Leaching Characteristics of Repacked Soil Columns as Influenced by Subsurface Flow Barriers

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ABSTRACT

Reducing the leaching of NO_3^--N is of great interest. The effects of different types of subsurface barriers on delaying and reducing anion leaching and the effect of barrier size on anion leaching were investigated. Three repacked soil columns filled with soil from a Sparta loamy fine sand (sandy, mixed, mesic Entic Hapludoll) mapping unit were used to run Cl^- breakthrough experiments under saturated, steady-flow conditions. Subsurface barriers used were no barrier (NB), a polyethylene disk placed above the Cl^-, the same disk placed below the Cl^-, a compacted soil layer created outside of the column and placed above the Cl^- (CA), and a compacted layer formed in situ above the Cl^-. Compared with NB, all barriers tested delayed initial breakthrough of Cl^- and reduced peak Cl^- concentration. Subsurface barriers delayed occurrence of the peak concentration, indicating that barriers prolonged residence time of Cl^- in the soil column. Among subsurface barriers used, the CA was most effective in delaying and reducing Cl^- leaching. Initial breakthrough of Cl^- was delayed by 0.9 relative pore volumes, and peak concentration was reduced by >50% with the CA treatment compared with the NB treatment. The occurrence of the peak concentration was also delayed by 1.2 relative pore volumes. Compared with the NB treatment, a 3-cm plastic disk, just large enough to cover the applied Cl^-, reduced peak concentration of Cl^-. A 5-cm-diam. barrier also delayed initial breakthrough of Cl^-, reduced peak concentration by 40%, and delayed occurrence of the peak by 0.6 pore volumes.

N ITROGEN FERTILIZER is one of the most essential and extensively used nutrients on crop lands. Leaching losses of N fertilizer are an economic problem for farmers and pose environmental concerns for the general public. In some studies, >50% of applied fertilizer N is not removed by the crop or stored in the soil. Nitrate leaching is thought to be a major cause of this loss (Blackmer, 1987). Nitrate leaching below the rootzone can contaminate drinking water supplies. Numerous studies have shown that NO_3^- concentrations in tile drainage effluent from row-cropped fields, in Iowa and elsewhere, often exceed the drinking water standard of 10 mg L^{-1} (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981; Baker et al., 1985).

Water-soluble anions such as NO_3^- move readily with either irrigation or rain water percolating through the soil. Nitrogen fertilizer must remain in the rootzone to be taken up by plants. Thus, a means of reducing percolating water flow rate or diverting percolating water away from applied fertilizer should maintain fertilizer N in the rootzone for an extended period.

A localized, impermeable subsurface barrier will divert infiltrating water away from the barrier. Low-flow regions should occur just above and below the centerpoint of the barrier. Maâledj and Malavard (1973) calculated stream functions from surface line sources when an impermeable barrier existed in the subsoil. Streamlines above the barrier were bent to go around the barrier (Fig. 1). Flow rates were reduced most just above and below the barrier.

Babu (1979) calculated equipotential lines for a steady-state flow of water in unsaturated soil with an impermeable, isolated, circular subsoil barrier. In some instances, the barrier caused an increase in water content and pressure head in soil above the barrier, whereas water content in the region below the barrier decreased substantially. These results indicate that infiltrating water was directed away from the soil volume below the barrier.

More recently, Kirkham and Horton (1990) showed that under saturated conditions, total water flow through a homogeneous soil profile was reduced most when an impermeable barrier was placed at the halfway point between the soil surface and the bottom boundary. The slowest flow occurred just above and below the barrier.

Leaching of NO_3^- may be reduced if fertilizer is placed in a low-flow region just above or below a localized subsurface water flow barrier. Recent development of a point-injector applicator (Baker et al., 1989) makes it possible to inject fertilizer N precisely into soil with little disturbance to soil, crop residues, or plant roots. During normal operation of the point injector, a hole is created in the soil surface at each injection point. This hole presumably provides a low-resistance pathway for water flow directly through the injected fertilizer. If the injection hole were closed by compacting the soil directly above the injection point with a press wheel, water flow through the compacted soil should be reduced (Reicosky et al., 1981). In effect, the compacted soil may act like a subsurface flow barrier and water flow may be directed away from the applied fertilizer.

