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Hydraulic Conductivity of Semi-Quasi Stable Soils: Effects of Particulate Mobility

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1. Introduction

Particulate mobility within the intra-soil aggregates and soil pores has profound effects on the stability of soils and consequently hydraulic conductivity. Soil structure or aggregation essentially describes the way the soil constituents (sand, silt, clay, organic matter) are arranged and the size and shape of pores between them (Geeves *et al.* 1996). On the basis of size, soil aggregates can be distinguished as macro-aggregates ($> 250 \mu\text{m}$) and micro-aggregates ($< 250 \mu\text{m}$) and with further breakdown, they can release finer particles ($< 20 \mu\text{m}$, Oades and Waters 1991). However, aggregates $< 2 \mu\text{m}$ (predominately clay floccules) are held together by forces derived from the interaction of clay particles. The loss of macroporosity is attributable to detachment and subsequent transport of aggregates (Roth *et al.* (1991; Sutherland *et al.* 1996) and further dis-aggregation can affect soil water retention (Neufeldt *et al.* 1999). Aggregates with low stability fracture easily and the breakdown into smaller sizes is a major cause reduced permeability through pore clogging as a result of loss of aggregation and porosity of surface soils. Once a crust is formed the water and solute transport properties change, for example increased rate of water infiltration with removal of crust by application of gypsum (Ramirez *et al.*, 1999). This surface crusts or sealing is often attributable to slaking and dispersion of clay minerals.

Dispersion is most commonly associated with sodicity and is highly sensitive to both the exchangeable sodium percentage (ESP) and total electrolyte concentration. Soils with a high ESP are more susceptible to dispersion due to its greater ability to develop diffuse double layers. The exchangeable sodium percentage (ESP) can be defined as:

$$ESP = \frac{(100 * \text{ExchangeableNa})}{CEC} \quad (1)$$

where, CEC is the cation exchange capacity.

Similarly, Sodium adsorption ratio (SAR) can also be used to define sodicity, particularly when using soil solutions.

$$SAR = \frac{[Na^+]}{(0.5([Ca^{2+}] + [Mg^{2+}]))^{0.5}} \quad (2)$$

Where, all [concentrations are expressed as mmol(+)/L].

In general, high levels of SAR decrease the stability of soil structures and microstructures usually become more unstable, deflocculated and dislodged as the ESP increases with more

production of fine or mobile particles. For example, in particulate facilitated transport, mobile colloids must be present in large concentrations and must be transported over significant distances (Kretzschmar *et al.* 1999). In most environments, mobilization is favoured by high pH, high SAR and low ionic strength resulting in severe decreases in permeability. Permeability or hydraulic conductivity is estimated using Darcy’s law for one-dimensional vertical flow (Klute and Dirksen 1986):

$$q = K * \partial H / \partial z$$

(3)

where q is the flux density, K is the hydraulic conductivity, $\partial H / \partial z$ is gradient of hydraulic head H , and z is the gravitational head.

Despite the considerable amount of research carried out, the processes by which the structural breakdown and pore clogging by particulate transport occur in soils are far from satisfactorily understood and also limited by suitable modelling procedures. For instance McDowel-Boyer *et al.*(1986) and Harvey and Garabedian (1991) by applying filtration theory, attributed poor estimates of transport with natural porous media to; (i) the wider pore size and particle size distributions, complex pore geometry and rough matrix surface or these materials and (ii) a wide particle size distribution mobile surface colloids. Using a cake filtration model, Mays and Hunt (2005) suggested that the increased head loss results from the formation of deposits with a decline in hydraulic conductivity. Reduced flow capacity of the soil matrix can be induced by the invasion and geochemical transformation due to plugged pore channels (Song and Elimelech, 1995) thus minimising erosion of base soils with reduction in filter permeability (Lee *et al.*, 2002).

Thus research was undertaken in an attempt to throw light on the dynamics of the processes of mobilisation during the flow of NaCl solutions through two soil materials of markedly different structural cohesiveness. The experiments were carried using saturated soil columns to determine hydraulic conductivity and particle size distribution as the criterion for the assessment of the dynamic flow processes.

