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Effects of Clay Type and Content, Exchangeable Sodium Percentage, and Electrolyte Concentration on Clay Dispersion and Soil Hydraulic Conductivity[1]

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ABSTRACT

The hydraulic conductivities and gradients along soil columns packed with montmorillonitic, vermiculitic, and kaolinitic soils adjusted to different levels of exchangeable sodium were determined at different salt concentrations. The data show that plugging of pores by dispersed clay particles is a major cause of reduced soil hydraulic conductivity for surface soils irrigated with sodic waters.

Additional Index Words: **hydraulic conductivity, clay dispersion, sodic soils, exchangeable sodium, water quality.**

ONE OF THE MAJOR FACTORS affecting the suitability of a water for irrigation is its sodicity hazard. While excessive sodium causes both crop toxicity and soil permeability problems, our greatest limitation in assessing the sodicity hazard is our inability to predict how the water will affect soil structure and permeability (Rhoades, 1972). Quirk and Schofield (1955) showed that the hydraulic conductivity (HC) of a given soil decreases with increasing exchangeable sodium percentage (ESP) provided that the electrolyte concentration is below a critical level (threshold level). Threshold values vary from soil to soil, however, and cannot generally be forecast without empirical tests, even for soils of similar clay content and type (McNeal and Coleman, 1966a; Naghshineh-Pour et al., 1970; Rhoades and Ingvalson, 1969; Thomas and Yaron, 1968). Some success in predicting HC reductions has been achieved for certain soil types and areas (McNeal, 1968; Yaron and Thomas, 1968).

Dispersion and swelling of clays within the soil matrix are interrelated phenomena, and either can reduce soil hydraulic conductivity. Swelling reduces soil pore sizes and dispersion clogs soil pores. If dispersed particles do not lodge, however, their transport can actually result in increased porosity and HC (Frenkel and Rhoades, 1977). Swelling is not generally appreciable unless the ESP exceeds about 25 or 30 (Aylmore and Quirk, 1959, Quirk, 1968; Shainberg and Caiserman, 1971). But dispersion can occur at ESP levels as low as 10 to 20 if the electrolyte level is < 10 meq/liter (Felhendler et al., 1974). That dispersion can occur at lower exchangeable sodium levels than swelling may be explained by the effect of exchangeable cation composition on the structural arrangement of clay particles (Aylmore and Quirk, 1959, 1962; Blackmore and Miller, 1961; Shainberg and Otoh, 1968; Quirk, 1968; and Shainberg and Caiserman, 1971). Calcium-saturated montmorillonite clay particles commonly consist of packets (tactoids) of four to nine clay platelets arranged parallel to each other at distances of 9Å. These structural units tend to maintain their integrity and behave as discrete entities. Consequently, the swelling of calcium montmorillonite is limited by its reduced effective surface area. With the first additions of sodium, ESP < 20, sodium is adsorbed on the external surfaces and edges while calcium remains in the interlayer positions of the tactoid. A more diffuse electrical double layer then develops around the tactoid, the extent varying with electrolyte concentration, creating repulsive forces between tactoids and an increasing electrophoretic mobility (Shainberg, 1968; Shainberg and Otoh, 1968; Bar-On et al., 1970).

As a result, dispersion of tactoids is enhanced but little interlayer swelling occurs, since tactoid integrity is maintained. With further addition of sodium (ESP about 25), exchangeable sodium "invades" the interlayer positions, diffuse double layers develop on the interlayer surfaces of each platelet, and interlayer repulsion and swelling increase along with deterioration of the tactoid structure (Shainberg and Caiserman, 1971; and Martin et al., 1964). The tactoids break down completely when the ESP reaches about 50.

Differences of opinion can be found in the literature as to whether swelling or dispersion is the major cause of reduced permeability of sodic soils. McNeal and Coleman (1966b), McNeal (1968), and Rowell et al. (1969) have published equations which relate saturated HC and swelling. McNeal and Coleman (1966b) considered dispersion and particle translocation the dominant mechanisms for HC decreases in coarse-textured soils and in soils that contain small amounts of expansible minerals. Felhandler et al. (1974) suggested that dispersion and soil pore blockage are the main causes of reduced HC in all soils of low ESP (<15). Rhoades and Ingvalson (1969) concluded that "dispersion rather than swelling seems to be the operative process which leads to permeability decreases in vermiculitic soil".

Waters sufficiently high in sodium to produce soils with ESP's > 25 to 30 are seldom used except when the waters are also relatively high in salt concentration or when chemical amendments are used in conjunction, or both. The most commonly faced situation is the evaluation of low salt concentration waters (< 15 meq/liter) of intermediate sodicity (SAR 5 to 20)[3]. Rainfall on soils previously irrigated with such waters accentuates the problem. For such situations, dispersion is more likely to limit HC than swelling, and the limiting layer will be at or near the soil surface. In irrigated soils, ESP and salinity are generally lowest at the soil surface and increase with depth through the root zone. The increased salinity with depth is usually sufficient to compensate for the increased level of ESP (Rhoades, 1968; Rhoades and Merrill, 1976).