The same principles might be applied to conventional fertilizer banding with a knife applicator. During normal operation, knife applicators create a furrow partly filled with loose soil directly above the fertilizer band. Undoubtedly, the soil above the fertilizer band is very permeable and provides pathways for preferential water flow directly through the band. Therefore, filling in the knife furrow and compacting the soil above the fertilizer band may redirect some of the water flow away from the fertilizer.

Abbreviations: NB, no barrier; PA, polyethylene disk above Cl^--vermiculite mixture; PB, polyethylene disk below Cl^--vermiculite mixture; CA, compacted soil layer formed outside column then placed above Cl^--vermiculite mixture; CS, compacted layer within column above the Cl^--vermiculite mixture.
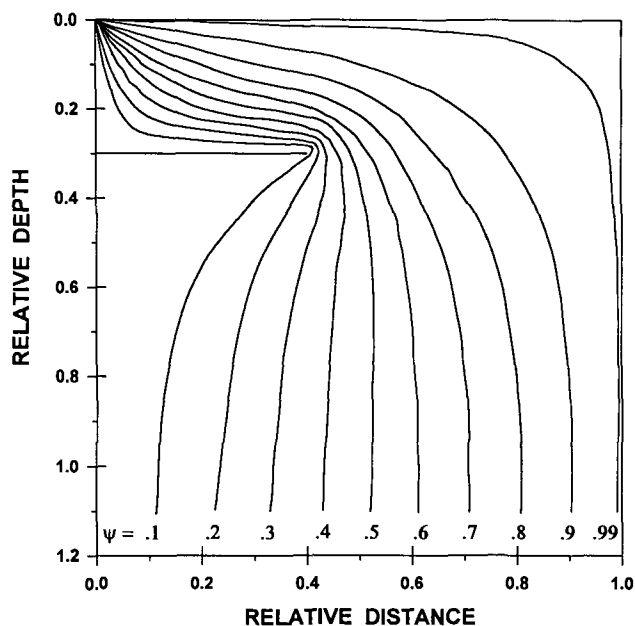
Fig. 1. Stream functions, ψ, stemming from a single line source. The line source is positioned at the origin of the coordinates (x, y) = (0, 0). An impermeable barrier exists horizontally at y = 0.3 (Maâledj and Malavard, 1973).

To investigate the potential of using subsurface flow barriers to reduce NO_3^- leaching, a laboratory study was conducted with these objectives: (i) to examine the relative effectiveness of different subsurface barriers on delaying and reducing anion leaching and (ii) to determine the effect of barrier size on anion leaching.

MATERIALS AND METHODS

The soil used in this study was obtained from a Sparta loamy fine sand mapping unit. All transport experiments were conducted with soil columns formed in a permeameter consisting of an acrylic plastic cylinder (18.4 cm long and 13.9 cm i.d.) clamped between two acrylic plastic plates. To ensure uniform packing of each soil column, the sides and the bottom plate of the soil column were tapped between incremental additions of air-dried sieved soil. After being packed, soil columns were saturated with a 0.005 M CaSO$_4$ solution for 8 h and saturated hydraulic conductivity was measured. Subsequently, each soil column was allowed to drain under the influence of gravity for 12 h before a Cl$^-$ solution or a subsurface barrier was applied.

A preliminary study was conducted on solution density effects on anion leaching. After the soil column was drained, 2.5 mL of either 2.0 M or 0.2 M CaCl$_2$ solution was hypodermically injected at a depth of 4 cm. Applied Cl$^-$ was leached by 0.005 M CaSO$_4$ solution either immediately after the injection of CaCl$_2$ solution or 28 or 29 h later.

In each transport experiment with a subsurface barrier, 20 mL of 0.025 M CaCl$_2$ solution adsorbed on 5 g of the commercial horticultural grade vermiculite was packed into the center of the soil column between the 2- and 5-cm soil depths after a 3-cm-diam. and 5-cm-deep hole had been excavated. After the Cl$^-$-vermiculite mixture and a subsurface barrier were applied, the soil column was leached with 0.005 M CaSO$_4$ solution under saturated, steady-flow conditions. In each experiment, a steady-state condition was achieved in fewer than 10 min and the experiment was completed in 2 to 4 h. Effluent exiting the bottom of the permeameter was collected with a

fraction collector and analyzed for Cl$^-$ concentration by means of colorimetric automatic titration (Adriano and Doner, 1982).

Three soil columns were constructed. Columns A, B, and C were used for Experiments 1 through 3, 4 and 5, and 6 through 9, respectively. Table 1 shows the measured soil physical properties of the soil columns.

