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Water and solute movement in soil as influenced by macropore characteristics
2. Macropore tortuosity

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Abstract

The paper describes the results of a laboratory study on the effects of macropore tortuosity on breakthrough curves BTCs and solute distribution in a Forman loam (fine loamy-mixed Udic Haploborolls) soil. BTC were obtained using 2-D columns (slab) containing artificial macropores of five different tortuosity levels. The BTCs were run under a constant hydraulic head of 0.08 m over an initially air dry soil. The input solutions contained 1190 mg l^{-1} of potassium bromide, 10 mg l^{-1} of Rhodamine WT, and 100 mg l^{-1} of FD&C Blue #1. A soil column without macropores served as a control. The displacement of a non-adsorbed tracer was not affected by the tortuosity level. An increase in macropore tortuosity progressively increased the breakthrough time, increased the apparent retardation coefficient (R'), decreased the depth to the center of mass of a given adsorbed tracer, and increased the anisotropy in tracer distribution profile. The relative importance of macropore tortuosity increased with an increase in the adsorption coefficient of the tracer. Compared to macropore continuity, the macropore tortuosity had greater impact on solute distribution profile than in its leaching. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

In recent studies, the macropore morphology has been characterized by simple parameters such as porosity, average length, and in rare cases with average macropore

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tortuosity (Ogden et al., 1992). In some studies, macropore tortuosity has been estimated from soil hydraulic characteristics such as the hydraulic conductivity and the water retention characteristics (Gish and Shirmohammadi, 1991). A few experiments have also been conducted with artificial macropores in repacked soil columns to understand the role of macropore morphology on preferential flow. In most of these experiments (Czapar et al., 1992; Steenhuis et al., 1994), a single straight artificial macropore has been studied. In a few studies where macropores were characterized, either in-situ (Edwards et al., 1993), or in undisturbed soil cores (Munyankusi et al., 1994), the importance of macropore tortuosity was unclear. Therefore, it is unknown how macropore tortuosity impacts preferential flow.

The goal of this research was to quantify the impact of various levels of macropore continuity and tortuosity on preferential flow of conservative and adsorbed tracers in soil (Allaire-Leung, 1997). In a companion paper, we described the results of a laboratory study on the effect of macropore continuity on preferential flow (Allaire-Leung et al., 2000). In this paper, we discuss the impact of macropore tortuosity levels on breakthrough curves (BTCs), apparent retardation coefficients, and anisotropy in concentration distribution profiles of both conservative and adsorbed tracers in a loam soil. Macropore tortuosity in this paper refers to the ratio of the true length to the apparent length (vertical extent) of a macropore. A straight macropore has a tortuosity factor of 1.0 whereas a tortuous macropore has a tortuosity factor greater than 1.0.

2. Materials and methods

2.1. Approach

The procedures used in this study are similar to the procedures described earlier by Allaire-Leung et al. (2000). Briefly, the experiment involved running the BTCs in a 2-D column (slab) containing macropores of various tortuosity levels. In this experiment, only one macropore was inserted in each column. The macropores were constructed from stainless steel screen (50 holes cm^{-2}) and were rectangular in shape (0.01×0.01 m wide, and 0.45 m long). In this study, five levels of tortuosity were simulated. These levels represented the tortuosity factor of 1.0, 1.1, 1.3, 1.5, and 3.0 (Fig. 1). Macropores were always open at the soil surface and closed at the bottom. A soil column without macropore served as a Control treatment.

In each column, the macropore was positioned in the chamber. The air-dry soil was then packed around it to a height of 0.6 m. Averaged over all trials, the bulk density of the soil was 1.53 Mg m^{-3} with a standard deviation of 0.1 Mg m^{-3}. The soil used in the experiment was the B horizon of Forman loam. The initial and boundary conditions were the same as in Allaire-Leung et al. (2000). The input solution contained 1190 mg l^{-1} of potassium bromide, 10 mg l^{-1} of Rhodamine WT, and 100 mg l^{-1} of FD&C Blue #1. After the addition of one and a half pore volumes of this solution, the input solution was switched to a solution that contained only 10 mg l^{-1} of Rhodamine WT and 100 mg l^{-1} of FD&C Blue #1. The tracer characteristics are described in Allaire-Leung et al. (1999).

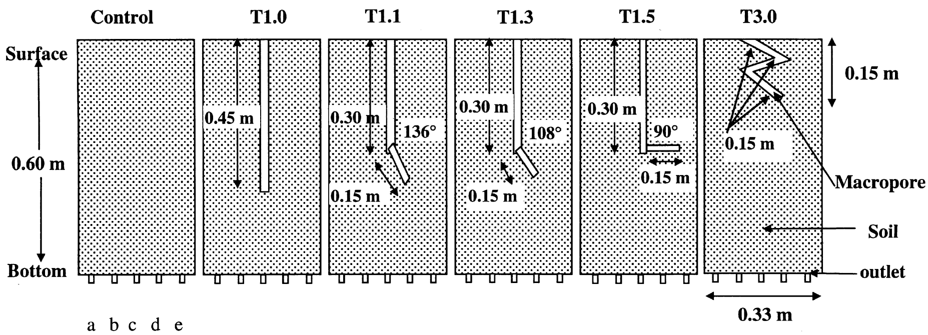

Fig. 1. Position of macropores in soil columns for various macropore tortuosity levels (not scaled).