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[3]SAR = $NA^+/[(Ca^{2+} + Mg^{2+})/2]^{1/2}$, where all solute concentrations are in meq/liter. SAR is a useful parameter for sodicity appraisal since the exchangeable sodium percentage (ESP) of a soil and the SAR of solution equilibrated with it are approximately equal numerically up to SAR values of about 30 for many arid-land soils. (U.S. Salinity Laboratory Staff, 1954).

Table 1—Physical and chemical characteristics of the soils.

Dominant clay type	Location (soil type)	Mechanical composition			CEC†	pH‡	$CaCO_3$	Mineralogical composition§						
		Sand	Silt	Clay				M	V	Chl	Q+F	m	I	K
		%			meq/100 g		%	%						
Montmorillonite	Imperial Valley, California	88.1	9.0	2.9	3.2	8.2	5.2							
	(–)	82.5	9.5	8.0	8.0	7.7	0.5							
		75.5	14.5	10.0	9.6	7.6	4.0	42	2	8	16	29	-	—
		67.3	17.8	14.9	13.2	7.6	4.9							
		35.7	46.3	18.0	15.5	7.6	7.2							
Kaolinite	San Diego Co., California (Fallbrook sl)	51.8	17.0	31.2	19.7	6.7	0.1	-	tr	-	-	-	10–30	>70
	North Carolina (–)	79.6	9.8	10.6	1.25	4.5	tr	-	10–40	-	-	-	-	>40
Vermiculite	Riverside County, California (Arlington fsl)	42.0	45.0	13.0	18.0	8.1	tr	-	72	-	14	-	-	14

† CEC — cation exchange capacity.
‡ pH in saturated paste.
§ Composition of clay fraction where the following minerals are identified by the symbols: M = montmorillonite, Q = quartz, I = illite, V = vermiculite, F = feldspar, K = kaolinite, Chl = chlorite, and m = mica.

Opinions also differ as to the effect of clay mineralogy on HC, especially with respect to kaolinite. McNeal and Coleman (1966a) and Yaron and Thomas (1968) concluded that the most labile soils were those high in 2:1 layer silicates, especially montmorillonite, and the least labile were those high in kaolinite and sesquioxides. El-Swaifey and Swindale (1969) studied the HC's of tropical soils whose clay fractions were dominated by kaolins, iron oxides, amorphous silicates and gibbsite and found negligible effect of exchangeable sodium even in the absence of salinity. McNeal et al. (1968) found that the "stability" of HC of tropical Hawaiian soils under high sodium and low salt conditions was greatly reduced by partial removal of free iron-oxides, and concluded that the cementing action of iron oxides prevented dispersion. Deshpande et al., (1968) concluded, however, that it was aluminum oxides, rather than iron oxides which had the greatest effect on soil stability during leaching with sodic water. Velasco-Molina et al. (1971), concluded that, in the virtual absence of electrolyte, the order of soil dispersion at a given ESP was: montmorillonitic>halloysitic>micas. At low ESP values, the micaceous soil sometimes dispersed more than the halloysitic-kaolinitic soil. Elgabaly and Elghamry (1970) found that the HC of ground and sieved kaolinitic systems decreased rapidly when leached with distilled water at ESP's of 10 or greater. Rhoades and Ingvalson (1969) concluded that the ESP needed to appreciably reduce HC was much higher for vermiculitic than for montmorillonitic soils.

Because of the limitations and inconsistencies described above, we obtained more information on the effects of relatively low ESP levels (10 to 30) and electrolyte concentrations on clay dispersion and hydraulic conductivity for soils of different textures and clay mineralogy.

MATERIALS AND METHODS

Properties of soils used are given in Table 1. Columns of these soils were prepared by packing sieved soil into plastic cylinders (5 cm in diam by 30-cm long) at bulk densities of 1.5 g/cm^3. Additional columns of Fallbrook (Typic Haploxeralf) and Arlington (Haplic Durixeralf) soils were prepared after adding sufficient quartz sand to yield clay percentages of 10.4 and 6.5, respectively. Similarly, the clay mineralogy of the kaolinitic soil from North Carolina was altered by adding montmorillonite clay (2% by weight). Columns of the Fallbrook soil at 10.4% clay were also packed at bulk densities of 1.43, 1.55, and 1.68 g/cm^3.

Saturated hydraulic conductivities (HC) of the columns were determined by leaching with a constant head device (Fig. 1) and measuring the drainage rate. The hydraulic heads along the columns were continually monitored during leaching, using the piezometer arrangement shown in the figure. Effluent solutions were collected in a fraction collector and amounts of suspended clay were determined by gravimetric and optical procedures