Chloride Breakthrough Experiments with Subsurface Barriers

A total of five experiments were conducted to determine the abilities of different types of barriers to reduce Cl$^-$ leaching. Barriers used were NB, PA, PB, CA, and CS.

In Experiment 1, NB was used. Soil was carefully removed from the top portion of the column to leave a hole 3 cm in diameter and 5 cm deep at the center of the column. The hole was filled to 2 cm from the surface with the Cl$^-$-vermiculite mixture. To reconstruct the original surface configuration, slightly moistened soil was placed on top of the mixture. Then, 0.005 M CaSO$_4$ solution was applied to the top of the soil column (ponded) using a mariotte reservoir. After completion of the experiment, several more pore volumes of the CaSO$_4$ solution were applied to flush any residual Cl$^-$ out of the soil column and the column was gravity drained for 12 h. For Experiments 2 through 5, placing the Cl$^-$-vermiculite mixture, leaching Cl$^-$, and flushing and draining the soil column were done exactly the same way as for Experiment 1, except that a subsurface barrier was placed in the soil column.

In Experiment 2, a 9-cm-diam. and 0.1-mm-thick disk cut out of a clear polyethylene sheet was placed in the column as a barrier (PA treatment). After the vermiculite used in Experiment 1 was carefully removed, a new Cl$^-$-vermiculite mixture was packed into the hole. Then, enough soil was removed so that the disk could be placed directly above the Cl$^-$-vermiculite mixture. The column was then repacked with slightly moistened soil.

In Experiment 3 (PB treatment), disk and vermiculite were removed from the column. Soil was further excavated from the column to extend the hole to a depth of 5 cm and a diameter of 9 cm. The same polyethylene disk was placed flat on the bottom of the new hole, which was then filled with air-dried soil. The column was saturated and drained, and a new Cl$^-$-vermiculite mixture was placed directly above the disk after a 12-h drainage period.

In Experiment 4 (CA treatment), a compacted soil layer 0.5 cm thick and 9 cm in diameter was placed above the Cl$^-$-vermiculite mixture in Column B. Before this experiment, the maximum bulk density of 1.9 Mg m^{-3} and the corresponding optimal gravimetric water content of 0.12 kg kg^{-1} for the soil used in this study were determined by a compaction test based upon ASTM Standard Test D-698-78, Method A (ASTM, 1982). To create a 0.5-cm-thick compacted soil layer with the maximum bulk density, soil at the optimal water content was compacted in a 10.1-cm-diam. mold by a rammer (3.2 kg and 7.5 cm in diameter) falling from 10 cm. Finally, the diameter of the compacted soil layer was trimmed to 9 cm.

Table 1. Measured soil physical properties of soil columns.

	Experiment		
	1–3	4–5	6–9
Column ID	A	B	C
Bulk density, Mg m^{-3}	1.432	1.490	1.448
Saturated hydraulic Conductivity, m s^{-1}	1.760×10^{-5}	1.075×10^{-5}	1.669×10^{-5}
One pore volume†, cm^3	1283	1223	1268

† Particle density of the soil was assumed to be 2.65 Mg m^{-3}.

In Experiment 5 (CS treatment), soil above the Cl⁻–vermiculite mixture was compacted in situ to form a compacted soil layer within the soil column. After removal of the compacted soil layer of Experiment 4, soil adjusted to the optimal water content was scooped into the hole. The rammer was dropped from 2 cm to form a compacted soil layer. The bulk density of the compacted layer was 1.63 Mg m⁻³.

Chloride Breakthrough Experiments with Barrier Diameters

In Experiments 6 through 9 (PA), polyethylene disks of different diameters were placed above the Cl⁻–vermiculite mixture in Column C to determine the effect of subsurface barrier size on Cl⁻ leaching. Disks with diameters of 3.0, 4.0, and 5.0 cm were placed above the mixture, and the resulting breakthrough curves were observed along with those for NB. To standardize the extent of disturbance caused by the excavation process, the top portion of the soil column was excavated to form a hole 9 cm in diameter and 2 cm deep before the Cl⁻–vermiculite mixture was placed, regardless of the barrier diameter.