The leachate was sampled from each of the five outlets at the lower boundary of the soil column. Leachate samples were taken several times during the first two days and subsequently once or twice a day depending upon the velocity of the percolating solution. The breakthrough experiments were stopped when eight pore volumes (PV) of solution had passed through the soil columns.

After completion of the breakthrough experiment, the soil columns were taken apart and sampled to evaluate the concentration distribution of Rhodamine WT and FD&C Blue #1. The companion paper (Allaire-Leung et al., 2000) describes sampling, dye extraction, and measurement procedures. It also describes the methodology for calculating the breakthrough time and the apparent retardation factor.

Each treatment was replicated three times using a complete randomized block design. The BTCs were compared using different techniques as described in Allaire-Leung et al. (2000). The statistical analyses were made using SAS/STAT software package release 6.12 for Window 95. Mean separations were made using LSD test.

3. Results and discussion

3.1. Water movement

Water breakthrough occurred significantly earlier ($P = 0.001$) in low tortuosity (minutes) than in high tortuosity treatments (hours). However, in relative times (PV), the breakthrough occurred at approximately the same time ($P = 0.08$) irrespective of the tortuosity level. As expected, it took about one pore volume of applied solution before the first drop of solution trickled out from the bottom of the column for all tortuosity treatments.

After 8 PV of solution has been applied at the column surface, percolation rate for the T1.0 treatment was about six times higher than that of the Control treatment (Fig. 2). At steady state condition, the extrapolated percolation rate for the T1.0 treatment would be about four times higher than that of the Control. Simple calculations using Darcy's law (Eq. (1)) show that the above ratios are approximately 4.0 for saturated flow conditions.

$$J_w = \left(-K_s^*(H+L)\right)/L \tag{1}$$

where J_w is water flux (LT^{-1}), K_s is the hydraulic conductivity (LT^{-1}), L the column

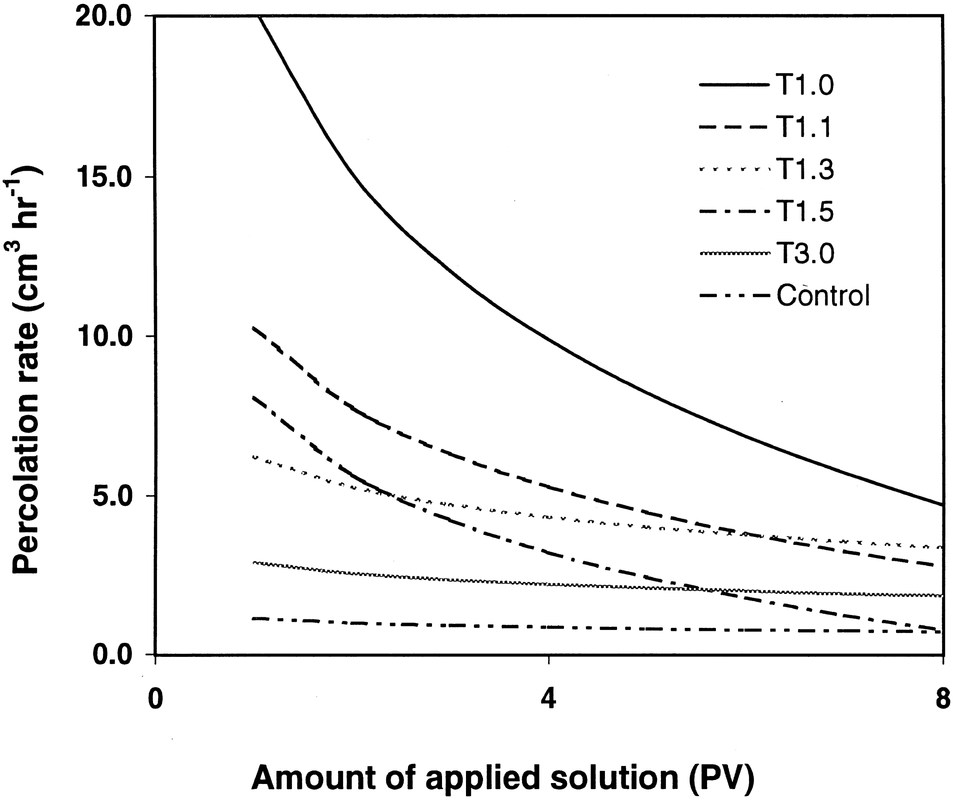

Fig. 2. Average (three replications and five outlets) water percolation rates as a function of the amount of applied solution for various macropore tortuosity levels.

length (L), and H the hydraulic head (L). For example, the J_w value for the Control treatment would be equal to -1.13 K_s ($-0.68/0/6$ K_s) as compared to -4.5 K_s ($-0.68/0.15$ K_s) for the T1.0 treatment. The J_w calculations for the T1.0 treatment are done for the 0.15 m soil below the macropore assuming that the macropore was full of water plus there was 0.08 m of water standing at the column surface. The ratio of water flux from T1.0 to the Control is then equal to 4.0.

