

EFFECT OF CLAY MINERALOGY AND ALUMINUM AND IRON OXIDES ON THE HYDRAULIC CONDUCTIVITY OF CLAY-SAND MIXTURES¹

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Abstract—Changes in hydraulic conductivity and clay dispersivity of clay-sand mixtures (four reference smectites and Fithian illite) as a function of concentration (0.01 M Cl⁻ and distilled water) and sodium adsorption ratio (SAR ≤ 30) of the percolating solution were measured. In addition, the effect of sand percentage, sand particle size, and addition of AlCl₃ and FeCl₃ on the hydraulic conductivity of the mixtures were measured.

Clay dispersion and migration out of the 3% clay columns was substantial. The clay dispersed only in the distilled water system; dispersion increased with an increase in the percentage of exchangeable Na and was about the same for the Wyoming montmorillonite and Fithian illite. Conversely, the clay swelled in the 0.01 M Cl⁻ solution. The swelling of the montmorillonites increased in the order: Upton, Wyoming = Belle Fourche, South Dakota > Polkville, Mississippi > Otay, California, and was higher than that of the Fithian illite. The swelling and dispersion of the clay accounted for the changes in hydraulic conductivity.

Mixtures treated with FeCl₃ and AlCl₃ were leached with NaCl-CaCl₂ solutions until the pH of the effluent exceeded 6.5. The composition of the exchangeable phase was then determined by the SAR of the leach solutions. At pH > 6.5, the polycations hydrolyzed and were present as the hydroxy-polymer species. The hydraulic conductivity of the mixtures decreased as exchangeable Na increased, but the decrease was less than in untreated mixtures. AlCl₃ was more effective in maintaining hydraulic conductivity than FeCl₃. In montmorillonite clay with an ESP of 20, less than 5% of a complete Al-interlayer was enough to prevent a reduction in hydraulic conductivity. Packets in the clay systems tested explain the high efficiency of the Fe and Al polycations.

Key Words—Aluminum oxide, Exchangeable sodium percentage, Hydraulic conductivity, Illite, Iron oxide, Montmorillonite, Salinity, Sand.

INTRODUCTION

One of the most important properties affecting the suitability of water for irrigation is its sodium content. The deleterious effects of excess sodium on many crops is well known; however, less information is available on the effect of sodium on soil structure, permeability, and hydraulic conductivity. Equally important and equally less well known is the effect of aluminum and iron hydroxides and oxyhydroxides on these same properties. The present paper reports the results of quantitative studies of the effect of sodicity, iron, and aluminum on soil hydraulic conductivity (HC).

Quirk and Schofield (1955) showed that the permeability of a soil decreased with increasing exchangeable sodium percentage (ESP) and decreasing electro-

lyte concentration of the percolate. In addition, clay content (McNeal *et al.*, 1968), clay mineralogy (McNeal and Coleman, 1966; Yaron and Thomas, 1968; Frenkel *et al.*, 1978), sesquioxide content (McNeal *et al.*, 1968), and ion release rate (Shainberg *et al.*, 1981) appear to affect soil response to ESP. McNeal and Coleman (1966), McNeal *et al.* (1968), Felhendler *et al.* (1974), and Frenkel *et al.* (1978) showed that soils respond differently to the same combination of salt concentration and ESP.

McNeal *et al.* (1968) showed that the hydraulic conductivity of soils rich in clay decreased the most when ESP was increased. Conversely, Frenkel *et al.* (1978), Pupisky and Shainberg (1979), and Alperovitch *et al.* (1981) showed that HC decreased most for loamy sand soils leached with distilled water. McNeal and Coleman (1966) and Yaron and Thomas (1968) concluded that the most labile soils were those rich in 2:1 layer silicates, especially montmorillonite, and the least labile were those rich in kaolinite and sesquioxides. Ve-

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Table 1. Sources and properties of the clays used in the study.¹

Mineral ²	CEC ³ (meq/100 g)	S ³ (m ² /g)	Octahedral substitution (atoms/unit cell)		Tetrahedral substitution (atoms/unit cell)
			Mg	Fe	
Smectite, Belle Fourche, South Dakota (API 27)	85	776	0.57	0.36	0.20
Smectite, Upton, Wyoming (API 25)	85	800	0.65	0.32	0.18
Smectite, Polkville, Mississippi (API 21)	105	760	0.90	0.29	
Smectite, Otay, California (API 24)	120	552	1.20	0.11	0.05
Illite, Fithian, Illinois (API 35)	15	120			

¹ Based on Low and Margheim (1979) and Low (1980).