RESULTS AND DISCUSSION

To examine the effect of subsurface barriers on Cl⁻ leaching, applied Cl⁻ must be maintained at the designated soil placement depth until the leaching experiment begins. Burns and Dean (1964) showed that a high soil moisture content caused NO₃⁻ to dissolve from a band of NaNO₃ and move from the band under the influence of gravity. Our preliminary study indicated that injection of highly concentrated CaCl₂ solution into a soil column that has been gravity drained also caused the applied solution to move downward immediately after injection. This drop-out phenomenon, i.e., the solution density effect, resulted in an unusually early Cl⁻ breakthrough.

Figure 2 shows the drop-out phenomenon when 2.5 mL of 2.0 M CaCl₂ solution with a density of 1.17 Mg m⁻³ at 20°C was injected at a soil depth of 4 cm. Relative Cl⁻ concentration was calculated as the ratio of measured Cl⁻ concentration of the effluent sample to greatest measured Cl⁻ concentration. Compared with the Cl⁻ breakthrough curve obtained by leaching Cl⁻ immediately after the injection, the breakthrough curve obtained by leaching 28 h after injection was shifted to the left by 0.3 relative pore volumes. This shift indicates that the applied CaCl₂ solution plume moved downward before leaching began. Figure 3 shows the result of a similar experiment on the injection of 2.5 mL of 0.2 M CaCl₂ solution with a density of 1.02 Mg m⁻³ at 20°C. When the solution was diluted, the drop-out phenomenon was greatly reduced. Delayed leaching of the applied solution, however, increased the spread (dispersion) of the breakthrough curve.

To maintain applied solutions at the depth of placement, vermiculite particles were used as an absorbent for the CaCl₂ solution. Figure 4 compares the injection of 2.5 mL of 0.2 M CaCl₂ solution and the application of 20 mL of 0.025 M CaCl₂ solution adsorbed on 5 g of vermiculite and placed between the soil depths of 2 and 5 cm. Relative to the direct solution injection, vermiculite substantially delayed leaching of Cl⁻. The Cl⁻ breakthrough curve for the vermiculite mixture was shifted to the right of the solution injection curve by nearly 0.7 relative pore volumes. Vermiculite also changed the spreading of the breakthrough curve. The placement of vermiculite particles obviously altered the pore water velocity distribution within that region. The infiltrating CaSO₄ solution possibly had a smaller velocity in the portion of the soil column with vermiculite than in the surrounding soil. Thus, Cl⁻ solution associated with vermiculite was gradually carried out by the passing
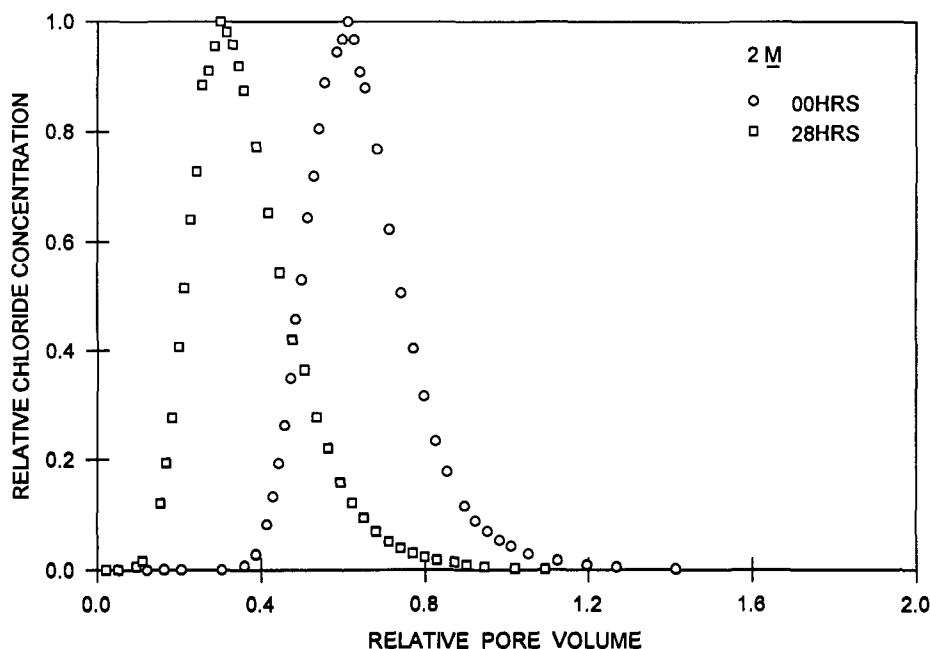

Fig. 2. Solution density effect on Cl⁻ breakthrough curve. After the injection of 2.5 mL of 2.0 M CaCl₂ solution, the leaching experiment began either immediately or was delayed for 28 h.