Percolation rates for the T1.1 and T1.3 treatments were slower than the percolation rates for the T1.0 treatment but faster than the Control (Fig. 2). The percolation rates for the T3.0 treatment were only slightly greater than the percolation rates of the Control treatment. Percolation rate for all treatments decreased with time (Fig. 2). For most tortuosity treatments, it took more than 8 PV ($\sim$ 25–35 days) to reach near steady state flow condition. This long transient time was probably due to high clay content ($\sim$ 25%) with a moderate shrink–swell potential in the Forman loam soil. The longer transient time could also be due to the settling of soil particles.

The differences in percolation rate between any tortuosity treatment and the Control were much higher at early than at later times. Initially (at 1 PV), the percolation rate for

T1.0 treatment (straight macropore) was 20 times the percolation rate for the Control treatment (no macropore). This ratio decreased to about 6 after 8 PV of solution had been applied at the soil surface. The reduction in percolation rate for the tortuosity treatments was due to reductions in hydraulic gradients between the soil surface and the lower end of the soil column and between the macropore and the surrounding soil matrix. The effect of soil swelling was minimal since the percolation rate of the Control treatment did not vary significantly with time. These results suggest that macropore tortuosity effects on preferential flow were more important at the start of the infiltration than at later times.

The above-results suggest that under intense rainfalls over a dry field soil, we would expect macropores to play an important role in carrying the water to deeper depths in the soil profile. However, the importance of macropore would change over time depending upon their shape. Their impact on water movement would decrease as their tortuosity increases. In fact, the Fig. 3 shows that all macropore tortuosity levels significantly influenced the water distribution in the soil column. At early times (PV = 0.1), the water distribution in treatments containing a macropore varied more in the horizontal than in the vertical direction. However at later times, it was the opposite especially for the high tortuosity treatment (T3.0). Although the percolation rates were similar between the Control and the high tortuosity treatment studied in this experiment (T3.0), the water

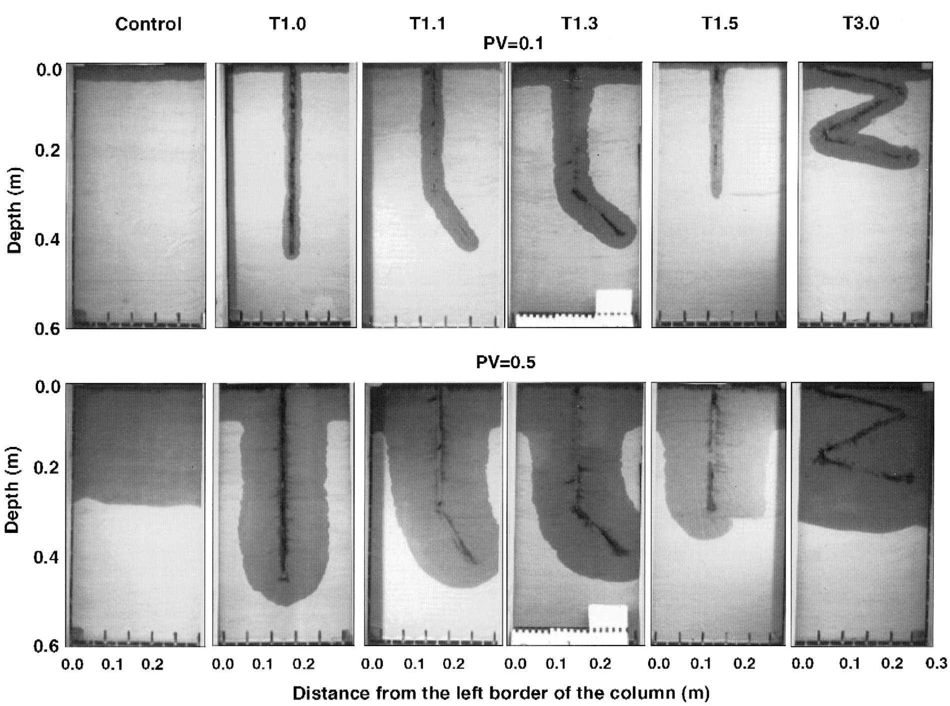

Fig. 3. Water distribution patterns in soil columns of various macropore tortuosity levels after 0.1 and 0.5 PV have infiltrated into soil columns (light color: dry soil, dark color: wet soil).

distribution patterns varied greatly between these two treatments, especially at early time (Fig. 3).