² Obtained from Ward's Natural Science Establishment, Rochester, New York.

³ CEC = cation-exchange capacity; S = specific surface area.

lasco-Molina *et al.* (1971) concluded, however, that in the near absence of electrolytes, the order of soil dispersion at a given ESP was: montmorillonite > halloysite > mica. Similarly, Frenkel *et al.* (1978) concluded that "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."

Several percent Al and Fe hydroxides and oxyhydroxides added to clay have been shown to dominate the surface properties of the clay (Keren, 1980; Oades, 1984; El Rayah and Rowell, 1973). The interactions, however, are always complex because of the tendency of Al and Fe species to hydrolyze, polymerize, and eventually precipitate in the presence of the clays unless low pH is maintained. Oades (1984) found that the addition of 20 mg Al or 60 mg Fe per gram of clay was needed to flocculate Na-exchanged montmorillonite. He also found that Al-polycations were much more efficient than Fe-polycations in blocking negative charges, decreasing water uptake, and swelling of montmorillonite. Thus, Oades (1984) speculated that Al-polycations possess a high positive charge and a planar shape, and that Fe-polycations are spheres (10–100 Å in diameter) with a low positive charge.

Frenkel and Shainberg (1980) reported that the hydroxy-Al polymers formed during the neutralization of Al- and Fe-montmorillonite suspensions by NaOH acted as cementing agents and prevented the dispersion of the structure. Only when the pH exceeded 9.0 and aluminates formed, did complete dispersion of the Na-montmorillonite take place. Conversely, neutralization of Fe-montmorillonite suspensions with NaOH resulted in a gradual breakdown of the Fe-montmorillonite particles. They concluded that the hydroxy-Fe polymers were not as effective as Al-polycations in preventing the dispersion of the particles by adsorbed Na.

Interactions between Fe, Al, and Na appear to affect

aggregate stability. McNeal *et al.* (1968), using a group of soils from Hawaii, found that ESP and electrolyte concentration did not affect HC until Fe- and Al-hydroxides were chemically removed. They concluded that the cementing action of iron oxides prevented swelling and dispersion. Conversely, Deshpande *et al.* (1968) and El Rayah and Rowell (1973) concluded that Al-oxides were more effective than Fe-oxides in stabilizing the soil structure against the dispersive effect of Na. The effects of the two sesquioxides probably depend on their distribution, chemical environment, and ageing history (Carstea *et al.*, 1970). Alperovitch *et al.* (1981) and Shainberg *et al.* (1981) found that a few red-brown loamy soils (Rhodoxerals) from Israel and California were the soils most susceptible to dispersion, in spite of the fact that these soils contained moderate amounts of sesquioxides.

Two sets of experiments are reported here: (1) the effect of clay mineralogy on the saturated HC of clay-sand mixtures equilibrated at different ESPs and leached with solutions of different electrical conductivities; and (2) the effect of AlCl₃ and FeCl₃ on the saturated HC of montmorillonite-sand mixtures equilibrated at different ESPs and leached with solutions of different electrolyte concentration.

MATERIALS AND METHODS

Materials

Experiment 1. Effect of clay mineralogy. Four montmorillonites and one illite from Ward's Natural Science Establishment, Rochester, New York, were selected for this study. Their source and identifying API numbers are given in Table 1 as are the amounts of octahedral substitution and cation-exchange capacities of these clays, as reported by Low and Margheim (1979) and Low (1980).

Clay-sand mixtures were prepared by mixing either 3 g of dry, powdered raw (no pretreatment) clay with

97 g of acid-washed quartz sand (0.59–0.71 mm diameter) or 5 g of clay with 95 g of acid-washed quartz sand (0.1–0.6 mm diameter). Columns of these clay-sand mixtures were prepared by packing 200 g of the 97% sand mixture or 100 g of the 95% sand mixture into 5-cm diameter plastic cylinders to a bulk density of 1.35 g/cm³. The amount of the clay-sand mixtures in the columns was found to have no effect on the hydraulic properties of the mixtures or on clay dispersion. The ratio of sand to clay and the sand size did, however, significantly affect the results. Based on a particle density of 2.65 g/cm³, the pore volumes of the columns containing the 200 g and 100 g mixtures were 72.6 and 36.3 cm³, respectively.