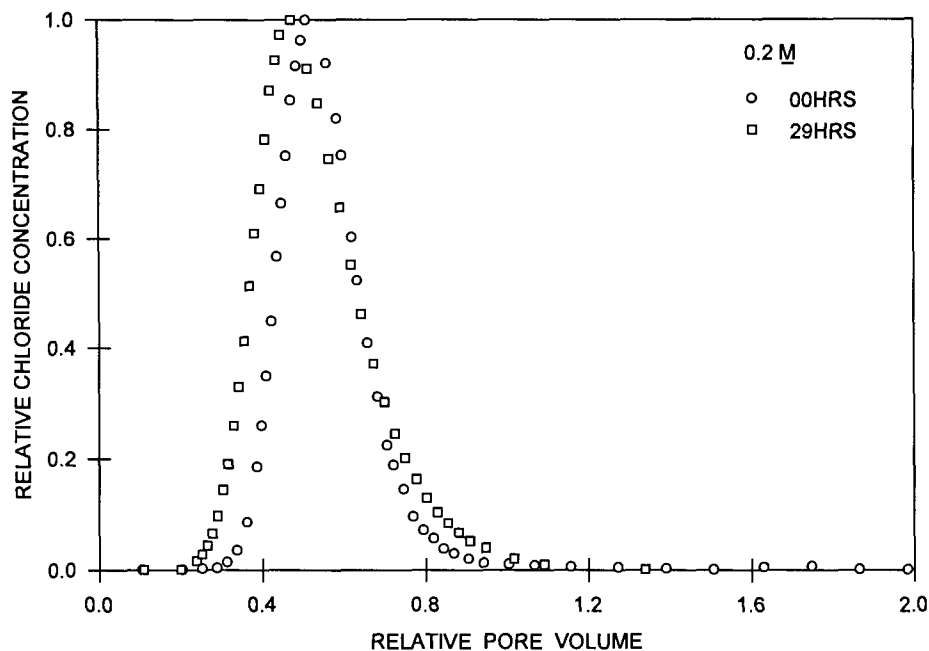Fig. 3. Solution density effect on Cl⁻ breakthrough curve. After the injection of 2.5 mL of 0.2 M CaCl₂ solution, the leaching experiment began either immediately or was delayed for 29 h.

CaSO₄ solution. This resulted in the increased dispersion. Because vermiculite particles delayed the downward movement of Cl⁻ solution until infiltration of Cl⁻ free solution, the use of vermiculite enabled a study of the true effect of subsurface barriers.

Effect of Barrier Types on Chloride Leaching

The effects of different subsurface barriers on Cl⁻ leaching are shown in Fig. 5. Relative concentrations were calculated as ratios of the measured Cl⁻ concentra-

tion of the effluent sample to the maximum measured Cl⁻ concentration of the NB treatment. In general, compared with NB, all subsurface barriers except for PB delayed the initial breakthrough of Cl⁻. Peak concentration was delayed and reduced substantially when subsurface barriers were used. Chloride was leached more gradually with the barriers than without (Table 2). Because of the high flow rates in this study (the duration of each experiment was 2 to 4 h), diffusion was not a major factor in overall Cl⁻ transport, although it might have taken place locally. The pore water velocity field of the