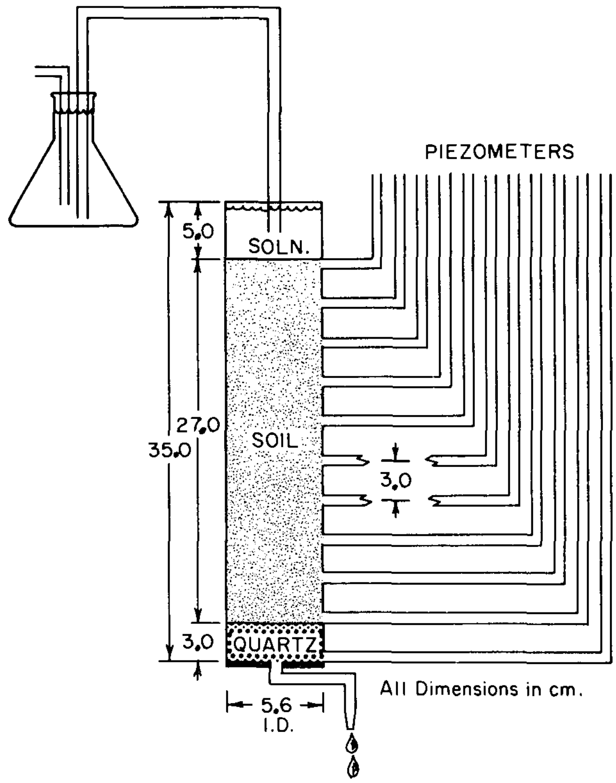

Fig. 1—Schematic of column, constant-head, and piezometer setup used to measure soil hydraulic conductivity and suction head changes.

Table 2—Saturated hydraulic conductivities (HC) and depths of limiting HC in columns of montmorillonitic, kaolinitic and vermiculitic soils as influenced by clay content, ESP, and bulk density.

Clay content	ESP	Bulk density	HC at electrolyte concentration (N) of 1.0	0.05	0.01	0.00	Percent relative HC†	Depth interval of limiting HC
%	%	g/cm³	cm/hour				%	cm
			Montmorillonite					
8.0	10	1.5	0.286	0.278	0.205	0.2011	70.3	-
10.0	10	1.5	0.077	0.074	0.061	0.042	54.8	-
15.0	10	1.5	0.0309	0.033	0.021	0.0017	5.5	-
18.0	10	1.5	0.014	0.0139	0.0089	0.0001	0.7	-
2.9	20	1.5	0.255	0.259	0.223	0.190	74.5	-
8.0	20	1.5	0.232	0.192	0.145	0.029	12.5	24–27
10.0	20	1.5	0.06	0.06	0.04	0.006	10.0	18–21
15.0	20	1.5	0.04	0.039	0.0158	0.0013	3.25	12
18.0	20	1.5	0.0131	0.0139	0.0067	0.00035	2.67	9–12
2.9	30	1.5	0.251	0.210	0.21	0.181	72.1	None
8.0	30	1.5	0.180	0.131	0.063	0.0096	5.33	-
10.0	30	1.5	0.115	0.104	0.031	0.0001	0.09	6–9
15.0	30	1.5	0.036	0.028	0.004	0.0003	0.83	3–6
18.0	30	1.5	0.014	0.013	0.001	0.0001	0.71	3
			Kaolinite (San Diego) (Fallbrook sl)					
10.4	10	1.55	0.785	0.782	0.78	0.546	69.6	-
10.4	10	1.68	0.306	0.305	0.305	0.028	8.15	15–21
10.4	20	1.43	2.634	2.750	2.56	0.733	27.8	27–30
10.4	20	1.55	0.670	0.695	0.636	0.07	10.4	18–21
10.4	20	1.68	0.416	0.406	0.400	0.005	1.2	9–12
10.4	30	1.43	2.13	2.27	2.10	0.220	10.3	27–30
10.4	30	1.55	0.785	0.784	0.760	0.057	7.8	9–12
10.4	30	1.68	0.122	0.117	0.105	0.001	0.8	6–9
31.2	10	1.50	0.125	0.120	0.110	0.0001	0.1	6–9
31.2	20	1.50	0.126	0.121	0.108	0.0001	0.1	15–18
31.2	30	1.50	0.143	0.130	0.083	0.0001	0.1	3–6
			Kaolinite (N. Carolina)					
10.0	20	1.50	0.0275	0.0275	0.028	0.027	98.2	None
10.0 + 2% Mont.	20	1.50	0.0110	0.010	0.0066	0.0001	0.9	3–6
			Vermiculite (Arlington fsl)					
6.5	10	1.5	0.14	0.130	0.121	0.06	42.9	-
13.0	10	1.5	0.011	0.011	0.00996	0.00197	17.9	-
6.5	20	1.5	0.102	0.089	0.0493	0.0008	0.78	6
13.0	20	1.5	0.011	0.015	0.0051	0.0006	5.45	3
6.5	30	1.5	0.102	0.086	0.0359	0.0005	0.495	6
13.0	30	1.5	0.013	0.013	0.0036	0.0004	3.08	3

† Upon leaching with distilled water relative to HC obtained with $1N$ solution.

described by Banin and Lahave (1968) and Felhendler et al. (1974). The pH and electrical conductivity (EC) of the effluents were determined by standard techniques (U. S. Salinity Laboratory Staff, 1954). The clays in the effluents were identified by X-ray diffraction analysis.

