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Controlling solute transport processes in soils by using dual-porosity characteristics of natural soils

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ABSTRACT

Soils are notorious for their heterogeneity, and macropores conduct solutions by bypassing the surrounding soils, sometimes wasting the applied fertilizer or remediation chemicals. It would be beneficial in agriculture or environmental engineering fields if solute transport in soils were controlled with relatively simple techniques. In this study, the solute transport process was controlled using dual-characteristics of the soil pore system. Specifically convection and dispersion were controlled by changing the structure-dependent flow regime. Soil samples with/without artificial small macropores (diameter = 1 mm) and undisturbed soil samples were prepared, and solute transport experiments were conducted, in which a variety of breakthrough curves (BTC) was obtained by changing flow rate (from 1 to 0.1 of saturated conductivity) and saturation (saturation to −3 kPa). The results for the artificial macropore system showed that completely different BTCs were obtained with small suction differences, namely saturation and −3 kPa. At saturation, the BTC showed a bi-modal distribution typical for soils with macropores. At a slightly unsaturated condition of −3 kPa, however, the BTC showed a normal distribution quite similar to that of a repacked soil column. The results for undisturbed soil showed that the BTC gradually transitioned from a bi-modal to normal distribution, with the suction changing from saturation to only −3 kPa. These results suggest that effective use of fertilizer or remediation chemicals is possible with a relatively simple and inexpensive technique, even when macropore networks are present.

1. Introduction

Understanding solute transport in soils is essential for many fields, from agriculture to environmental engineering. In the agriculture field, the fate of fertilizers or pesticides is partly determined by solute transport processes. In environmental engineering, effective remediation of contaminated soils depends on how much solute is delivered into the finer pores where the contaminants are usually concentrated. Unfortunately, water and solute transport in soils are sometimes governed by macropore flow, where macropore networks are formed by root channels, earthworm burrows, and cracks or fissures [1]. These conduct water flow rapidly to the deeper profile without interaction with other soil bodies. For example, heavy rain could ruin the fertilizer application by leaching it below the root zone. Macroporous soil structure may channel remediation chemicals to the deeper profile without contaminant purification. Thus it is necessary for agricultural and contaminant remediation applications to avoid macroporous bypass flow and allow slow diffusion through the matrix.

In recent years, macropore contributions to water flow in field soils have been investigated in detail. For example, in agricultural applications, Mohanty et al. [2] reported that the estimated discharge rate of tile drainage was improved with consideration of the macropore contribution. In environmental engineering applications, Mishurov et al. [3] reported that there were optimal sizes and flow rates for a macroporous sand column which conducted the colloids effectively. In that study, the convection and dispersion process played a major role in solute transport in soils. In general, convection and dispersion processes affect the solute transport in soils greatly, where uniform distribution of solute was achieved by a normal distribution of breakthrough curves (BTCs) [4]. Nutzmann et al. [5], Toride et al. [6] and Tokumoto et al. [7] also have presented studies on the water saturation dependence of the dispersion process.

Gerke and van Genuchten [8] estimated hydraulic characteristics of the dual-porosity of soils, for which hydraulic conductivity yielded dual curves for macropore and matrix domains. Haws et al. [9] researched not only the macropore contribution, but also the intra-ped diffusion process. Mori et al. [10,11] examined bypass flow in root channels and revealed the drainage process in natural soils where drainage proceeded in order from macropore to matrix. There were distinct changes in the drainage pattern

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between macropore and matrix; therefore, it would be expected that there was a difference in hydraulic properties between them [12]. Soil macropore networks establish a dual-domain transport in which water and solutes are preferentially channelled through soil macropores while slowly diffusing into and out of the bulk soil matrix.

The motivation for this study came from the observation of differences in drainage processes in natural soils, where the macropore drained first and then the matrix. If there were great differences in water flux, there should be differences in convection and dispersion properties. If this process is controlled, chemicals could be delivered to the desired location within the soil profile. Moreover, if control could be achieved by a simple technique, it would be quite beneficial for cost-effective use of fertilizer in agriculture or remediation chemicals in environmental engineering. Many studies have reported on the macropore contribution to the solute transport; however, its threshold has not been described in detail. In most cases, relatively large macropores of millimeters or centimeters were used to evaluate the clear properties (e.g. Kohne and Mohanty, [13]). However, macropores of less than 1 mm also showed much contribution to solute transport [10,11,12]. In addition, some fundamental studies have been carried out within relatively short periods (e.g., hours [3]), although the actual application needs weeks or months. Seyfried and Rao [14] investigated characteristics of solute transport in aggregated soils by effluent analysis, but they did not use sensors to study the bypassing process inside the soil column.