In the T1.0 and T1.1 treatments, the applied solution almost instantaneously (0.01 PV) reached the bottom of the macropore (Fig. 3). However in the T1.5 treatment, the applied solution moved up to the 90° bend of the macropore. The horizontal part of the macropore remained empty from few hours to few days depending upon the replication (Fig. 3) due to air entrapment. This may also occur under field conditions when macropores of different orientation (horizontal and vertical) meet or contain chambers such as insect nest, at their lower end. Subsequent water distribution patterns in T1.5 treatment showed that the horizontal part of the macropore acted more as a barrier to water flow until it was filled-up with water. These results suggest that in modeling preferential flow, macropore similar to T1.5 where air entrapment may occur could be simplified by ignoring the horizontal part of the macropore and by only considering the vertical extent of these macropores. This simplification, however, only applies to breakthrough predictions and not to water distribution predictions.

The above-discussion shows that none of the macropore tortuosity level can be neglected while modeling water movement in soil. This is because in case of less tortuous macropores, tortuosity impacts water percolation rates whereas in case of highly tortuous macropores, tortuosity affects the water distribution profile.

3.2. Tracer movement

3.2.1. BTCs

Fig. 4 shows the effect of tortuosity on BTCs of three different tracers. The BTCs in this figure are only for one replication. The BTCs of the two other replications were nearly similar. Each point of the BTC represents a weighted average concentration of the

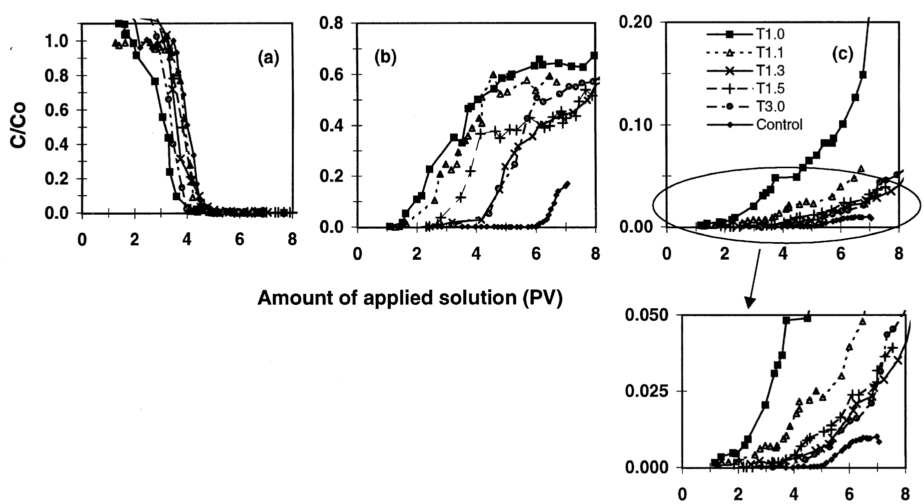

Fig. 4. Breakthrough curves of (a) Br^-, (b) Rhodamine WT, and (c) FD&C Blue #1 as influenced by macropore tortuosity level.

tracer from five outlets. The weights were equal to leachate volume from each of the five outlets.

The measured relative concentration of bromide in some early samples was higher than 1.0. This was assumed to be due to anion exclusion and to some interference from electrolytes in the soil solution during bromide measurements. Since the measured bromide concentrations were not corrected for above analomies, its mass recovery was about 110%. The mass recoveries of Rhodamine WT and FD&C Blue #1 were not determined.

Bromide BTCs (Fig. 4a) were not significantly influenced by macropore tortuosity ($P = 0.15$). At any given relative time, there was no significant ($P = 0.30$) difference in the bromide concentration of the leachate among the treatments. This is expected considering that we were displacing bromide from the soil matrix in all treatments and the effect of open–close macropore in highly tortuous treatments in bypassing bromide-free solution through the soil matrix was minimal. In less tortuous treatments, there was some impact of the macropore in bypassing bromide-free solution through the soil matrix. However, when expressed in relative times, the BTCs of all tortuosity treatments were nearly same.

The relative concentration of Rhodamine WT in the percolate solution after an application of 3.5 PV of input solution showed significant differences ($\sim$ 35–50 fold higher, $P = 0.001$) between the low tortuosity (T1.0 and T1.1) treatments and the Control (Fig. 4). For high tortuosity treatments (T1.3, T1.5, and T3.0), the relative concentration ($C/Co \sim 0.13$) was also significantly ($P = 0.001$) higher than that of the Control treatment ($C/Co = 0.009$) but lower than that of the low tortuosity treatment. At a later time (PV = 7), all tortuosity treatments had much higher ($\sim$ 2 fold) relative concentration of Rhodamine WT in the leachate than the Control treatment (Fig. 4b). These results suggest that all tortuosity levels influence the movement of an adsorbed tracer. However, the presence of a macropore per se had more influence on solute leaching than the tortuosity levels.