The above HC determinations were made after each soil column had been adjusted to the desired ESP. The columns were first leached with $1N$ NaCl–$CaCl_2$ solution of proper proportion to give sodium adsorption ratios (and approximate ESP's, see Footnote 3) of either 10, 20, or 30. The HC's of the soil columns obtained by using $1N$ solutions were taken as the "base" hydraulic conductivities, K_o. Subsequently, the columns were successively leached with solutions of the same SAR but of decreased salt concentration (0.05, 0.01, and $0.0N$) until new steady-state HC's, (K_i's) and effluent compositions were achieved. Relative HC's (K_{rel}) were calculated as K_i/K_o. The extent of dispersion and pore plugging were ascertained from observed changes in piezometric head along the columns upon change in solution concentration and from amounts of clay appearing in the effluents.

RESULTS AND DISCUSSION

Kaolinitic Soils

The HC of kaolinitic soils was not significantly affected by the ESP (10 to 30% range) as long as the concentration of the leaching solution was at least $0.01N$ (Table 2). However, the HC of the nonacid, kaolinitic soil from California was markedly reduced when leached with distilled water ($0.00N$); the extent of the reduction was approximately the same for all ESP levels. The HC of the acid, kaolinitic soil from North Carolina was not reduced even when leached with distilled water. Reasons for the stability of this soil are discussed later.

Effects of bulk density and clay content on HC were evaluated using the Fallbrook soil. For a given ESP, the HC decreased as bulk density increased (Table 2). However, HC decreased more drastically as clay content increased. Upon leaching with distilled water, the HC of 31% clay, kaolinitic soil was reduced to essentially zero at all ESP's used. The reductions in HC were accompanied by increases in pH, appearance of suspended kaolinitic clay in the effluents, and marked changes in hydraulic gradients along the soil columns. The depths in the soil columns where HC became limiting increased with reductions in clay content and bulk density. This would be expected because smaller pores and increased tortuosity make soils of higher clay content and bulk density more susceptible to

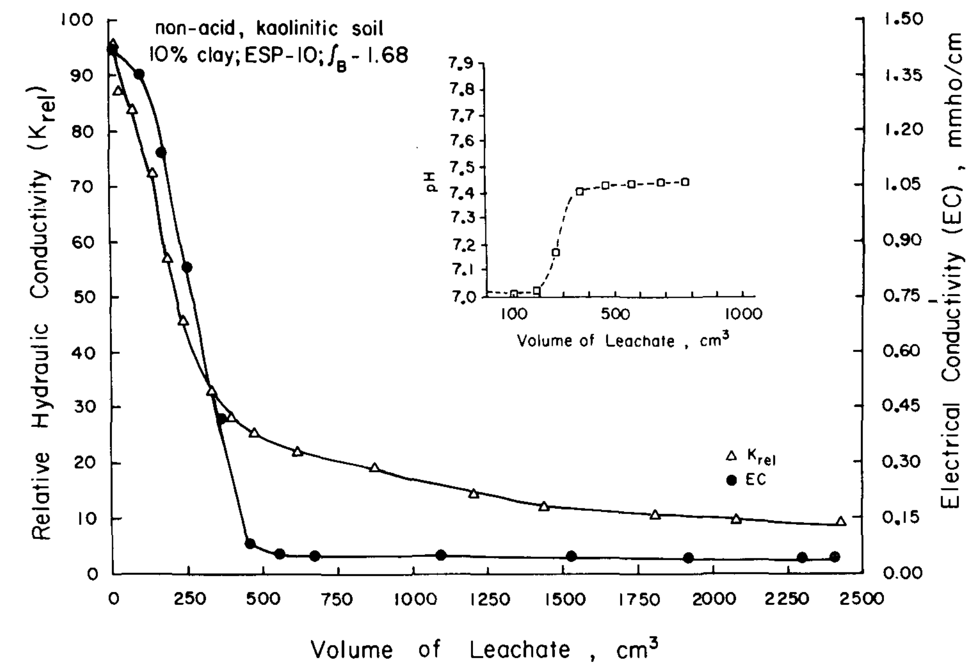

Fig. 2—Relative hydraulic conductivity (K_{rel}), electrical conductivity (EC), and pH changes produced by leaching with pure water Fallbrook (10% clay, ESP-10) soil of bulk density 1.68g/cm³.

blockage and constriction of transmitting pores by lodgement of dispersed particles and by clay swelling.

Our data clearly show that dispersion and subsequent lodging caused the reduction in HC of the nonacid, kaolinitic soils. Additional supportive data are shown in Fig. 2, 3, and 4 for the 10% clay, nonacid kaolinitic soil adjusted to an ESP of 10 and bulk density of 1.68 g/cm³. Reductions in HC started immediately after the distilled water was applied to the soil with 60% of the reduction occurring before 1 pore volume (250 cm³) passed through the column (Fig. 2). The EC of the leachate also decreased drastically, the pH increased, and suspended clay started to appear in the effluent with the breakthrough of the distilled water (Fig. 2 and 3). The almost immediate reduction in HC was due to "plugging" of pore channels with dispersed clay. Evidence of this "plugging" is shown in Fig. 4 where the change in hydraulic (suction) head (ΔH) with volume of leachate is presented. Positive ΔH values represent increases in hydraulic gradient, i.e., decreases in hydraulic conductivity in the segment. Negative ΔH values represent decreases in hydraulic gradient, i.e., increases in hydraulic conductivity in the segment. The data show that HC became restricted at a depth of about 9 cm after 100 cm³ of leaching; with continued leaching (1,000 and 2,500 cm³), HC decreased further and the point of restriction shifted deeper into the column to 18 to 21 cm. Above the

