

Reduction in Hydraulic Conductivity in Relation to Clay Dispersion and Disaggregation¹

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ABSTRACT

The saturated hydraulic conductivities (HCs) of three California soils (Arlington, Fallbrook, and Pachappa Haplic; Durixeralfs, Typic and Mollic Haploxeralfs, respectively) were determined at successively diluted electrolyte solutions with a constant sodium adsorption ratio (SAR) of 0 or 10, followed by deionized water. When these soils were Ca-saturated and then leached with deionized water, very little clay dispersion (0–0.05 g soil column⁻¹) occurred and yet the HC was reduced to about 2, 24, and 72% of the maximum HCs for Fallbrook, Arlington, and Pachappa soil columns, respectively. At SAR 10, replacement of the most dilute solution (2.5 mol m⁻³) with deionized water resulted in a rapid reduction in the HC to zero for both the Arlington and Fallbrook soils. The appearance of clay in the effluent solutions indicated that the dispersed clay was mobile in the soil columns and thus not plugging a major part of the soil pores. The major cause of reductions in HC is concluded to be the reduction of large conducting pores as a result of aggregate failure (slaking). This conclusion is supported by the fact that the HC of Fallbrook soil, which contained the least stable aggregates, was reduced to zero despite its having the greatest proportion of macropores; and that clay dispersion did not cause plugging of conducting pores for the Pachappa soil, which had the most stable aggregates despite its having the highest proportion of micropores.

Additional Index Words: sodium adsorption ratio, electrolyte concentration, sodic soils, soil structure, aggregation.

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SEVERAL INVESTIGATORS have concluded recently that the dispersion of clay and its subsequent lodgement in soil pores is responsible for loss in soil hydraulic conductivity (HC) when the soil is slightly sodic and/or the percolating water is low in electrolyte concentration (Frenkel et al., 1978; Felhendler et al., 1974; Pupisky and Shainberg, 1979; Shainberg et al., 1981a, b). Their conclusion was based upon the observation that swelling was insignificant under such conditions and that dispersed clay appeared in the effluent solutions concurrent with loss of HC. However, the concentrations of dispersed clay in these effluent solutions were found to peak when approximately one pore volume of the infiltrating solution that produced the reduction in HC had passed through the soil column. The concentration of dispersed clay then declined once more with further leaching. Reductions in HC continued even as the concentration of dispersed clay in the effluent declined.

The hypothesis that clay dispersion is the major mechanism responsible for reduction in HC poses the following questions: (i) Is it possible for the clay to disperse without the simultaneous breakdown of soil

aggregates? and (ii) How can the drop in HC continue with a concomitant reduction in the concentration of clay in the effluent solution? Abu-Sharar (1985) provided data that showed that aggregate failure and disaggregation (slaking) into aggregate sizes as small as 5 μm in diameter occurred for soils as the soil solution was diluted. Such slaking would appreciably reduce the amount of macropores and should reduce HC correspondingly. Significant amounts of dispersed clay were observed only when the electrolyte concentration was reduced to near the critical coagulation concentration (CCC) of a clay suspension made up of <1 μm clay from the respective soil (Abu-Sharar, 1985).

The objective of this study was to test the hypothesis that slaking, not clay dispersion, is the major cause of observed decreases in the HC of arid and semiarid soils that are leached with successively more dilute electrolyte solutions of constant and relatively low sodium adsorption ratios (SAR).

MATERIALS AND METHODS

Three California soils, Arlington (coarse-loamy, mixed, thermic Haplic Durixeralfs), Fallbrook (fine-loamy, mixed, thermic Typic Haploxeralfs), and Pachappa (coarse-loamy, mixed, thermic Mollic Haploxeralfs) were used for this study. Dry aggregate-size distribution was determined by sieving the <2-mm air-dry fraction of each soil. Particle-size distribution was determined by wet sieving of the sand fractions followed by quantitative sedimentation-fractionation of the clay and silt fractions using 1 mol NaCl m⁻³ solution. Organic carbon (OC) was determined by a modification of the Walkley-Black method (1934). Cation exchange capacity (CEC) was determined by the sodium acetate method (U.S. Salinity Laboratory Staff, 1954). X-ray diffraction analysis was carried out according to the method described by Jackson (1979).

