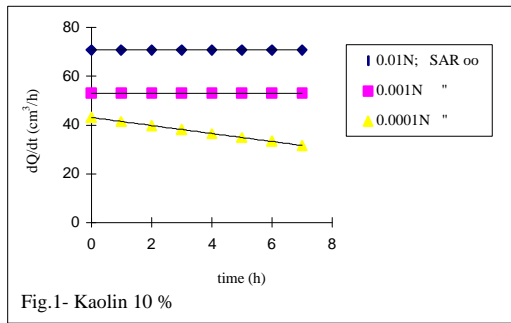
Two commercial clay minerals (Kaolin and Illite) were employed in this investigation. The Kaolin was a BDH product, whereas the Illite was a source clay (n° 36, Morris, Illinois) obtained from Ward's Natural Science Establishment Inc. The samples were hand ground with a pestle and mortar, and a 2% suspension was made by shaking with distilled water. The separation of the less than 2μ esd (equivalent Stokes diameter) fraction was carried out by repeated sedimentation and decantation according to the procedure of Parfitt and Greenland (1970) with minor modifications. Ultrasonic vibration (USV) was applied to the suspension for 15 min in order to achieve the best separation of the clay fraction. The clays were then made homoionic (Na^+) by washing the suspension three times with NaCl 1N at pH 3.0, twice with NaCl 1N at pH 5.7, and then repeatedly with distilled water until the clay dispersed. Further washings were carried out until the conductivity of the suspension was of the same order as that of distilled water. The sodium clays were separated each time by centrifugation for 30 min at 12,000 rpm. X-ray diffraction analysis of the source clay (Illite) was performed by a Philips X-ray diffractometer PW 1730, Co $K\alpha$ / Fe filtered 35 KV, 25 mA radiation.

Hydraulic Conductivity Experiments

To perform flow experiments, Kaolin/, and Illite/sand mixtures at rates of 5, 10, and 15% clay were prepared from the purified homoionic clays by adding opportune amounts of clay to distilled water (1:5 ratio) stirring continuously for 15h. The suspension was then mixed with the opportune amount of acid-washed quartz sand (0.1-0.3 mm in diameter) and dried in an airy oven at 60°C, stirring occasionally for better uniformity. The columns were prepared by packing about 40g of clay-sand mixture in plexiglas cylinders (2.3 cm inside diameter and 11.5 cm length) at an average bulk density of 1.43 g/cm³. The bottom of the columns, made of holes, was covered with a strip of cotton material and a synthetic inert screen. A quartz sand layer was put at the bottom of the columns. Quartz sand was also spread on the top of the columns to minimize surface disturbance during leaching experiments. The columns were wetted from below and kept saturated with the percolating solution. The clay-sand columns were then leached, under a constant hydraulic head, with solutions of low electrolyte concentration (0.01, 0.001, and 0.0001 N) at SAR ∞. All experiments were carried out in duplicate and the average value of the effluent volume Q (cm³) as a function of time t (h) was recorded. The experimental data were then processed according the equations proposed by Aringhieri and Capurro (1994), whereas Darcy's equation was applied to the flow process when linear relationships were observed.

RESULTS AND DISCUSSION

For both Kaolin/ and Illite/sand systems the flow rate, at a constant SAR value (∞), decreased as the electrolyte concentration of the percolating solution decreased (Fig. 1 and Fig. 2). Moreover, the flow rate kept constant with time at the two highest electrolyte concentrations, so Darcy's equation was applied to the calculation of the saturated hydraulic conductivity (K_{sat}) to characterize the flow process. On the other hand, the flow rate decreased with time at the lowest electrolyte concentration (non-Darcy behaviour). In this case the model proposed by Aringhieri and Capurro (1994) was applied to describe quantitatively the flow process, and calculate the characterizing parameters K_{sat}° and α .

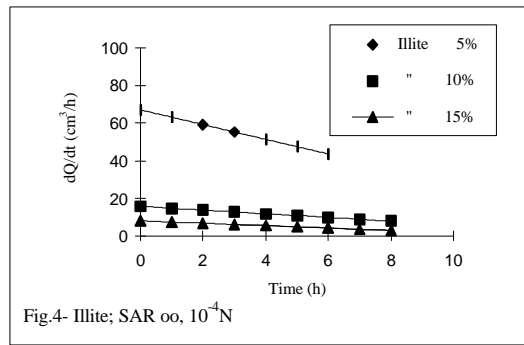
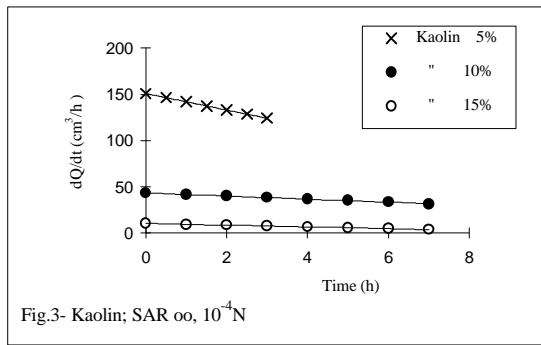