2. Materials and methods

2.1 Soil samples and their characteristics

Two different soil samples were used as porous media; sample A and B with distinct physico-chemical characteristics (Table 1) analysed using standard methods (Klute 1986;

Soil Property	Sample A	Sample B
Sand (%)	83.3	89.0
Silt (%)	6.6	1.9
Clay (%)	10.1	9.1
Texture	Sandy loam	Loamy sand
Electrical conductivity (µS/cm)	42	380
pH(water)	6.1	8.7
CEC (mmol _c / g)	3.4	8.1
Organic Carbon (%)	0.03	0.55
Clay mineralogy	Kaolinite,vermiculite	Kaolinte, smectite
Bulk density (g/cm ³)	1.61	1.58

CEC-cation exchange capacity

Table 1. Physico-chemical characteristics of soil samples

Klute 1986b). Sample A provides a classic example of a relatively fragile agricultural soil which is highly susceptible to structural breakdown and permeability problems while sample B is a completely disrupted and reconstituted material (sand and clay) and presents similar structural problems.

2.2 Particle size distribution measurements

The particle size distributions (Table 2) for the various sized fractions of these porous media were determined using the sedimentation or grain size mechanical wet sieving method (Day 1965) for the particle size range from 45-2000 μm while a laser light scattering technique (Mastersizer Microplus Ver.2.18, c/o Malvern Instruments Ltd, 1995) was used for the range $< 45 \mu\text{m}$. A mixture of air dried soil ($<2 \text{ mm}$) with water was boiled and 6 % hydrogen peroxide solution was added to remove organic matter followed by a calgon/NaOH mixture to disperse the soil. Suspensions were collected for various fraction sizes according to the sedimentation theory or Stokes’s law (Stokes, 1891). For the sand fractions suspensions were separated using sieves of various diameters (1000, 500, 250, 125, 45 μm). Suspensions passing through 45 μm together with effluents from subsequent leaching experiments were analyzed for particle size distribution using a Malvern Mastersizer analyser following leaching experiments. Suspensions were dispersed in the Mastersizer’s ultrasonic bath unit (equipped with a small angle light scattering apparatus, Helium-neon laser; $\lambda =$ of 633 nm, as a light source) for about 25 minutes. Suspension concentrations were adjusted until an obstruction of a least 0.2 % is reached for best results using refractive indices of 1.59 and 1.33, respectively for clay and deionised water with a particle density of 2.6 g/cm^3 . Both values assumed to be representative for the soil material used for analysis.

	Sample A	Sample B
<i>Size fractions (μm)</i>	<i>% particle fraction (g/g)</i>	
1000 – 2000 μm	12.37	1.70
500 – 1000 μm	26.78	12.81
250 – 500 μm	21.30	57.46
125 – 250 μm	15.92	13.67
45 – 125 μm	2.41	2.40
$< 45 \mu\text{m}$	4.52	1.00

Table 2. Particle size fractions for samples A and B

2.3 Hydraulic conductivity measurements

2.3.1 Constant head hydraulic conductivity measurements

A glass Marriotte bottle, filled with deionised water was used to maintain a constant head, with ambient temperature during the experiment varying from 20 to 22 $^{\circ}\text{C}$. The flow was from the bottom to the top of the columns to prevent air entry. The hydraulic head across the soil samples (ΔH) was kept at an average of 30 cm and 40 cm for samples A and B, respectively. ΔH was measured as equivalent to the vertical distance from upper water level (on the Marriotte bottle) to the bottom at the leachate collection point. The flow was continuous during leaching in order to maintain saturation throughout the experiments. In the case of flow interruptions, columns were kept saturated by tightly closing the system to avoid air entry. Hydraulic condtivity (HC) was initially measured using the deionised water followed by 1mmol NaCL to subsequently measure pore size distribution before and after

leaching with 1mmol NaCl. Any turbid percolate observed during the experiment was collected and stored in plastic bottles for further analysis of effluent particle size distribution using the Malvern Mastersizer technique, and for mineralogical characterization. Using a column and constant head experimental set up, equation 3 can be re-written as $K = (4VL) / (\pi d^2 \Delta t \Delta H)$: where V (cm^3) is the volume of water collected during time interval Δt (minutes), L (cm) is the length of column soil sample, d (cm) is the inner diameter of the column and ΔH (cm) is the change in hydraulic head across the soil sample.