Experiment 2. Effect of sesquioxides. Five grams of powdered Wyoming montmorillonite (API 25) was mixed with 95 g of acid-washed quartz sand (0.1–0.6 mm diameter). The clay-sand mixtures were thoroughly mixed and wetted with 10 ml solutions of 0.1 M, 0.05 M, or 0.025 M AlCl₃ or FeCl₃. In the control treatment, the clay-sand mixture was wetted with 10 ml of distilled water. The mixtures contained 20, 10, or 5 centimole Al/kg clay, or 5.4, 2.7 or 1.35 g Al/kg clay, respectively, and 20, 10, or 5 centimole Fe/kg clay, or 11.2, 5.6, or 2.8 g Fe/kg clay. The highest amount of Al and Fe used in this study was only 20–25% of the amount of the polycation needed to flocculate the clay in Oades' (1984) experiments and less than 5% of the amount needed to cover completely the planar surface of the montmorillonite (Barnhisel, 1977). Following 3 hr of equilibration at room temperature, the wetted mixtures were dried in an oven at 105°C and cooled in a desiccator.

Methods

In both experiments, the saturated hydraulic conductivity of the columns was used to measure the effect of the treatment. Each column was initially wetted from the bottom with 0.5 M Cl⁻ solution with an appropriate sodium adsorption ratio (SAR) and kept saturated. Saturated HC was determined by leaching the column with the solutions using a constant head device and measuring the drainage rate. Effluent was collected incrementally using a fraction collector, and suspended clay contents in the various increments were determined by gravimetric and optical procedures (Shainberg *et al.*, 1981).

SAR solutions of 0, 5, 10, 20, and 30 (experiment 1) and 0, 5, 10, and 20 (experiment 2) were applied. The ESP of the clay in equilibrium with a given SAR solution was assumed to equal the SAR value, and the two indexes of exchangeable Na are used interchangeably (U.S. Salinity Laboratory Staff, 1954). The HCs of the columns obtained using 0.5 M solutions were taken as the "base" HC. Columns were then consecutively leached with 0.05 and 0.01 M Cl⁻ solutions of

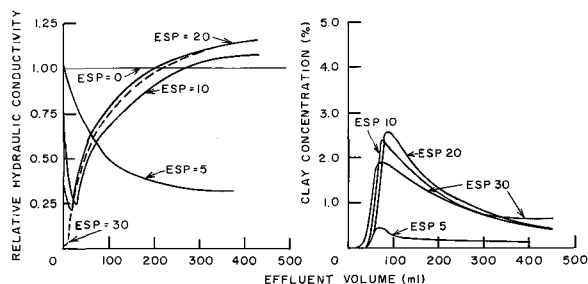


Figure 1. Effect of equilibrium exchangeable sodium percentage (ESP) on relative hydraulic conductivity and clay content in effluent from 3% Wyoming montmorillonite–97% (0.59–0.71 mm diameter) sand mixture leached with distilled water. The y-axis intercept reflects hydraulic conductivity when eluent is changed from 0.01 N Cl⁻ to distilled water.

the treatment SAR until steady state flows and effluent compositions were achieved. About 500 ml of saturating solution was used to achieve the equilibrium soil ESP and solution electrolyte concentration. The final eluent was distilled water. Each treatment was replicated three times, and the agreement between replicates was very good.

RESULTS AND DISCUSSION

The experimental results are shown as curves of "relative hydraulic conductivity" as a function of the mixture ESP and effluent volume. The relative HC is the ratio between treatment HC and the HC of a 0.5 M salt solution. In most of the illustrations, relative HC is presented as a function of the effluent volume for the treatment where distilled water displaces 0.01 M solution. The intercept of each curve is the relative hydraulic conductivity for 0.01 M solutions of the various SAR treatments.

Effect of clay mineralogy

Leaching the 3% montmorillonite–sand mixtures with distilled water clearly showed the effect of the ESP (Figure 1). When distilled water displaced a 0.01 M Cl⁻ solution of CaCl₂ (ESP = 0), no change in the HC of the mixture was noted. When the clay-sand mixture was leached with a 0.01 M Cl⁻ solution having an SAR of 5, the relative HC was maintained at 1.0 (the intercept in Figure 1). The concentration of electrolytes in this solution was enough to prevent the deleterious effect of Na⁺ at this low ESP. Leaching the ESP-5 mixture with distilled water caused a gradual HC drop, and some clay appeared in the effluent. The maximum clay concentration in the effluent at this ESP was 0.45% (w/v) at 1.0 pore volume of leachate.