The BTC of Rhodamine WT did not reach C/Co of 1.0. Instead it leveled off at C/Co of around 0.7 (Fig. 4). Allaire-Leung et al. (1999) showed that about 20% of the Rhodamine WT was lost during sample storage, preparation, and manipulation. We believe this loss partially explains the relative concentration of less than unity for Rhodamine WT after 8 PV of the solution had been applied at the soil surface. An additional reason for the plateau of the relative concentration at 0.7 may be due to the fact that the soil particles have not reached their maximum Rhodamine WT adsorption capacity.

For Rhodamine WT and FD&C Blue #1, the time to breakthrough varied with the tortuosity level (Fig. 4b). Rhodamine WT brokethrough 3 to 4 times faster in T1.0 treatment (1.0 PV) than in the Control treatment (4.6 PV). Comparatively, the FD&C Blue #1 brokethrough only 2 to 3 times faster in the T1.0 treatment (2.0 PV) than in the Control treatment (5.5 PV). The breakthrough time for both dyes increased rapidly with an increase in tortuosity level up to a tortuosity of 1.3. At higher tortuosity, the breakthrough of solution was nearly the same. These results suggest that in predicting breakthrough time using computer models of macropore flow, more emphasis should be placed in describing the less tortuous macropores than the more tortuous macropores.

The effect of tortuosity on the BTCs of FD&C Blue #1 was similar to that of Rhodamine WT. At any given time, FD&C Blue #1 concentrations in the leachate followed the trend: T1.0 > T1.1 > T1.3 ≈ T1.5 ≈ T3.0 > Control treatment. This again indicates that all tortuosity levels influence solute movement but the degree of influence depends upon the tortuosity level. For a given pore volume, the relative concentrations of FD&C Blue #1 were generally lower than that of Rhodamine WT (Fig. 4c). This is expected considering that the FD&C Blue #1 has a greater tendency to adsorb on this soil than the Rhodamine WT (Allaire-Leung et al., 1999). For all tortuosity levels, the relative concentration of FD&C Blue #1 continuously increased with time, thus suggesting that the adsorption capacity of the soil had not been reached even after 8 PV. The above results suggest that the importance of macropore tortuosity on solute movement depends on the type of tracer used. For an adsorbed tracer applied in solution, macropores of all tortuosity levels will modify their BTC. However, tortuosity had no significant influence in displacement of non-adsorbed tracers such as bromide when the non-adsorbed tracer is already present in soil and is then being displaced with a tracer-free solution.

The variation in BTCs between the five outlets of the column was also interesting. Fig. 5 is an example of this variation for the Rhodamine WT and FD&C Blue #1 dyes

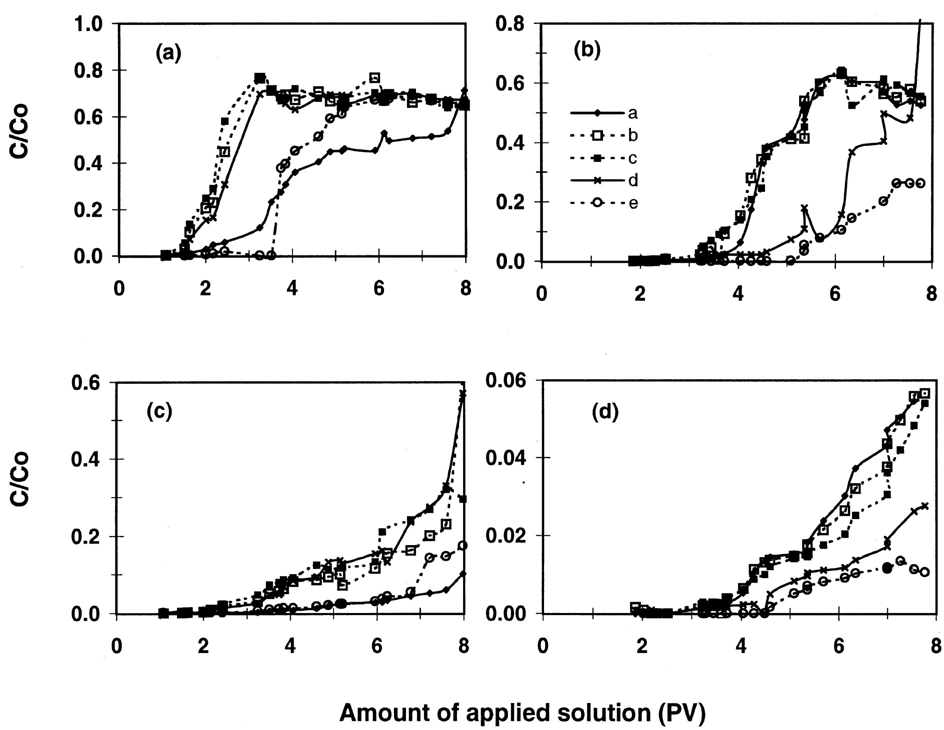

Fig. 5. Variation between outlets in the breakthrough curves of Rhodamine WT for T1.0 (a) and T1.5 (b) treatments, and of FD&C Blue #1 for T1.0 (c) and T1.5 (d) treatments.