Pore-size distributions of the soil columns were estimated from water-retention versus water-potential curves determined using sintered glass funnels and the Haines method over the low pressure ranges (measured at 5 cm suction interval) and pressure-plate, ceramic-membrane apparatus for the higher pressure range (10 to 800 KPa). The column samples were pre-wetted with 0.1M CaCl_2 solution to avoid swelling and subsequently leached with deionised water followed by 1 mmol/L NaCl solution adjusted at pH 8.5. Since the soils were predominately kaolinitic in nature and therefore have low swelling potential. Similarly, the water-retention data was transformed to pore-size distribution using the form of Kelvin equation:

$$\Delta P = (2\sigma / rp) \quad (4)$$

where, ΔP is the pressure difference (Pa) across an air-water interface, σ is the surface tension of water (Jm^{-2}) and rp is the radius of a circular capillary tube (m).

2.3.2 Pressure leaching experiments

Pressure leaching simulations and/or experiments were carried out using soil columns as shown schematically in Figure1. Soil samples (< 2 mm) were initially mixed with 0.9–1 mm acid-washed sand to provide a rigid skeletal structure to facilitate flow and colloidal mobility. The proportions of mixtures were 50% soil–50% sand and 30% soil–70% sand, for samples B and A, respectively. The mixtures were uniformly wet packed into acrylic soil columns (400 mm long, 25 mm diameter, 2 mm wall thickness, cross-sectional area 4.91 cm^2 , volume 196 cm^3) and saturated with the desired electrolyte concentrations. Holes were bored at various column depths (X_i), for horizontal insertion of pressures sensors (P_i) at 50 mm (X_1) and 250 mm (X_2), along the column from the inlet (Fig. 1). Miniature pressure transducer with tensiometers T5–7/5 model (UMS, 2000) each with 1.5 m cable length and 5 cm shaft length and 20 mm diameter were connected to the system for online pressure monitoring and measurements of saturated hydraulic conductivity with time.

A peristaltic pump (designed with a system maximum discharge pressure of 300 kPa at 0 – 40° C), was used to pump solutions of ionic strengths of 1 mmol/L NaCl into the soil columns in a vertical upward flow. During leaching, pressures were measured. For continuous online pressure measurements, an Agilent 34970A model data logger-PC system (Agilent Technologies 2003) was used as a data acquisition system. To ensure equilibration of the system and to enable particle-hydrodynamic settling, the columns were saturated with 1 mmol/L NaCl solution overnight (for at least 12 hours). Prior to experimental runs, a steady state was attained by measuring outflow rates until a constant value was achieved. Hydraulic conductivity was then estimated from equation 3 (Darcian flow under hydrodynamic dispersion). Further, to simulate or quantify the effect of ionic strength, the columns were also leached with 10, 2.5 and 1 mmol/L NaCl solution to measure the extent of hydraulic conductivity decrease in response to the electrical conductivity.