Clay/sand mix	δ (g/cm ³)	Electrolyte conc.	SAR	K_{sat} (cm/h)	K^o_{sat} (cm/h)	α 10 (h ⁻¹)	K^o_{sat}/α (cm)	r^2
Kaolin 10%	1.48	10 ⁻² N	∞	11.5	*	*	*	0.999
"	1.48	10 ⁻³ N	"	8.9	*	*	*	0.999
"	1.43	10 ⁻⁴ N	"	*	6.8	0.44	154.5	0.997
Illite 10%	1.52	10 ⁻² N	∞	4.7	*	*	*	1
"	1.48	10 ⁻³ N	"	2.8	*	*	*	0.999
"	1.45	10 ⁻⁴ N	"	*	2.7	0.85	31.8	0.99

Tab.1- Characteristic parameters of the flow process for Kaolin and Illite/sand systems at different electrolyte concentration.

Under the same conditions, the flow rate was higher for Kaolin than Illite system (see values for K_{sat} or K^o_{sat} in Tab. 1) eventhough Kaolin dispersed more than Illite as revealed by the optical density of eluates (data not reported). This was probably due to dispersion and continuous long-distance movement of extremely fine Kaolin particles and their depletion from the system which results in a higher hydraulic conductivity. This mechanism was also suggested by Pupinsky and Shainberg (1979) in their work on hydraulic properties of sandy soils. In addition, the swelling of expanding interlayered (2:1) clay minerals present in the source clay referred as Illite, as observed by X-Ray diffraction analysis, may contribute in reducing the hydraulic conductivity of this system by plugging in some extent its conducting pores.

A progressive reduction in the flow rate with time always occurred at the lowest electrolyte concentration (10⁻⁴ N) and SAR ∞ , regardless of the percentage of clay in the mixture. A decrease in the flow rate of the percolating process was also observed, for both systems, when the percentage of clay in the mixture increased (Fig. 3 and Fig. 4).



Clay/sand mix	δ (g/cm ³)	Electrolyte conc.	SAR	K_{sat}^o (cm/h)	α 10 (h ⁻¹)	K_{sat}^o/α (cm)	r^2
Kaolin 5%	1.41	10 ⁻⁴ N	∞	23.6	0.66	357.5	0.998
" 10%	1.43	"	"	6.8	0.44	154.5	0.997
" 15%	1.42	"	"	1.7	1.41	12.1	0.98
Illite 5%	1.47	10 ⁻⁴ N	∞	10.8	0.73	147.9	0.997
" 10%	1.45	"	"	2.7	0.85	31.8	0.99
" 15%	1.42	"	"	1.4	1.23	11.4	0.98

Tab.2- Characteristic parameters of the flow process for Kaolin and Illite/sand systems at different clay percentages.

The decrease in the drainage rate when increasing the clay content was higher for Kaolin than Illite, as shown from the respective K_{sat}^o values (Tab. 2), eventhough their behaviour was quite similar at the highest percentage of clay in the mixture. That means that variations in the clay percentage of the system affect the flow rate more for Kaolin than Illite.

As shown from r^2 values, Eq. 4 correlated well the experimental data, thus confirming the validity of the applied model which makes possible the quantitative characterization of non-Darcy flow processes under saturated conditions. The value of the rate constant α is linked to the speed by which modifications can occur in the porous material during the percolation. The value of K_{sat}^o (initial hydraulic conductivity) quantifies the conditions at the beginning of the process and, therefore, the extent of structural modifications occurring in the porous system during the saturation with the percolating solution. In this respect, the values obtained for K_{sat}^o and α have shown that structural modifications, in both systems, occurred mainly during the saturation of the column with the percolating solution, and to a lesser extent during the flow process. Concerning the overall flow process, values for K_{sat}^o/α indicate that Illite is much more subject to structural modifications than Kaolin system.

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Key words: Clays, hydraulic conductivity, SAR, electrolytes

Mots clés : argiles, conductivité hydraulique, SAR, électrolytes

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