Soil columns were prepared by packing samples of <2-mm soil into glass cylinders (0.046-m i.d. by 0.300-m long) at bulk densities of 1.30, 1.46, and 1.50 Mg m⁻³, respectively, for the Arlington, Fallbrook, and Pachappa soils. The bottom of each cylinder contained an extra-coarse fritted glass disc. The cylinder was longitudinally calibrated with a scale of 1-mm divisions. Each soil column was wetted from below by capillarity using an electrolyte solution of the desired SAR level and a total salt concentration of 500 mol m⁻³. Duplicate columns were run simultaneously. The effluent of each column discharged to a siphon device and in turn into a fraction collector in 24-mL increments. A Mariotte bottle maintained a constant hydraulic head during leaching. The change in HC of the columns as a function of leaching volume was determined using a Timex-Sinclair 1000 computer with a Timex-Sinclair 1016 extended memory. When the siphon device was filled to a reference point by the percolating solution, electrical contact was made via a KHCO₃ solution-filled manometer, and a signal was sent to the computer through a custom-made interfacing circuit. The real time was read and stored in the computer's memory for recall. This special arrangement provided a time record of changes in percolation rate and, hence, HC.

Initial measurements of HC were made by leaching the soil columns with electrolyte solution of the desired SAR at a total concentration of 50 mol m⁻³. When the HC reached steady state, usually in about 24 h, all of the time data stored in the computer's memory were retrieved. Then, new mea-

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Table 1. Selected chemical, mineralogical, and physical properties of the soils studied.

Soil series	Sand	Silt	Clay	Texture	Organic carbon	CEC	Dominant clay†
	g kg ⁻¹				g kg ⁻¹	mol _c kg ⁻¹	
Arlington	403	402	195	loam	2.4	0.174	V, M, K
Fallbrook	730	182	88	sandy loam	5.4	0.077	M, V, K
Pachappa	499	359	142	loam	4.6	0.090	V, M, K

† V = vermiculite, M = mica, K = kaolinite.

measurements of HC were initiated as the leaching solution was successively replaced with more dilute solutions of the same SAR. Deionized water was used as the most dilute "solution" for SAR treatments of 0 and 10. When dispersed clay appeared in the effluent, its concentration was determined by optical transmission measurements (% T) at 420 nm, using a spectrophotometer. The dispersed clay was subsequently flocculated and determined gravimetrically.

RESULTS AND DISCUSSION

Some important properties of the three soils are presented in Table 1. The clay content of the Fallbrook soil was 88 g kg⁻¹, whereas those of the Pachappa and Arlington soils were 142 and 195 g kg⁻¹, respectively. The most abundant clay mineral in the Arlington and Pachappa soils was vermiculite. Mica and small quantities of kaolinite were also present. These three minerals were also present in the Fallbrook clay; however, mica was the most abundant clay mineral. The OC content was quite low in all of these soils (<6 g kg⁻¹).

Slaking and Reduction in HC

Because of variability in packing the soil columns, HC results were expressed as a percent of the maximum HC obtained while using the solution of highest electrolyte concentration in each dilution series. Results of the HC measurements as a function of electrolyte concentration at constant SAR of 0 or 10 are given in Tables 2, 3, and 4, and in Fig. 1.

The initial dry-aggregate size distributions are presented in Table 5. This determination was carried out to provide an estimate of the initial pore-size distribution present in each soil column before leaching, and to help explain the observed variation among soils in their maximum HCs and their different suscepti-

Table 3. Hydraulic conductivity and amount of clay dispersed for the Fallbrook soil in relation to electrolyte concentration and SAR level of the leaching solution.

Electrolyte concentration		Hydraulic conductivity		Dispersed clay
dS m ⁻¹	mol m ⁻³	cm h ⁻¹	% of max	g soil column ⁻¹
SAR 0				
0.065	5.59	20.00	100.0	nd†
0.042	3.48	20.09	100.9	nd
0.020	1.79	17.36	86.8	nd
0.000	0.00	0.35	1.8	0.05
SAR 10				
0.530	50.00	11.40	100.0	nd
0.210	20.00	11.13	97.6	nd
0.165	15.00	3.75	32.9	nd
0.112	10.00	2.35	20.6	nd
0.057	5.00	1.14	10.0	0.06
0.028	2.50	0.04	0.4	0.07
0.000	0.00	0.00	0.0	0.25

† nd = none detected.

Table 2. Hydraulic conductivity and amount of clay dispersed for the Arlington soil in relation to electrolyte concentration and SAR level of the leaching solution.