In this study, the contribution of macropores within 1 mm to solute transport was investigated. Macropore structures in natural soils were examined by X-ray radiography, and control of solute transport was performed with macroporous soils for more than a month, the time frame needed for engineering applications. The objectives of this study were two-fold: to investigate the macropore contribution to convection and dispersion processes which govern how much solution is delivered into finer pores; and to examine how we can control solute transport processes in structured soils where macropores are predominant.

2. Materials and methods

2.1. Soils

Undisturbed soil samples from agriculture field (Andisol) were used in the experiments. They were collected in stainless columns (diameter 8.0 cm, height 6.0 cm) for the hydraulic conductivity experiment, and in PVC columns (diameter 8.0 cm, height 25.0 cm) for the solute transport experiments. Cubic duralumin sample holders (5 cm × 5 cm × 5 cm) were also used for X-ray radiography, which reveals the internal macropore structure [10,11]. Soils were sampled from 30–50 cm depths under the undisturbed conditions. Physical properties of the soil are shown in Table 1. Macropore volume was estimated by the drainage water from the saturation when −6 kPa suction was applied at the bottom (equivalent to macropore diameter of 50 μm) of the sample. Saturated hydraulic conductivity was measured by the steady state method [15], while unsaturated hydraulic conductivity was estimated by a multi-step outflow experiment [16,17,18] shown in Fig. 3. Multi-step pressurized desorptions were conducted for undisturbed soils; whereas, outflow volume and matric potential were measured during the experiments. Then the hydraulic model was fitted to the obtained outflow and matric potential for parameter estimations. Abrupt changes in conductivity were observed between saturation (Ks_u) and unsaturation (lines), which was about one order of magnitude or greater. Estimated saturated hydraulic conductivities for undisturbed soils were similar to the number obtained from repacked soil (Ks_r). The reason for this abrupt change can be explained by X-ray radiography.

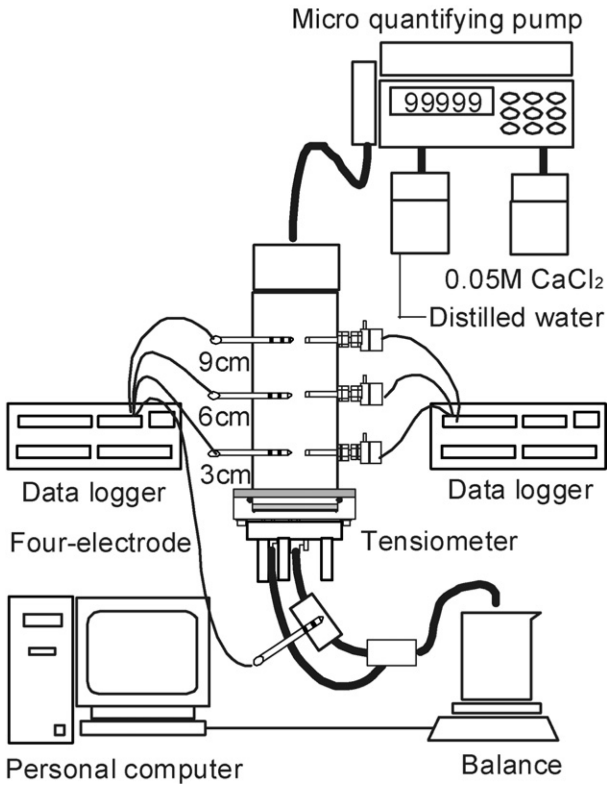

Fig. 1. Experimental set-up for solute transport experiment.

2.2. X-ray radiography of soil pores

X-ray radiography was taken according to Mori et al. [10,11]. Radiography was taken when equilibrium was achieved with −6 kPa (equivalent to a macropore diameter of 50 μm), after allowing the contrast agent to intrude into the soil. Fig. 4 shows that many

Table 1
Physical properties of examined soils.

Soil	Andisol		
Structural conditions	Repacked soil	Repacked soil with artifitial macropores	Undisturbed soil with root created macropores
Sampling depth (cm)	30–50	30–50	30–50
Ks (10^{-5} cm/s)[a]	1.47	16.7	17.0
K-3 (10^{-5} cm/s)[b]		0.461	1.68
Porosity (m^3/m^3)	0.572	0.582	0.632
Macroporosity (m^3/m^3)	0	0.010	0.085
Bulk density (Mg/m^3)	1.05	1.05	0.95

[a] Saturated hydraulic conductivity,

[b] Hydraulic conductivity when suction of −3 kPa was applied.