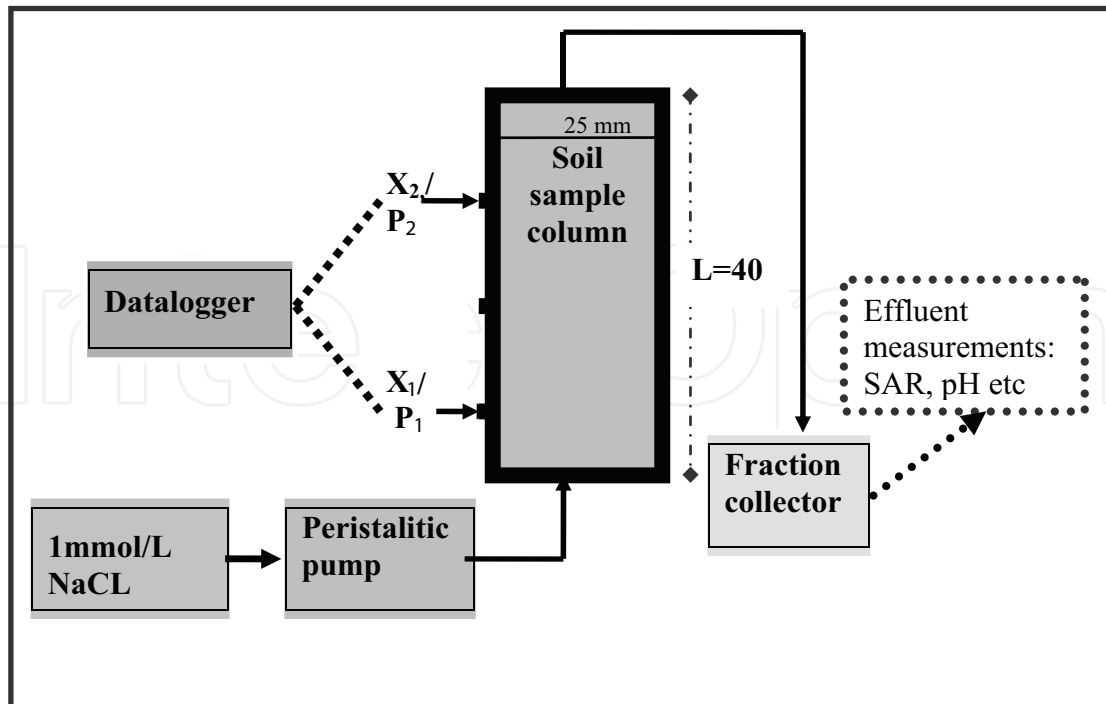


Fig. 1. Schematic diagram for pressure leaching experiment for hydraulic conductivity measurements ($X_{1(\text{inlet})} = 50$ mm and $X_{2(\text{outlet})} = 250$ mm from bottom of column and P1 and P2 are respective pressures points)

3. Results and discussion

3.1 Hydraulic properties associated with dispersion of aggregates

The pore-size distributions were obtained from water retention data (θ vs h) in Figs. 2a and 3a for sample A and B, respectively; where θ is volumetric water content and h is suction or pressure head. The pore radius r of samples were generating by differentiating $d\theta/dh$ from the measured water contents and pressure head or suction measurements. The pore-size distributions for the columns packed with samples are shown in Figs. 2b and 3b for sample A and B, respectively. The pore size distribution for the sample A soil columns were broader with the peak occurring at approximately $8 \mu\text{m}$ while those for the sample B were much narrower with a peak at approximately $12 \mu\text{m}$.

The small shift in the narrow distribution for Sample A following leaching would be consistent with small dispersion and relocation of particles (see Figs 4 and 5). The broader distribution for the Sample B residue became substantially narrower following leaching (Figs 2 and 3). This change would explain the dramatic decrease of hydraulic conductivity by 4 orders of magnitude (See section 3.2). Similar observations were made by Leij *et al.* (2002) who observed that over the total number of pores decrease, the mean pore size decreased from an initial 49.4 to $28 \mu\text{m}$ after disturbance. This dispersion-dependent pore size distribution changes in samples were manifested by decrease of porosities: 0.370 to $0.354 \text{ cm}^3/\text{cm}^3$ for sample A and 0.431 to $0.417 \text{ cm}^3/\text{cm}^3$ for sample B following leaching with 1 mmol/L NaCl . i.e a decrease of porosity by 9% and 3% for sample A and B, respectively. This accounted for the subsequent decreases of actual hydraulic conductivity from 6.1 to 0.02 cm/h and from 1.5 to 0.14 cm/h for sample A and B, respectively (see section 3.2)