Electrolyte concentration		Hydraulic conductivity		Dispersed clay
dS m ⁻¹	mol m ⁻³	cm h ⁻¹	% of max	g soil column ⁻¹
SAR 0				
0.060	5.24	6.14	100.0	nd†
0.040	3.17	6.06	98.7	nd
0.020	1.65	6.00	97.7	nd
0.004	0.33	3.60	58.6	nd
0.000	0.00	1.45	23.6	nd
SAR 10				
0.530	50.00	7.68	100.0	nd
0.210	20.00	6.49	84.5	nd
0.165	15.00	6.08	79.2	nd
0.112	10.00	6.01	78.4	nd
0.057	5.00	5.14	66.9	nd
0.028	2.50	2.84	37.0	0.05
0.000	0.00	0.00	0.0	0.12

† nd = none detected.

bilities to the effects of clay dispersion and/or slaking on their losses of HC during leaching. If clay dispersion and pore-plugging are responsible for the loss of HC, one would expect soils with a greater proportion of macropores to be less susceptible than soils with a finer pore size distribution. However, if slaking induces reductions in HC, soils dominated by macropores should be more susceptible than soils with fewer macropores. Soil aggregate breakdown causes a reduction in the proportion of macropores and consequently a sharp reduction in HC because most of the solution flow occurs through the larger pores (Lagerwerff et al., 1969). Breakdown of soil aggregates should also be greater in more porous soils since they are less constrained. The Fallbrook soil had the highest percentage of >1-mm aggregates and the lowest percentage of <0.5-mm aggregates. The Pachappa soil had

Table 4. Hydraulic conductivity and amount of clay dispersed for the Pachappa soil in relation to electrolyte concentration and SAR level of the leaching solution.

Electrolyte concentration		Hydraulic conductivity		Dispersed clay
dS m ⁻¹	mol m ⁻³	cm h ⁻¹	% of max	g soil column ⁻¹
SAR 0				
0.120	10.72	3.42	100.0	nd†
0.065	5.59	3.43	100.3	nd
0.042	3.48	3.36	98.2	nd
0.021	1.80	3.15	92.1	nd
0.000	0.00	2.46	71.9	0.04
SAR 10				
0.210	20.00	2.51	100.0	nd
0.165	15.00	2.50	99.6	nd
0.112	10.00	2.39	95.2	nd
0.057	5.00	2.12	84.5	0.01
0.028	2.50	1.93	76.9	0.04
0.000	0.00	1.04	41.4	0.11

† nd = none detected.

Table 5. Dry aggregate size distribution of the soils studied.

Soil	g kg ⁻¹ of dry aggregates of a mean diameter (mm)†		
	>1	>0.5-<1	<0.5
Arlington	369	270	361
Fallbrook	532	266	202
Pachappa	240	123	637

† g kg⁻¹ of total soil, dry weight basis.

just the opposite proportions, while the Arlington soil had roughly equal distributions of the various size fractions (see Table 5). Therefore, pore space in Fallbrook soil columns was expected to be more thoroughly dominated by macropores, that of Pachappa columns by micropores, and that of Arlington columns influenced by both. The maximum HC values of the soils were consistent with their dry aggregate-size distributions. The HC of the Fallbrook soil was the highest, that of the Pachappa soil was the lowest, and that of the Arlington soil was intermediate.

As previously reported by Abu-Sharar (1985), slaking and clay dispersion were more extensive for the Fallbrook soil compared to the Arlington and Pachappa soils at comparable levels of SAR and electrolyte concentration. The results of our HC study showed a similar trend. At SAR 0 and an electrolyte concentration of 1.65 mol m^{-3} , the HC of the Arlington was reduced by only 2.3% while, at an electrolyte concentration of 1.8 mol m^{-3} , the HCs of the Pachappa and Fallbrook soils were reduced by 7.9 and 13.2%, respectively. Abu-Sharar (1985) showed that slaking (breakdown of soil aggregates into size fractions $>2 \mu\text{m}$) but not clay dispersion (further breakdown of fine soil aggregates and release of $<2\text{-}\mu\text{m}$ clay) occurred at

these concentrations and SAR levels. Furthermore, the extent of clay dispersion even at an electrolyte concentration of 0.3 mol m^{-3} was very small compared to that of the slaking of large soil aggregates into sizes as small as $20 \mu\text{m}$. For example, the dispersion of only 6.8% of the total clay content in the Fallbrook soil was associated with a slaking of 40% of the total $<20\text{-}\mu\text{m}$ particles (Abu-Sharar, 1985). Therefore, the sharp reduction in HCs observed when the lowest concentration of the leaching solution was replaced by deionized water is more likely attributable to slaking than to clay dispersion. In fact, the amounts of dispersed clay collected in the effluents were too little to be accurately measured. Moreover, upon leaching with deionized water, the HC of the Fallbrook soil was reduced to almost zero (1.8%), while that of the Arlington and the Pachappa soils were reduced to 23.6 and 71.9%, respectively.