in T1.0 and T1.5 treatments. For the T1.0 treatment, the breakthrough occurred much earlier from the outlets that were closer (b,c,d) to the lower end of the macropore than the outlets farther away (a,e) from the macropore. Comparatively for treatment T1.5, the dye concentration in the leachate was lower from the outlets that were directly below the horizontal arm of the macropore (d,e). These results suggest that while conducting laboratory BTC experiments with undisturbed soil columns, one need to collect the leachate from several outlets at the bottom of the soil column to fully characterize the types of macropore that may be present in a given soil. In a field situation, however, one needs to position sampling cups close to each other so as to intercept the preferential flow. In-situ variation in BTCs among various sampling cups can also delineate the importance of preferential flow or frequency of macropore for a given soil.

3.2.2. Retardation factor

The apparent retardation coefficient of Rhodamine WT and FD&C Blue #1 decreased significantly with a decrease in macropore tortuosity (Table 1). The ratio of the apparent retardation coefficient of a given treatment to the Control treatment ranged from 2.0 (T3.0) to 5.2 (T1.0) for Rhodamine WT. The corresponding values for the FD&C Blue #1 were 2.3 (T3.0) and 5.6 (T1.0). This shows that the movement of FD&C Blue #1 was slightly more affected by macropore tortuosity than that of Rhodamine WT. In other words, the macropore tortuosity impact on contaminant transport increases with an increase in the adsorption coefficient of the tracer. This suggests that tortuosity is one additional factor that increases the variation in solute movement through soil depending upon the tracer adsorption characteristics (Fig. 6).

3.2.3. Concentration distribution

As expected, bromide was completely washed out of the profile from all treatments after an application of 8 PV of bromide-free solution at the column surface. The average concentrations of Rhodamine WT and FD&C Blue #1 in the soil profile after 8 PV of solution application were also not significantly ($P = 0.50$) affected by macropore tortuosity. This suggests that after a long period of leaching, the tortuosity does not affect the average bulk mass of a tracer in soil.

Table 1
Effect of macropore tortuosity on apparent retardation factor and depth to the center of mass of Rhodamine WT (RWT) and FD&C Blue #1 (Blue) after 8 PV have been applied at the soil surface. LSD = Least significant difference at confidence level $\alpha = 0.05$

Tortuosity	R'		Depth to the center of mass (m)		
	RWT	Blue	RWT	Blue	Both dyes
1.0	1.07	1.97	0.285	0.281	0.284
1.1	1.34	2.55	0.246	0.282	0.264
1.3	1.84	2.57	0.246	0.270	0.258
1.5	2.18	2.60	0.222	0.169	0.220
3.0	2.71	4.88	0.219	0.238	0.228
Control	5.52	11.01	0.145	0.058	0.131
LSD	1.51	2.10	0.06	0.22	0.082