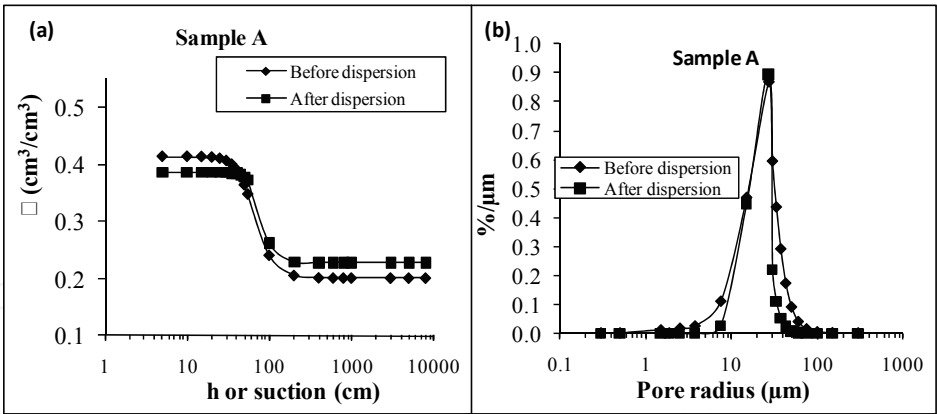


Fig. 2. Soil water retention (a) and pore-size distribution (b) for sample A

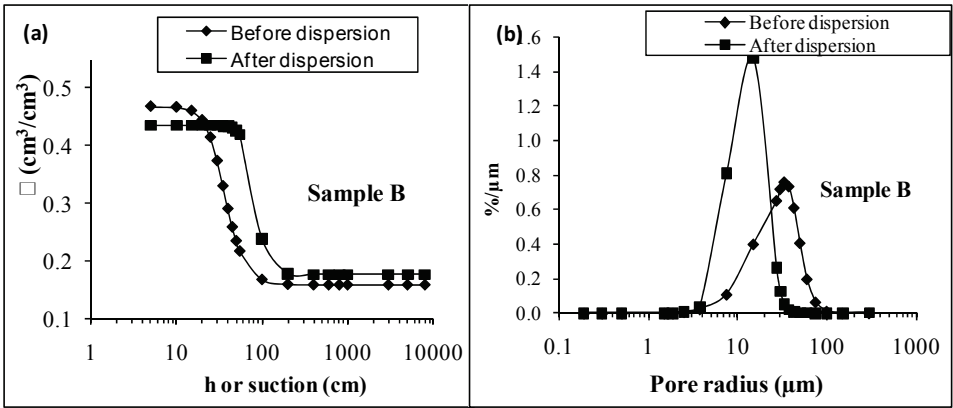


Fig. 3. Soil water retention (a) and pore-size distribution (b) for sample B

Similarly, using measured particle size distribution (Fig 4), soil structure was modelled at the pore scale (Dikinya *et al.*, 2007) to explain the different response of the two samples to the experimental conditions (see Fig 5). The size of the pores was determined as a function of deposited clay particles. The modal pore size of sample B as indicated by the constant water retention curve was 45 μm and was not affected by the leaching process. In the case of the sample B, the mode changed from 75 to 45 μm. This reduction of pore size corresponds to an increase of capillary forces that is related to the measured shift of the water retention curve of the two samples.