At SAR 10, the Pachappa soil showed a remarkable stability as the electrolyte concentration was successively reduced; there was no sharp reduction in HC until the 2.5 mol m^{-3} solution was replaced by deionized water. At these two levels, the HC values were 76.9 and 41.4% of the initial value, respectively. The least stable soil (Fallbrook) underwent a sharp reduction (64.7%) in HC once the electrolyte concentration was reduced from 20 to 15 mol m^{-3} . The HC was further reduced to almost zero upon leaching with a 2.5 mol m^{-3} solution. A significant reduction (29.9%) in the HC of the Arlington soil occurred when the 5 mol m^{-3} electrolyte concentration was reduced to 2.5 mol m^{-3} , and it was further reduced to zero when deionized water replaced the 2.5 mol m^{-3} solution.

Clay Dispersion and Reduction in HC

As shown in Tables 2, 3, and 4, there was very little clay dispersion at SAR 0 even when the soil columns were leached with deionized water. In contrast, at SAR 10, substantial clay dispersion occurred in the Arlington and Fallbrook soils upon replacing the 2.5 mol m^{-3} solution with deionized water. Complete sealing of these soils had occurred upon infiltrating about 60 mL of deionized water (one pore volume equaled 118 and 92 cm^3 for the Arlington and Fallbrook soil columns, respectively). The amounts of dispersed clay discharged in the effluents from these soils are given in Tables 2 and 3. In contrast, the HC of the Pachappa soil was not reduced to zero even when percolating deionized water at SAR 10. Whenever there was clay dispersion, the % T was found to reach a minimum immediately after percolation of about one pore volume of the solution that initiated dispersion; then the % T was found to increase gradually once more. It was found (Abu-Sharar, 1985) that clay dispersion occurred in these soils upon reduction of the electrolyte concentration to the critical coagulation concentration (CCC) of the $<1\text{-}\mu\text{m}$ clay fraction of each soil for an appropriate level of SAR. The CCC is defined here as the minimum electrolyte concentration for a given level of SAR at which the onset of clay flocculation is observed after 24 h. Emerson and Bakker (1973) gave two reasons for the occurrence of clay dispersion in soils leached with more dilute solutions: (i) reduction in the electrolyte concentration below the CCC level,

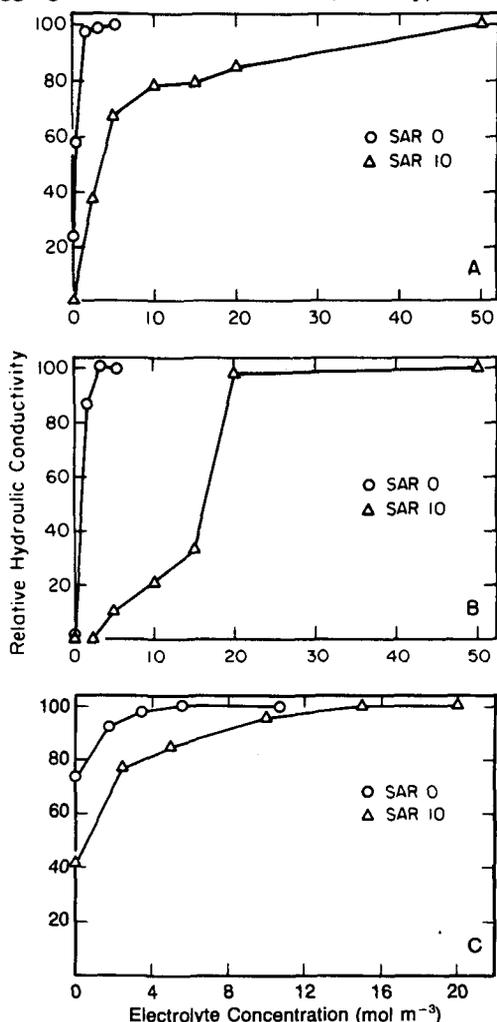


Fig. 1. Relative hydraulic conductivity of the Arlington (A), Fallbrook (B), and Pachappa (C) soils as a function of the electrolyte concentration and SAR level of the leaching solution.