As the ESP of the clay increased, the relative HC of the mixtures leached with 0.01 M Cl⁻ solutions (the y-intercepts in Figure 1) decreased. The change in relative HC between an ESP of 0 and 10 was minimal (15%), compared to the change between ESPs of 10

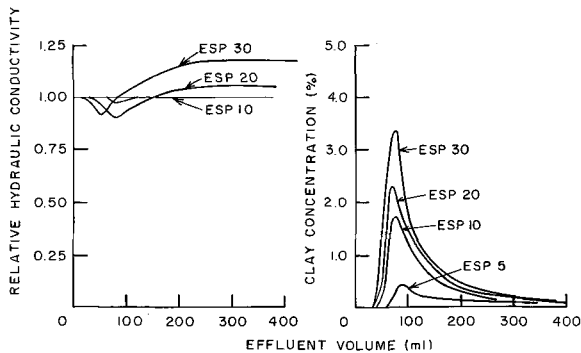


Figure 2. Effect of equilibrium exchangeable sodium percentage (ESP) on relative hydraulic conductivity and clay content in effluent from 3% illite–97% (0.59–0.71 mm diameter) sand mixture. The y-axis intercept reflects hydraulic conductivity when eluent is changed from 0.01 N Cl^- to distilled water.

and 20 (a further drop of 50%). The decrease in HC in 0.01 M Cl^- solutions was suggested by Shainberg *et al.* (1981) and Shainberg and Letey (1984) to be due to clay swelling, which reduces pore diameters. Montmorillonite dispersion was not expected at this electrolyte concentration, which is well above the flocculation value of the clay (Oster *et al.*, 1980). Introducing 10% Na into the exchange complex of the clay increased the swelling of the clay only slightly. Swelling of the clay increased markedly as the ESP was increased above 10%. Similar observations were made by McNeal and Coleman (1966) and Shainberg and Letey (1984), who also found that replacing about 15% of the adsorbed Ca with Na had little effect on the swelling of the clay, but that a further increase in the ESP caused a sharp increase in swelling for montmorillonitic soils.

When the 0.01 M Cl^- solutions of SARs of 10, 20, and 30 were replaced by distilled water, the relative HC of the mixture dropped sharply to less than 25%, followed by a sharp increase (Figure 1). Also, the concentration of clay in the effluent peaked at about one pore volume before slowly dropping (Figure 1). The maximum clay concentration and the shape of the clay concentration–effluent curves seemed not to be greatly affected by the soil ESP. Similar HC and clay concentration curves were reported for sandy soils by Frenkel *et al.* (1978) and Pupisky and Shainberg (1979). The high clay percentage in the effluent indicated that dispersion and long-distance movement of the clay particles had taken place. Deposition of the clay particles in pore spaces led to the sharp drop in the HC values. The subsequent increase in the HC was explained by Pupisky and Shainberg (1979) as due to a change in the mechanism of flow. As the clay dispersed in the distilled water, the flow changed from flow of solution in a sandy clay matrix where the sand particles are covered with a skin of clay, to flow of suspension in a pure sand matrix. Removing the clay skin from the

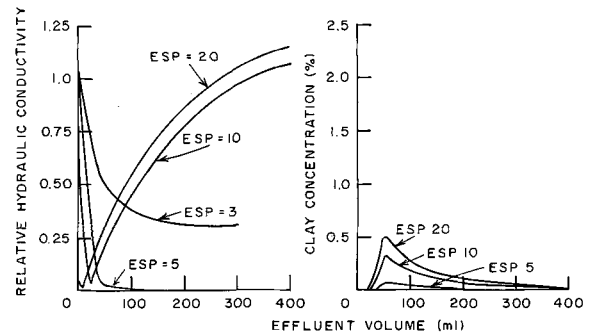


Figure 3. Effect of equilibrium exchangeable sodium percentage (ESP) on relative hydraulic conductivity and clay content in effluent from 5% montmorillonite–95% (0.1–0.6 mm diameter) sand mixture. The y-axis intercept reflects hydraulic conductivity when eluent is changed from 0.01 N Cl^- to distilled water.

sand particles increases both the pore radii and the HC. With further leaching the increase in pore radii resulted in relative HC greater than 1.0 (Figure 1).