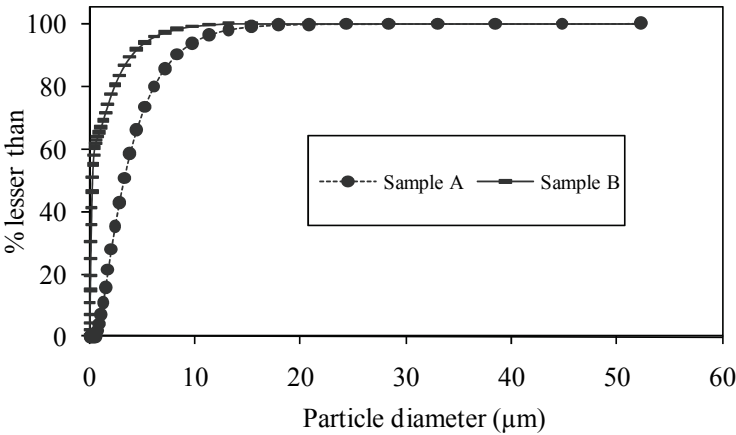


Fig. 4. Particle size distribution of effluents

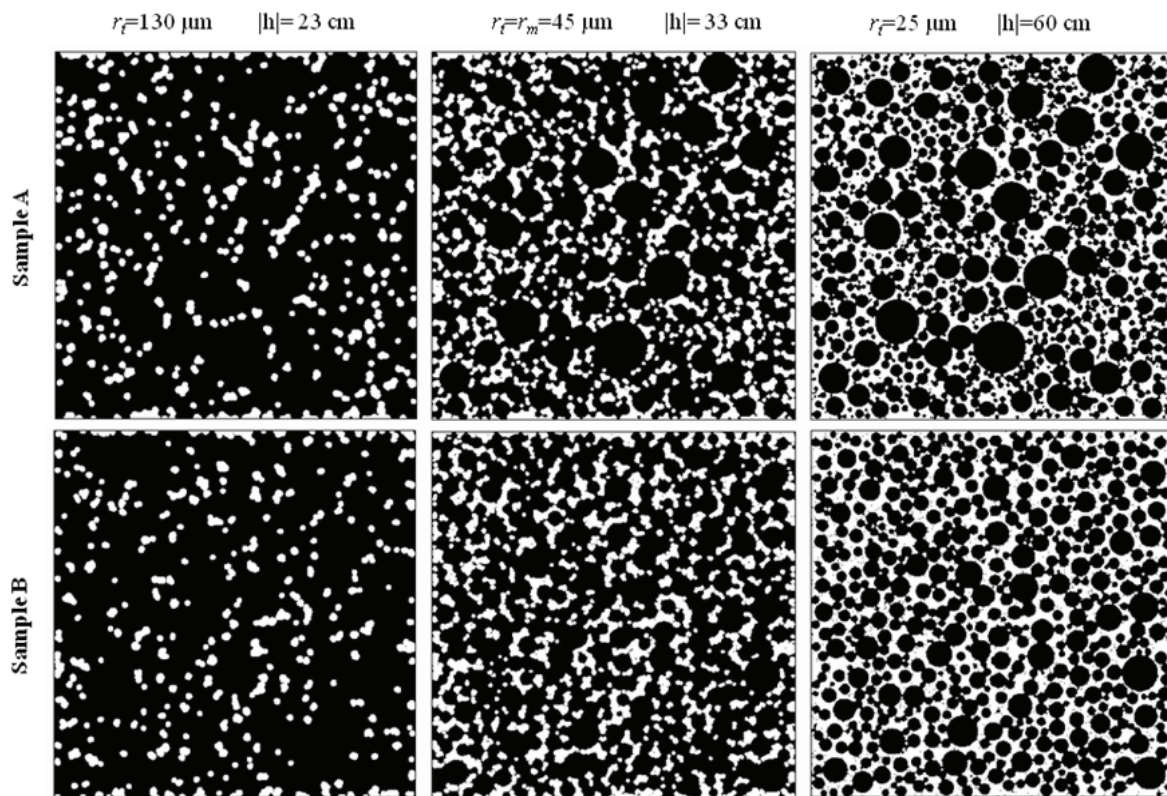


Fig. 5. Size-dependent pore connectivity for soil samples A and B. All particles and pores smaller than the threshold value r_t , are shown in black and pores of radius $r \geq r_t$ in white.

Source: [Dikinya *et al.* 2007].

Comparison of the modelled pore size distribution with the measured water retention curves for the four cases; (i) Sample B before the release process, (ii) Sample A before the release, (iii) Sample B after the re-deposition and (iv) Sample A after the re-deposition, have revealed that measured water retention curves were very similar for the cases i), iii) and iv). The air entry values of these three curves were 2-3 times the value observed for sample B before the release process (ii). The same phenomenon was simulated with the pore model: the mode of the modelled pore size distribution was similar (about $45 \mu\text{m}$) for (i), (iii) and (iv) and about 75 to $95 \mu\text{m}$ for ii). The ratio of the capillary forces associated with these values of the modes is somehow equal to 1.67 to 2.11 and is similar to the measured ratio of the air entry values.

3.2 Hydraulic conductivity under constant head using Mariotte bottle device

The hydraulic conductivity (HC) was found to progressively decrease with time. This decrease was attributed to decreases of pore radii associated with increased instability of soil intra-aggregates during leaching. Sample B was substantially more prone to structural disintegration than sample A with actual hydraulic conductivity decreases from 6.1 to 0.02 cm/h and from 1.5 to 0.14 cm/h, respectively as manifested by a relative marked measured shift of the water retention curve. In sample B there was appreciable decrease of the HC to 8.5 % of the initial value. This was attributed to localized pore clogging (similar to a surface seal) affecting hydraulic conductivity, but not the microscopically measured pore size distribution or water retention. This decrease could be explained with the modelled destruction of large pores due to particle re-deposition.