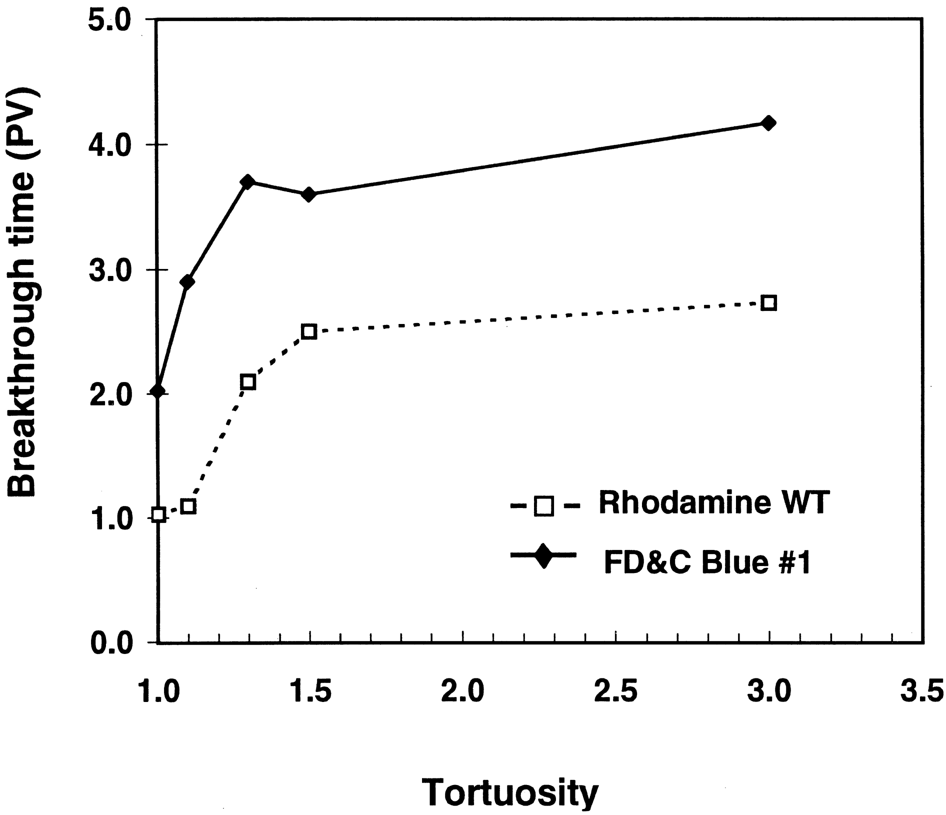

Fig. 6. Effect of macropore tortuosity on the time to breakthrough for Rhodamine WT and FD&C Blue #1.

Except from the Control treatment, the depth to the center of mass of Rhodamine WT was not significantly different ($P = 0.80$) from that of FD&C Blue #1 at a given tortuosity level (Table 1). However, the depth to the center of mass of both dyes for all tortuosity treatments was significantly different from that of the Control ($P = 0.001$). The center of mass of a dye was closer to the soil surface with an increase in tortuosity (Table 1). This was expected considering that the vertical extent of the less tortuous macropores was deeper than that of the more tortuous macropores (Fig. 2). These results again indicate that the effect of macropore tortuosity on solute transport increases with an increase in the adsorption coefficient of the dye.

The concentration distribution profiles of FD&C Blue #1 appeared to be highly related to the position and tortuosity of the macropores in different treatments (Fig. 7). For example in T1.0 treatment, the FD&C Blue #1 was mostly concentrated just below the lower end of the macropore. A slight lateral movement of the chemical away from the macropore indicates some dispersion (physical process) or diffusion (chemical process). Although the FD&C Blue #1 concentration profile of T1.1 treatment was similar to that of the T1.0 treatment, the tracer had a slight tendency to flow to the right. This tilt to the right in dye movement was expected because of the slight bend in the