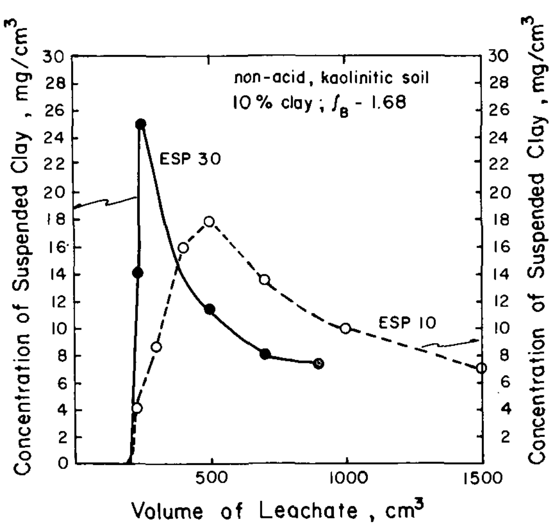

Fig. 3—Concentrations of suspended clay in the effluent produced by leaching with pure water columns of Fallbrook (10% clay, ESP 10 or 30) soil of bulk density 1.68 g/cm³.

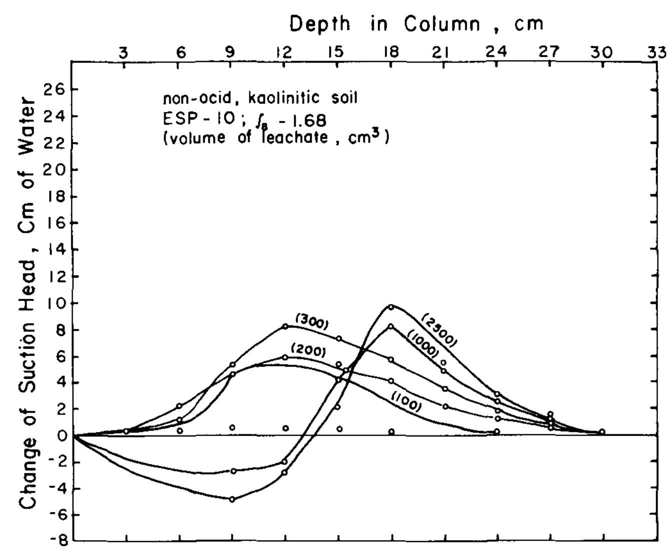

Fig. 4—Changes of suction head produced by leaching with pure water a column of Fallbrook (10% clay, ESP-10) soil of bulk density 1.68 g/cm³.

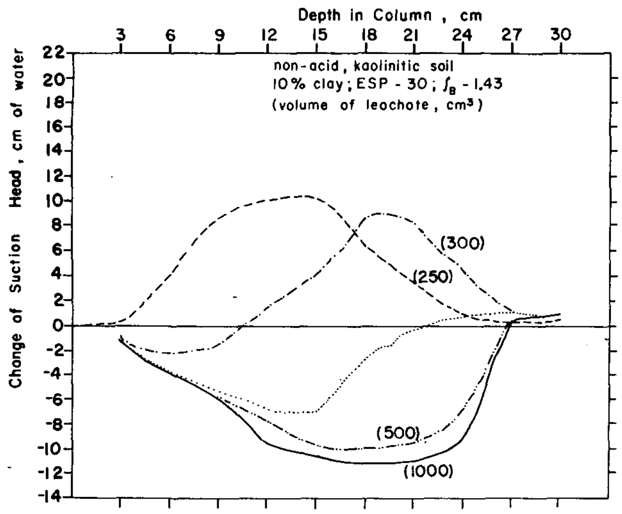

Fig. 5—Changes of suction head produced by leaching with pure water a column of Fallbrook (10% clay, ESP-30) soil of bulk density 1.43 g/cm³.

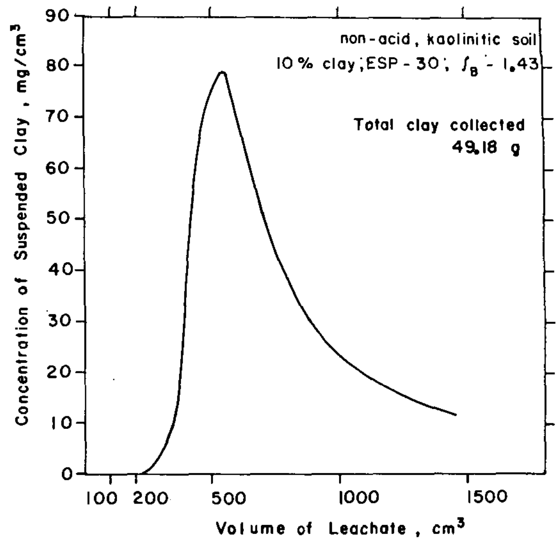

Fig. 6—Concentration of suspended clay in the effluent produced by leaching with distilled water a column of Fallbrook (10% clay, ESP-30) soil of bulk density 1.43 g/cm³.