3.3 Hydraulic conductivity associated with particle mobility and pressure build-up

The dynamics of the process of structural disintegration in soil columns were further evaluated by simultaneously measuring changes in pressure gradients along the columns and sodium adsorption ratio (SAR) during pressure leaching with solutions of 10, 2.5, 1 mmol/L NaCl. Steady increases in pressure gradient ($\Delta P/\Delta L$) and corresponding decreases in RHC with time were observed for both soils and follow similar trends at all column depths indicating continuous particle accumulation in filter pores. The most severe increases in $\Delta P/\Delta L$ and decreases in RHC always occurred near the inlet to the columns and the decline gradually decreased along the column. An increase of $\Delta P/\Delta L$ and decrease in RHC with decreasing ionic strengths was also observed for both soils. The decreases in RHC and increases in $\Delta P/\Delta L$ were clearly influenced by the size as well as the concentration of migrating particles in the porous medium. The finer mobile particles in the mining residue were clearly more readily self-filtered at the lower electrolyte concentration than the larger sample B particles, producing more rapid increases in $\Delta P/\Delta L$ and decreases in RHC. This more effective particulate movement and more rapid plugging is undoubtedly due to increased development of the diffuse double layer, swelling and dispersion within the soil matrix at these concentrations.

A more dramatic decrease of saturated hydraulic conductivity was noticeable for the less cohesive sample A than for the aggregated sample B. Due to differences in the clay mineralogy and its treatment history involving greater disruption, sample A is far more sensitive to particle mobilisation and pore clogging than sample B. Sample A is therefore more likely to encounter constriction and retention thus allowing smaller sized particles to become entrapped behind the coarser fraction, forming a filtration zone. The more clogging occurs the greater is the decrease of hydraulic conductivity and the smaller is the amount of particles being released. This particularly enhanced at the lower electrolyte concentrations. Further, RHC of both soil samples has been shown to decrease with time and with increasing SAR with the reduction being substantially greater for the less cohesive sample B. This was probably due to dilution of high-sodicity soil irrigation water that can cause induce swelling, aggregate slaking and particle clay dispersion (Bagarello *et al.* 2006).

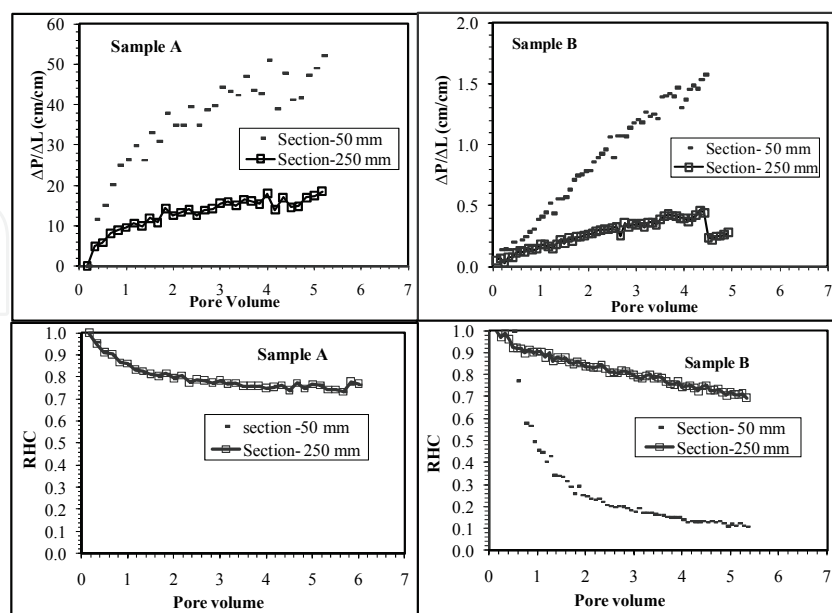


Fig. 6. Pressure build up (upper curves) and hydraulic conductivity (lower curves) attributable to structural disintegration and particle migration during leaching experiments.