The HC and clay concentration curves of the mixture with an ESP of 10 are of special interest. Whereas in 0.01 M Cl^- solution, the mixture with an ESP of 10 behaved in a way similar to one with an ESP of 0 (pure Ca system), when leached with distilled water it behaved like a clay–sand mixture with an ESP of 20 and 30. When the swelling mechanism was the predominant mechanism for the HC decrease, the mixture with an ESP of 10 behaved like the clay having an ESP of 0. When distilled water displaced the solution, however, 10% Na was enough to disperse the clay (Oster *et al.*, 1980), and the clay–sand mixture behaved like the mixtures having higher ESPs.

It is evident from Figure 1 that ESPs as low as 5 are sufficient to disperse the clay and to cause considerable HC changes. Demixing of the cations in a Na/Ca–montmorillonite (Oster *et al.*, 1980) accounts for the high “efficiency” of exchangeable sodium in dispersing the clay.

In a 3% illite–sand mixture (0.59–0.71 mm sand), as long as the electrolyte concentration in the leaching solutions exceeded 0.01 M Cl^- , no change in the HC and no clay dispersion were observed (Figure 2), presumably because illite is a non-expandable clay. Only slight changes in the HC were observed when the illite–sand mixture was leached with distilled water (Figure 2). Conversely, the concentration of clay in the effluent of a Na–illite–sand mixture was high, exceeding that of montmorillonite with an ESP of 30 (Figure 1).

It is evident that illite is more dispersible than montmorillonite. Oster *et al.* (1980) arrived at a similar conclusion based on the flocculation values of illite and montmorillonite. They found that a higher electrolyte concentration was needed to flocculate illite saturated with a given Na/Ca ratio than montmorillonite and

Table 2. Relative saturated hydraulic conductivity of clay-sand mixtures mixed with various amounts of sesquioxides as a function of the mixture's exchangeable sodium percentage and the interclay electrolyte concentration.

Concentration (M Cl ⁻)	ESP 10 ¹				ESP 20			
	0	5	10	20	0	5	10	20
Al (centimole/kg clay)								
0.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.05	1.00	1.00	1.00	1.00	0.50	0.70	0.92	0.92
0.01	0.70	0.82	0.92	0.94	0.05	0.10	0.73	0.88
Distilled water	2	2	0.22	0.44	2	2	0 ³	0.11
Fe (centimole/kg clay)								
0.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.05	1.00	1.00	1.00	1.00	0.50	0.50	0.70	0.92
0.01	0.70	0.70	0.75	0.80	0.05	0.05	0.10	0.46
Distilled water	4	4	0 ³	0.10	4	0 ³	0 ³	0 ³

¹ ESP = exchangeable sodium percentage.

² See Figure 6.

³ Hydraulic conductivity too slow to measure accurately.

⁴ See Figure 7.

suggested that the high dispersivity of illite is due to a "bad" contact between the terraced planar surfaces of illite and its edges. This observation suggests that illitic soils are more sensitive to dispersion and clay movement than soils containing montmorillonite clays.

The effect of ESP on illite clay dispersion was more pronounced than for montmorillonite. With an increase in ESP, the peak clay concentration increased (Figure 2). In montmorillonite-sand mixtures, the effect of higher ESP on increasing peak clay concentration was not evident. Apparently, in the montmorillonite mixture the increase in swelling caused by exchangeable Na narrowed the pores enough to inhibit clay dispersion and movement. Thus, an increase in clay dispersion and movement was offset by the increase in swelling and the decrease in space for the clay movement. Dispersing the clay skin from the sand particles in the illite-sand mixtures increased the pore radii and raised the relative HC to >1.0 (Figure 2).

Experiment 1 was repeated using a mixture of 5% Wyoming montmorillonite and 95% 0.1–0.6-mm quartz sand (Figure 3) because the 3% clay-sand mixture appeared to accelerate clay movement. The higher clay percentage and smaller sand size increased clay swelling, produced a larger decrease in HC, and decreased the amount of clay in the effluent (Figures 1 and 3). The results from the 3% clay mixtures were more variable and the effects of clay swelling and dispersion less apparent compared to the 5% clay mixtures. For these reasons, the remaining experiments were made on columns packed with the 5% clay–95% 0.1–0.6-mm quartz sand mixture.