"plugging" point, the column (Fig. 4) shows an increased HC, since ΔH is negative. We conclude from this that the porosity of this upper section of the soil column was increased by loss of clay (Fig. 3). Results were similar for the ESP 20 and 30 treatments except that positive ΔH values and suspended clay concentrations were greater with the higher ESP treatments and the depth of "plugging" was shallower. The extent of dispersion is relatively less at ESP 10 and, hence, HC is greater than at higher ESP's. For this reason the clay moves farther through the soil pores before plugging occurs. At ESP 30, the dispersion and consequent plugging were so intensive that only a small amount of clay moved through the column (Fig. 3).

With lower bulk density, reduction in HC was less for a given level of exchangeable sodium (Table 2) because the higher flow rates and larger pores allowed the dispersed clay to migrate through the column (Fig. 5 and 6). Given sufficient time, the HC of the column should increase once more since the HC above the plugged section was increased always substantially by clay loss. About 20 and 50% of the total clay in the ESP 20 and 30 columns, respectively, had been removed by the end of the experiment. With increased time or hydraulic head, clay loss would be accentuated and the flow rate should eventually increase. Conceivably, this process might be a cause of the "piping" failures of earthen dams (Frenkel and Rhoades, 1977). The finer textured Fallbrook soil (31.2% clay) provided the necessary conditions for marked reductions in HC with low exchangeable sodium content even though bulk density was low (1.5) (Table 2).

The HC has been frequently found to be less affected by exchangeable sodium in kaolinitic soils than in soils of other clay mineralogy. However, we found the HC of nonacid, kaolinitic soil to be quite affected by exchangeable sodium. A reason for this apparent anomaly stems from the different pH character of the kaolinitic soils studied.

The edges of clay plates, where the tetrahedral silica sheets and the octahedral alumina sheets are disrupted and primary bonds broken, carry a positive double layer in acid solutions with H and Al ions acting as potential-determining ions, and a negative double layer in alkaline solutions, with hydroxyl ions acting as potential-determining ions. Hence, the sign and magnitude of the charge on clay edges are pH dependent. In acidic kaolin aggregates, because of the opposite charge of the edge and face double layers, edge-to-face association occurs (internal mutual flocculation). Aggregates are broken up by reversing the positive-edge charge and creating a negative-edge double layer. This eliminates the positive-edge to negative-face attraction and creates a strong edge-to-edge as well as edge-to-face repulsion. The edge charge of kaolins has been shown to reverse with increasing pH (Schofield and Samson, 1954). Further, the addition of small amounts of montmorillonite to kaolin soils has been shown to promote the dispersion of kaolin flocs. This phenomenon has been ascribed to the breakup of the edge-to-face particle association of kaolin structure by the adsorption of negatively charged montmorillonite particles (faces) on the positively charged kaolin edges.

The difference in the HC of kaolinitic soils seems explainable in view of the above description of particle charges and double-layer properties in kaolins. The kaolinitic soils studied by others have been acidic and contain appreciable amounts of iron oxides. Under such conditions, one would expect their structure to be appreciably stabilized through strong edge-to-face bonds. Because one of the kaolinitic soils that we studied was nonacidic, its edge-to-face bonds would be expected to be weaker and hence more susceptible to disruption. When the electrolyte concentration decreases below about 10 meq/liter, exchangeable sodium is hydrolyzed from kaolin through exchange by H^+ from dissociated water. (Unpublished data of H. Frenkel and D. L. Suarez). This exchange reaction causes an increase in pH of nearly 0.5 unit (as shown in Fig. 2) which in turn promotes the neutralization of positive edge charge, the breakup of the edge-to-face association of

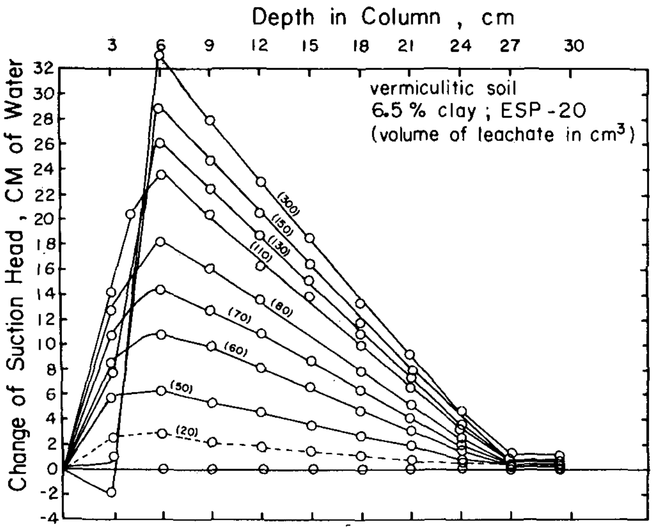

Fig. 7—Changes of suction head produced by leaching with pure water a column of Arlington (6.5% clay, ESP-20) soil.

kaolin structure which was described above and hence dispersion.