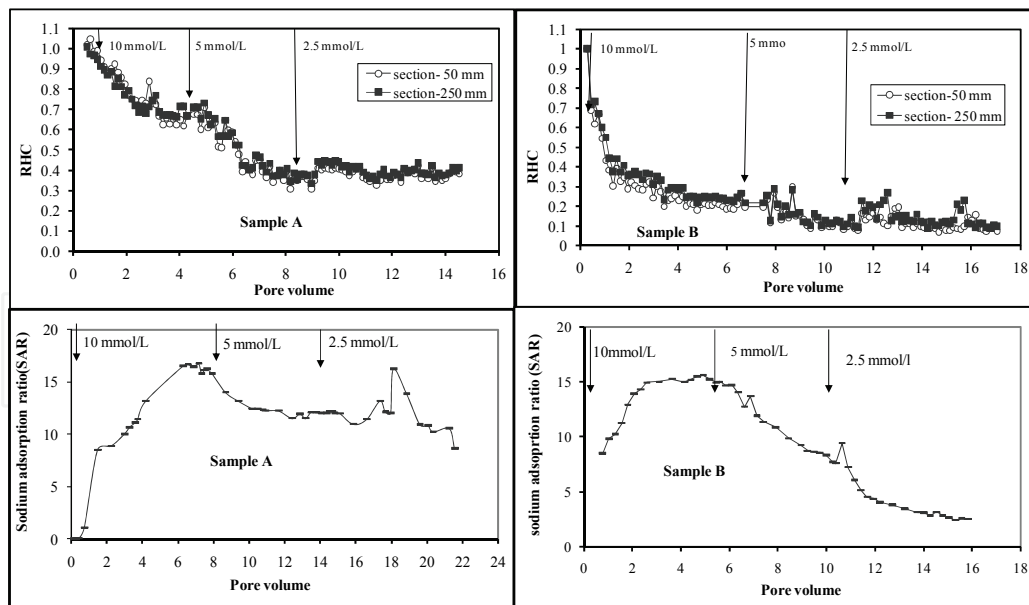


Fig. 7. Effect of ionic strength on relative hydraulic conductivity (RHC) and its associated sodium adsorption ratio (SAR) during leaching experiments.

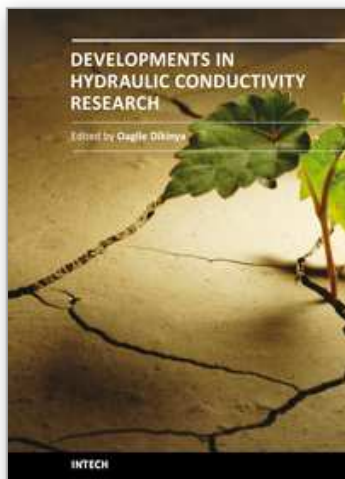
4. Conclusions

The dynamics of the process of structural disintegration in soil columns were evaluated by simultaneously measuring changes in pressure gradients along the columns and concentrations during pressure leaching. The decreases in RHC and increases in $\Delta P/\Delta L$ were clearly influenced by the size as well as the concentration of migrating particles in the porous medium. The finer mobile particles in Sample B were clearly more readily self-filtered at the lower electrolyte concentration than the larger sample A, producing more rapid increases in $\Delta P/\Delta L$ and decreases in RHC. This more rapid decrease in RHC particularly at the lowest concentration (1 mmol/L) was consistent with measured SAR. The effects of clay mineralogy are evident with the kaolinite- smectite sample B having a more marked decrease in RHC with increasing ionic strength compared with the kaolinitic sample A clays.

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This book provides the state of the art of the investigation and the in-depth analysis of hydraulic conductivity from the theoretical to semi-empirical models perspective as well as policy development associated with management of land resources emanating from drainage-problem soils. A group of international experts contributed to the development of this book. It is envisaged that this thought provoking book will excite and appeal to academics, engineers, researchers and University students who seek to explore the breadth and in-depth knowledge about hydraulic conductivity. Investigation into hydraulic conductivity is important to the understanding of the movement of solutes and water in the terrestrial environment. Transport of these fluids has various implications on the ecology and quality of environment and subsequently sustenance of livelihoods of the increasing world population. In particular, water flow in the vadose zone is of fundamental importance to geoscientists, soil scientists, hydrogeologists and hydrologists and allied professionals.

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