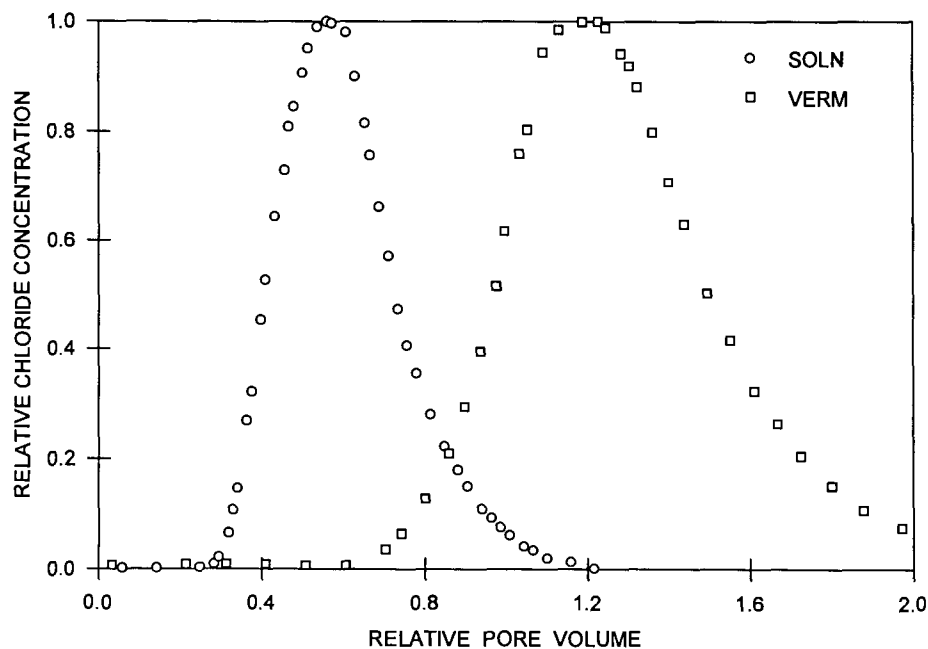Fig. 4. Chloride breakthrough curves for two different Cl⁻ application methods. SOLN denotes injection of 2.5 mL of 0.2 M CaCl₂ solution at 4 cm soil depth, and VERM denotes placement of 20 mL of 0.025 M CaCl₂ solution adsorbed to 5 g of vermiculite from 2 to 5 cm soil depths.
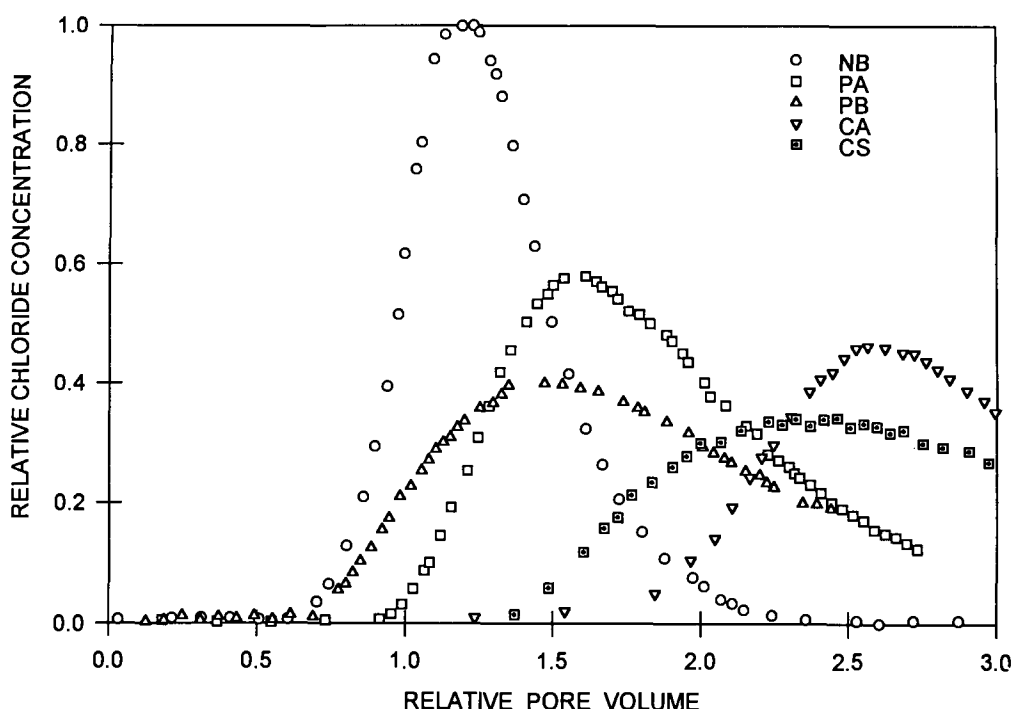
Fig. 5. Effects of different types of subsurface barriers on Cl⁻ leaching. NB, no barrier; PA, polyethylene disk placed above the Cl⁻; PB, polyethylene disk placed below the Cl⁻; CA, compacted soil layer placed above the Cl⁻; and CS, compaction in situ above the Cl⁻.

column was distorted by subsurface barrier (Maâledj and Malavard, 1973). This distortion alters the distribution of pore water velocities, and different barriers resulted in different velocity distributions. Thus, shapes of Cl⁻ breakthrough curves in Fig. 5 reflect both the pore water velocity distributions created by different subsurface barriers and the placement of Cl⁻ within the velocity fields.