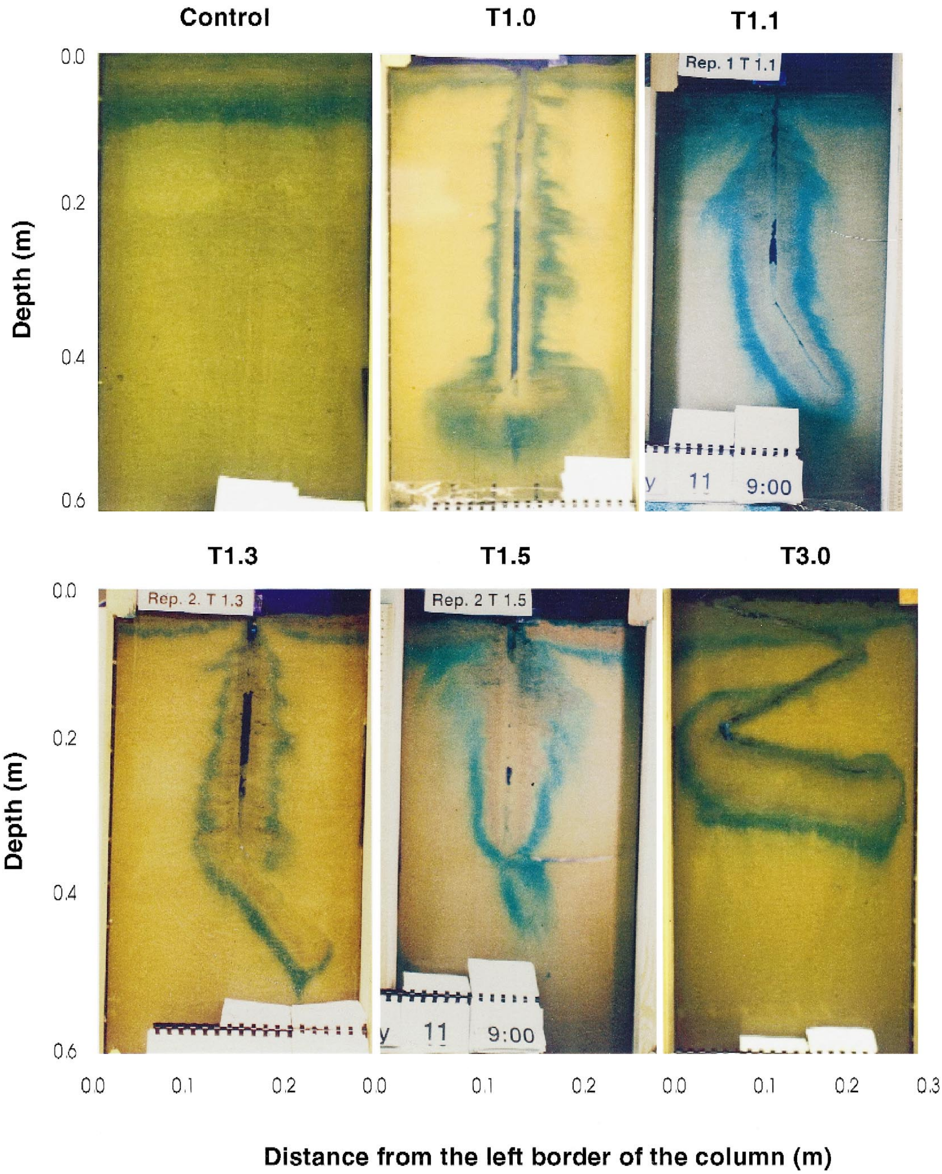

Fig. 7. Stained pathways showing the influence of macropore tortuosity on the movement of FD&C Blue #1 after 4 PV have infiltrated into the soil columns.

macropore (Fig. 1). The FD&C Blue #1 distribution pattern for T1.3 treatment was also similar to T1.0 treatment, except that there was a bit more pronounced concentration of the dye to the right side of the column (Fig. 7). For the T1.5 treatment, the horizontal limb of the L-shape (T1.5) macropore was not clearly visible in the distribution of

FD&C Blue #1 (Fig. 7). This is expected considering that the horizontal part of the macropore did not carry much dye solution as compared to the vertical part of the macropore. The FD&C Blue #1 distribution in T3.0 treatment indicates a complex pattern of dye movement. Significantly greater portion of the dye moved away from the lower end of the macropore than from the upper part probably due to a pressure difference.

The concentration distribution of Rhodamine WT was not visible to the naked eye. However, the dye extraction indicated that the Rhodamine WT distribution patterns for various treatments were similar to those of the FD&C Blue #1 (Allaire-Leung, 1997).

In terms of anisotropy in the concentration distribution profile, the tracer distribution in the Control treatment was nearly uniform in the horizontal direction but varied more in the vertical direction (Fig. 7). Contrarily, the tracer concentration varied more in the horizontal direction than the vertical direction for all tortuosity treatments (Fig. 7). For a given tortuosity treatment, the variation in concentration distribution of Rhodamine WT, either in the vertical or in the horizontal direction, was similar to that of the FD&C Blue #1. However, the variation in concentration distribution profile was larger for the FD&C Blue #1 than for the Rhodamine WT (Allaire-Leung, 1997). These results suggest that the presence of a tortuous macropore changes the anisotropy of the contaminant distribution from the vertical to the horizontal direction. The above results also suggest that all tortuosity levels have an impact on the concentration distribution profile of solutes, and the use of an average macropore tortuosity for a given soil in computer simulation models is not sufficient to predict the effects of macropore on solute distribution profile.

Although the soil wetness condition and the macropore tortuosity levels studied in this experiment were somewhat unnatural, the results still provide useful guidelines for simulating macropore tortuosity effects on solute transport in soil. For example, the displacement of bromide initially present in soil was not significantly affected by the tortuosity when plotted in terms of relative time. For this type of tracer, it may be better not to include the tortuosity effects in the model if the simulation involves displacement of this solute from the soil. Furthermore, it is likely that the field variation in soil hydraulic properties will have a much greater impact on bromide movement than the tortuosity effects. Therefore, it may be advisable to put more emphasis on characterization of soil hydraulic parameters than trying to be precise in selecting the tortuosity value for predicting displacement of bromide initially present in the soil.

Initial air-dry soil condition used in this experiment, although not common is realistic. For example, these conditions can occur when flood irrigation is applied on a dry soil or when a sudden rainfall occurs in dryland areas and causes runoff over an initially dry soil. Under these conditions there will be high rates of water flow in the macropore. The macropore used in this study were stable, however, under high flow rates, there is a possibility that natural macropores can collapse. Many of the earthworm macropores are generally coated with mucous like substance, and are unlikely to collapse during flooding. The macropore shapes chosen were schematic representation of what has been found in the literature. For example, the z-shape macropore could be a macropore connected to other short macropores as shown by McKenzie and Dexter (1993).

4. Conclusions

In general, all macropore tortuosity levels are important in controlling the movement of water and solutes in soil. For many contaminant transport characteristics such as the BTC shape, the depth to the center of mass, and the concentration distribution profile, the importance of tortuosity increases with an increase in tracer adsorption characteristics. For a conservative tracer, macropore tortuosity effects were minimal when the tracer was being displaced by water. For an adsorbed tracer, the impact of macropore on the BTC decreased progressively as tortuosity increased but the impact on the distribution profile was as important for all tortuosity levels. This presents difficulties in deciding how best to simplify macropore tortuosity in computer simulation models. The importance of a given level of tortuosity additionally depends upon macropore continuity. Additional studies are needed to fully characterize the impact of different tortuosity levels in different soil types under different boundary conditions.

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