To test this concept we measured the HC of an acidic, kaolinitic soil from North Carolina under conditions similar to those used with the Fallbrook soil. The HC (Table 2) of this soil was not reduced by leaching with distilled water in the ESP range 10 to 30, as would be expected for such an acid soil. However, when a small amount of montmorillonitic clay (2% by weight of soil) was added, the HC decreased as the electrolyte concentration was reduced. This was not likely due to dispersion and plugging by the montmorillonite particles per se, because other soils investigated that contained the same amount of montmorillonitic clay did not display this phenomenon (see montmorillonitic soil data of Table 2). We believe that the negatively charged montmorillonite particles were adsorbed on the positively charged edges of the kaolinite particles or associated aluminum hydroxy groupings, thereby disrupting the bonds between positively charged edges and negatively charged cleavage faces of adjacent kaolinite particles and other interparticle bonds. This interaction was demonstrated by Schofield and Samson (1954). The increased pH produced by the hydrolysis of exchangeable sodium from the montmorillonite enhances this reaction. The dispersion and subsequent lodging of these montmorillonite-kaolinite units upon leaching thus produced the observed reductions in HC.

Vermiculitic Soil

The vermiculitic soil used in our studies is the same one used by Rhoades and Ingvalson (1969), who found that in the range of ESP 0 to 20 the Arlington soil did not swell extensively in the electrolyte concentration range of 800-5 meq/liter. We found (see Table 2) appreciable reductions in HC in the ESP range 20 to 30 at an electrolyte concentration of 10 meq/liter, but only negligible reductions at ESP 10. However, upon leaching with distilled water, HC was markedly reduced even at ESP 10. The HC was essentially zero at ESP 20 and 30 for the distilled water leaching treatments. From the curves in Fig. 7, we can see that when leaching with distilled water was begun, clay dispersed in the top of the column and pore channels became plugged at about the 6-cm depth. With further leaching, this deposition of dispersed clay continued, resulting in an HC of essentially zero by the time 125 cm^3 of leachate was collected. The blockage became so effective that little clay actually passed through the column (only 1.6 g of clay with 1,000 cm^3 of leaching). As exchangeable sodium and clay content increased, HC was reduced more and the depth of plugging became shallower. In terms of HC, the vermiculitic and kaolinitic soils behaved similarly.

Montmorillonitic Soils

The HC data obtained with the montmorillonitic soils, which varied in clay content from 2.9 to 18.0% but had a uniform clay mineralogy (consisting of 42% montmorillonite, 29% mica, 16% quartz plus feldspar, and 13% of other species according to McNeal et al., 1968), are given in Table 2. Equivalent reductions in HC occurred at higher salt concentrations with montmorillonitic soils than with kaolinitic soils. Decreases in HC were, of course, magnified with increasing ESP at a given electrolyte concentration. With 15% clay, HC decreased 32% at ESP 10 and 89% at ESP 30 upon leaching with 10 meq/liter, SAR 10 and 30 solutions, respectively; with 18% clay, the corresponding decreases were 32% and 93%, respectively. When leaching solution was changed from 10 meq/liter to distilled water, HC decreased markedly at clay contents greater than 10% at all levels of exchangeable sodium. At lower clay contents, similar reductions occurred only at ESP levels of 20 and 30. The decreases in HC with distilled water leaching were accompanied by the appearance of clay in the effluents except for the soil with 18% clay, which essentially became impermeable.

Appreciable swelling is not expected with these montmorillonitic soils at ESP levels of 20 or less at electrolyte concentrations of about 10 meq/liter, yet HC was observed to be reduced appreciably. Illustrative data for the case of 8% clay and ESP 20 are given in Fig. 8. When leached with 10 meq/liter, SAR 10 solution, the HC dropped to about 65% of the initial value. With distilled water, the HC dropped sharply and clay appeared in the effluent (low light transmission) as the EC decreased. The amount of clay in the effluent at first increased as the EC decreased and then decreased as the column became plugged with dispersed clay. Apparently the same processes of dispersion and pore plugging observed with the kaolinitic and vermiculitic soils occur also in the montmorillonitic soils and cause reductions in HC under conditions where swelling should be negligible. The HC did not increase upon leaching once more with the high electrolyte solution (data not given), as would be expected if swelling and shrinkage of pores were the cause of the reduced HC.

Clay dispersion and plugging also caused the reduced HC in soils of higher clay content and higher ESP (Fig. 9). The appreciable reduction in HC at 10 meq/liter (see Table 2) was accompanied by plugging in the column at the 9-cm