Compared with NB, the PA treatment delayed the initial breakthrough of Cl⁻ by ≈0.3 relative pore volumes. Peak concentration was reduced 40% and delayed ≈0.4 relative pore volumes compared with the same treatment. Tailing of the PA breakthrough curve was less prominent than that of the PB treatment curve. Apparently, the Cl⁻-vermiculite mixture must have been relatively close to the boundaries of the low-flow region, and the Cl⁻ moved rapidly once it left its initial position.

According to the theoretical studies, PB should have been more effective than PA in delaying and reducing leaching of Cl⁻ (Maâledj and Malavard, 1973; Babu, 1979; Kirkham and Horton, 1990) because of low-flow regions both above and below the barrier. Solution con-

Table 2. Fraction of the applied Cl⁻ leached for different types of barriers with solution–vermiculite mixture.

Treatment†	Relative pore volume				
	0.6	1.2	1.8	2.4	3.0
NB	0.01	0.45	0.95	1.00	–
PA	0.00	0.06	0.54	0.87	–
PB	0.01	0.16	0.53	0.78	–
CA	0.02	0.04	0.07	0.26	0.64
CS	0.04	0.08	0.20	0.50	0.81

† NB = no barrier; PA = polyethylene disk above Cl⁻-vermiculite mixture; PB = polyethylene disk below Cl⁻-vermiculite mixture; CA = compacted soil layer outside column above Cl⁻-vermiculite mixture; CS = compacted layer within column above Cl⁻-vermiculite mixture.

taining Cl⁻ was thought to rest on the barrier and to move slowly in a horizontal direction towards the edge of the barrier. After moving around the barrier, a portion of the Cl⁻ solution could subsequently move towards the low-flow region below the barrier. In our experiment, PB did not delay the initial breakthrough of Cl⁻ compared with NB. One possible explanation for this may be that the mixture occupied a relatively large volume and part of the Cl⁻-vermiculite mixture may have been in a high-flow region above the barrier. Thus, dissolved Cl⁻ was carried away relatively quickly and the initial breakthrough of Cl⁻ occurred as fast as with NB. The breakthrough curve for PB, however, showed a lower peak concentration than did either PA or CA. The peak concentration for PB was reduced 60%, and the peak concentration delayed 0.2 relative pore volumes, compared with those for NB. Tailing of the PB breakthrough curve was also more prominent than that of PA, and Cl⁻ residence for PB was greater (Table 2).

The CA treatment was the most effective barrier in delaying the initial Cl⁻ breakthrough, which occurred 0.9 pore volumes later than that of NB. The greater thickness of the compacted soil layer may have affected distribution of pore-water velocities and increased the size of the low-flow region below the barrier compared with a thinner plastic disk. Peak concentration was reduced by >50%, and position of the peak was delayed ≈1.3 relative pore volumes compared with that of NB. Because the initial breakthrough of Cl⁻ was substantially delayed, this treatment had the longest Cl⁻ residence time (Table 2).

The CS treatment was less effective in delaying the initial breakthrough of Cl⁻ than was CA. Breakthrough occurred at ≈1.3 relative pore volumes, a delay of 0.7
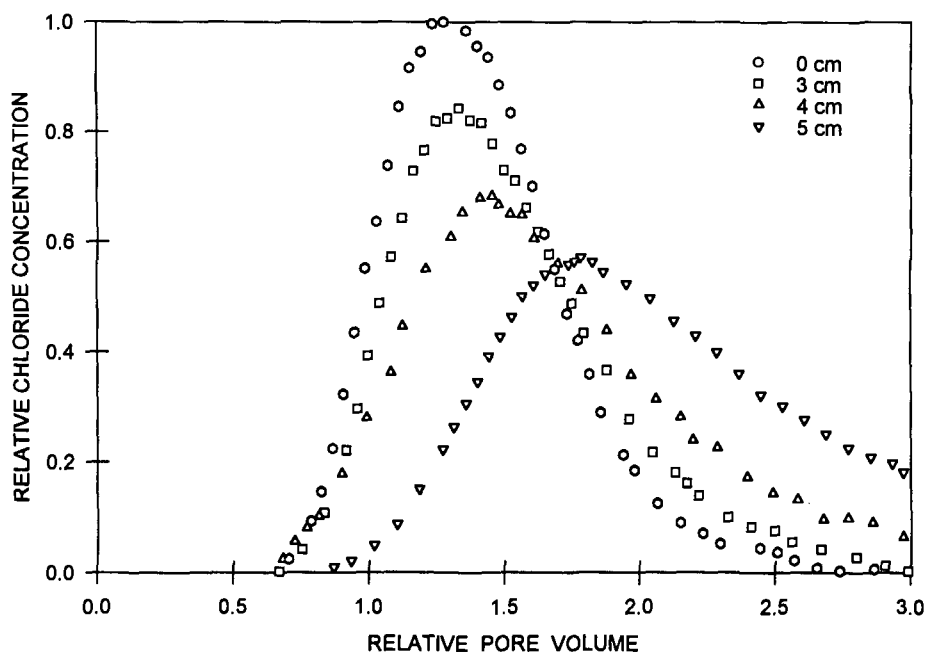
Fig. 6. Effect of differently sized subsurface barriers placed above the applied Cl⁻.