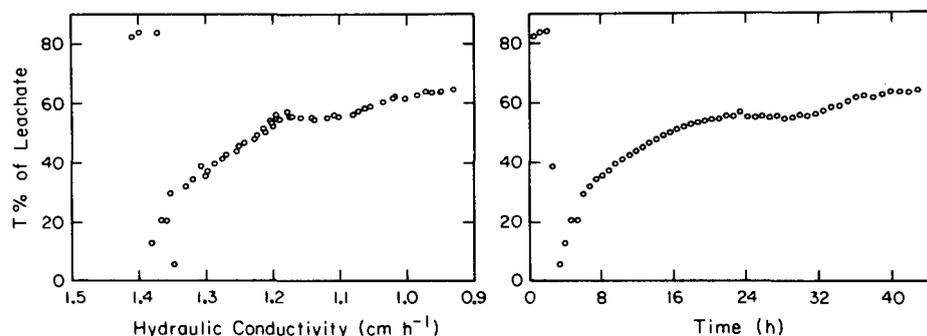


Fig. 2. Percent optical transmission of the leachate from the SAR 10-treated Pachappa soil as a function of (1) the HC upon leaching with deionized water (left) and (2) the duration of leaching with deionized water (right).

and (ii) the creation of a steep salt gradient between the dilute solution in the external surroundings of the soil aggregates and the more concentrated solution within the aggregates ("osmotic explosion" effect). Shainberg et al. (1981a) speculated that the osmotic effect was the cause of the peak in clay concentration of effluents after having leached soil columns with about 1.5 pore volumes of a sufficiently dilute solution. They indicated that the sudden reduction in electrolyte concentration of the leaching solution from 10 or 50 mol m⁻³ to 0, 1, 2, or 3 mol m⁻³ caused an osmotic explosion in the soil aggregates, which led to peak clay concentration in the front of displacing solution. This peak was followed by decreasing amounts of dispersed clay in the subsequent effluent, presumably because of the resultant diffusional adjustment between salt solutions within and external to the soil aggregates.

To minimize the opportunity for the osmotic explosion effect, we reduced the electrolyte concentration very gradually in this study. Even so, the concentration of the dispersed clay in the effluent solution peaked as discussed above and as shown in Fig. 2 for Pachappa soil. Clay dispersion was initiated after percolation of about one pore volume (87 cm³) of deionized water. The HC continued to decrease without additional clay dispersion (Fig. 2, left). The reduction in HC from 1.4 to 0.9 cm h⁻¹ occurred over a period of about 52 h (Fig. 3). From these observations it could be concluded that clay dispersion occurred because electrolyte concentration was reduced to a level that induced clay dispersion, and not because of the osmotic effect. Because the total clay dispersed from the Pachappa soil column was only 0.3% of the total clay present in the soil (it took more than 40 h to collect this amount of dispersed clay), and because a continuous reduction in HC occurred even though there was a continuous decrease in clay concentration of the effluent, it is concluded that clay dispersion and plugging of conducting pores by dispersed clay was not the major mechanism for the observed reduction in HC. Slaking might have continued at a slow rate, causing a continuous reduction in HC.

The extensive slaking of the Arlington and Fallbrook soils, which took place when deionized water percolated through these soils, apparently had an overwhelming effect on their HCs. All of the conducting pores were apparently sealed off, and thereby caused the HC to drop to zero. Although the concentration of dispersed clay was very high, the relatively

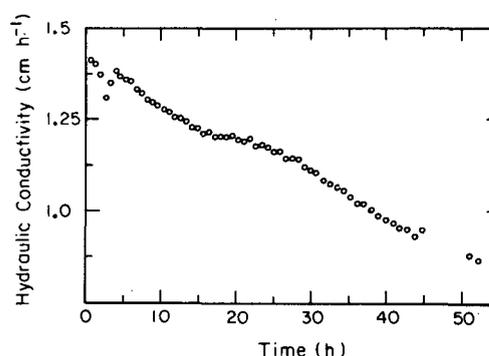


Fig. 3. Hydraulic conductivity of SAR 10 treated Pachappa soil upon leaching with deionized water.

higher proportion of macropores in the Fallbrook soil did not allow a free passage of dispersed clay as would have been expected from the hypothesis of clay dispersion and plugging of conducting pores. Instead, the dominance of the macropores led to an instability of soil aggregates by providing larger space in their surroundings, which was conducive to slaking and thus to collapse of soil structure. The breakdown of these aggregates, as expected, caused a slight decrease in bulk volume of the soil columns. For the three soils, this reduction in bulk volume ranged from 2 to 3%.

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