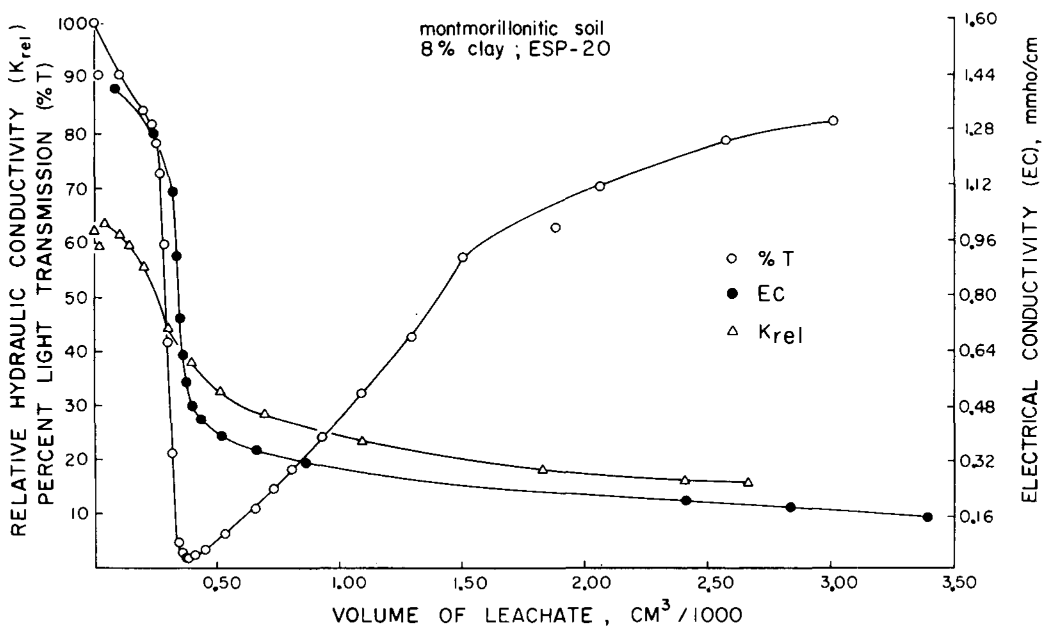

Fig. 8—Relative hydraulic conductivity (K_{rel}), electrical conductivity (EC), and percent light transmission of effluent produced by leaching with pure water montmorillonitic (8% clay, ESP-20) soil.

depth. Suspended clay also appeared in the leachate (data not given). Upon initiation of leaching with distilled water, further clay dispersion and migration occurred in the near-surface soil and blocking formed at a depth of 3-6 cm. As before, the reduced HC could not be overcome by reintroducing high salt solution.

Dispersion appears to be the main cause of reduced permeability of montmorillonitic soils even under conditions of relatively high exchangeable sodium (30%) and high clay content (18%). Dispersion and plugging are intensified with increased ESP and clay content and reduced electrolyte concentration. With very coarse-textured soils (2.9% clay), plugging does not occur because the pores are too large and the water velocity is too fast. However, this phenomenon becomes significant for soils containing 8% clay, with 10% exchangeable sodium, and

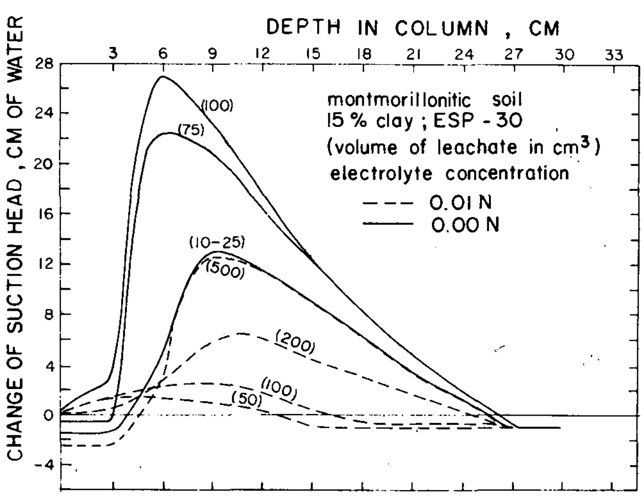

Fig. 9—Changes of suction head produced by leaching a column of montmorillonitic (15% clay, ESP-30) soil with pure water and 0.01N, SAR 30 solution.

an electrolyte concentration of < 10 meq/liter. The electrolyte concentrations at which HC is appreciably reduced (>25%) at ESP's of 10, 20, and 30 are 10, 20, and 30 meq/liter, respectively.

CONCLUSIONS

We have presented data which show that plugging of pores by dispersed clay particles is the major cause of reduced HC in montmorillonitic, vermiculitic, and kaolinitic soils in the range of exchangeable sodium and electrolyte concentration most commonly encountered in soils irrigated with sodic waters of questionable suitability, (SAR's of 10 to 30 and salt concentrations of 0 to 10 meq/liter). The exact levels of exchangeable sodium and electrolyte concentration at which HC is appreciably reduced vary with mineralogy, clay content, and soil bulk density. The sensitivity to excessive exchangeable sodium and low electrolyte concentration increases with clay content and bulk density. The HC of relatively coarse-textured soils with ESP's of 10 or more (clay percentages as low as 8) is also appreciably reduced by dispersion at sufficiently dilute electrolyte concentrations. Although the kaolinitic soil was less sensitive than the montmorillonitic soil at low electrolyte concentrations, its HC was reduced markedly, even at an ESP of 10, when leached with nearly pure water. The effects of ESP, such as would occur during rainfall infiltration, and solution concentration on HC were similar for both montmorillonitic and vermiculitic soils.

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