relative pore volumes compared with that of NB. When the compacted layer was formed in situ, the rammer was dropped from 2 cm instead of 10 cm to minimize the thickness of the compacted layer. This procedure resulted in a compacted layer that was not as dense as that formed for CA, and water velocities below it were probably greater than those found below the CA barrier. But, the breakthrough curve for CS was the most gradual and had the flattest peak, indicating that a localized compaction in situ above a banded fertilizer can delay and reduce NO_3^- leaching. Peak concentration was reduced by >60%, and the occurrence of the peak was delayed ≈ 1.2 relative pore volumes compared with the peak of NB, and it was the smallest of all the subsurface barriers tested.

Effect of Barrier Diameter on Chloride Leaching

The effect of barrier size was examined by means of the PA treatment. Figure 6 and Table 3 show the results of several Cl⁻ leaching experiments using barriers with different diameters. Relative concentration was calculated as a ratio of the measured Cl⁻ concentration of the effluent sample to the greatest measured Cl⁻ concentration of NB. The 3-cm disk was just large enough to cover the upper surface of the packed Cl⁻-vermiculite mixture. Peak concentration was reduced only $\approx 10\%$ by a 3-cm disk (compared with NB), but the general shape of the breakthrough curve was almost identical to that of NB. Fraction of the applied Cl⁻ leached was slightly smaller than that of NB (Table 3).

Compared with NB, the 4-cm disk reduced peak concentration $\approx 30\%$ and delayed the occurrence of the peak concentration by ≈ 0.2 relative pore volumes. The breakthrough curve for the 4-cm disk was broader than the curves for both the 0- and 3-cm barriers (Fig. 6).

A delay of the initial Cl⁻ breakthrough by 0.6 relative pore volumes occurred when a 5-cm disk was used. The

peak concentration was $\approx 40\%$ lower than that of NB. Shape of the 5-cm disk curve was flatter than other breakthrough curves, and tailing was prominent. Fraction of the applied Cl⁻ leached was smaller for the 5-cm disk than for other barrier sizes (Table 3).

A small impermeable 5-cm-diam. barrier, which extended only 1 cm beyond the edge of the applied Cl⁻-vermiculite mixture, delayed initial breakthrough of Cl⁻ and significantly reduced Cl⁻ leaching. This finding indicates that a relatively small localized subsurface barrier has the potential to delay and reduce leaching of anions.

In summary, the results of this laboratory investigation indicate that a small subsurface barrier has the possibility of reducing or delaying leaching of anions. In practice, controlled small-scale localized compaction possibly by tractor wheels above an injected NO_3^--N fertilizer band has potential of reducing or delaying leaching losses of NO_3^-. Further, prolonged NO_3^- residence time in a soil profile may enable increasing plant uptake efficiency and lead to reducing the application amount of N fertilizer.

Table 3. Fraction of the applied Cl⁻ leached for differently sized barriers with solution-vermiculite mixture, using a plastic sheet placed above the applied Cl⁻.

Barrier diameter	Relative pore volume				
	0.6	1.2	1.8	2.4	3.0
cm					
0	0.00	0.29	0.88	0.99	1.00
3	0.00	0.22	0.73	0.90	0.92
4	0.00	0.17	0.63	0.86	0.94
5	0.00	0.03	0.35	0.70	0.88

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