The relative saturated HC of 5% montmorillonite-sand mixtures, mixed with various amounts of sesquioxides as a function of the mixture's ESP and the interclay electrolyte concentration is presented in Ta-

ble 2. Only the interaction between ESP and electrolyte concentration is discussed here; the effect of sesquioxides is discussed below under experiment 2.

Swelling of the clay is the dominant mechanism affecting the HC of the mixtures at concentrations >0.01 M Cl⁻. An ESP of 10 was insufficient to reduce the HC of the mixture in equilibrium with 0.05 M Cl⁻ solutions. A combination of the same electrolyte concentration and an ESP of 20 resulted in a 50% decrease in the relative HC. For the mixture in equilibrium with a solution concentration of 0.01 M Cl⁻, the relative HC dropped to 70% and 5% for mixtures with ESPs of 10 and 20, respectively. Most of the changes in swelling apparently took place between ESPs of 10 and 20. At ESPs below 10, most of the exchangeable Na concentrated on the external surfaces of the clay tactoids, without increasing the fraction of the surface area that could swell (Oster *et al.*, 1980). As the ESP of the clay was increased from 10 to 20, exchangeable Na penetrated into the internal surfaces of the packets, increasing the fraction of the surfaces which swelled (Table 2).

Clay mineralogy affected the HC of the clay-sand mixtures (Figure 4). Little clay was observed in the effluent because the matrix prevented clay migration (data not presented). The effect of clay swelling on the relative HC of the mixture was evaluated from the y-axis intercepts. The order of the change in relative HC was Wyoming = Belle Fourche ≫ Polkville > Otay montmorillonites > Fithian illite. The swelling of the smectites from Polkville and Otay and the illite was not enough to change the HC of the mixtures saturated with an ESP of 10; however, the differences between these minerals was evident when the mixtures were equilibrated with SAR-20 solutions. This order of swelling is similar to that reported by Low and Marg-

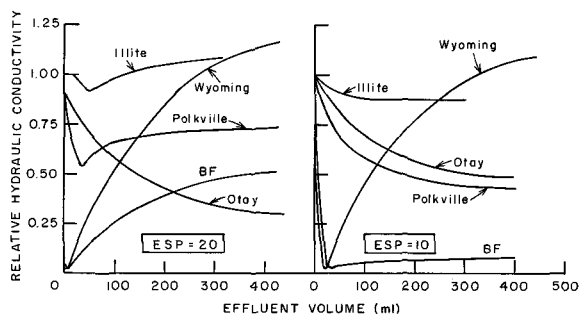


Figure 4. Effect of equilibrium exchangeable sodium percentage (ESP) on relative hydraulic conductivity of smectite-sand and illite-sand mixtures (5% clay and 95% 0.1–0.6 mm diameter sand).

heim (1979). The swelling of the smectites depended mainly on the fraction of the clay that expanded, as reflected by its specific surface area (Table 1). The specific surface area of the clay depends also on the surface charge density and the *b*-dimension of the clay (Low and Margheim, 1979). Both the *b*-dimension and the charge density increased with an increase in the ionic substitution in the octahedral layer of clay structure, and both affected also the fraction of the clay that expanded. Smectite clays with higher charge density appeared to have lower specific surface areas and swelling, and should less affect the HC of soils leached with electrolyte solutions (Table 1 and Figure 4).

The HC of the various clay-sand mixtures varied markedly when they were leached with distilled water. In illite-sand mixtures, the change in HC with leaching was small; illite dispersed when the Na was introduced, but the lack of swelling enabled the dispersed clay particles to move through the matrix without affecting the HC. At the other extreme was the Wyoming montmorillonite; its low charge density allowed it to swell the most, which caused large changes in HC. In addition, this clay dispersed readily. Its high dispersion and the change in the mechanism of flow from solution flow in clay-sand mixtures to suspension flow in a sand matrix (Pupisky and Shainberg, 1979) was a consequence of the increased HC.

The montmorillonites from Belle Fourche and Wyoming showed similar swelling, but different dispersion properties. The Belle Fourche montmorillonite dispersed less than the Wyoming montmorillonite; thus, the change in the mechanism of flow found for the Wyoming clay at an ESP of 10, was not observed for the Belle Fourche clay. The swelling and limited dispersion of the Belle Fourche clay resulted in a very low relative HC at an ESP of 10. At an ESP of 20, an increase in clay dispersion produced an HC increase as it did for the Wyoming montmorillonite at an ESP of 10.

The Otay and Polkville montmorillonites were intermediate in their swelling and dispersion character-

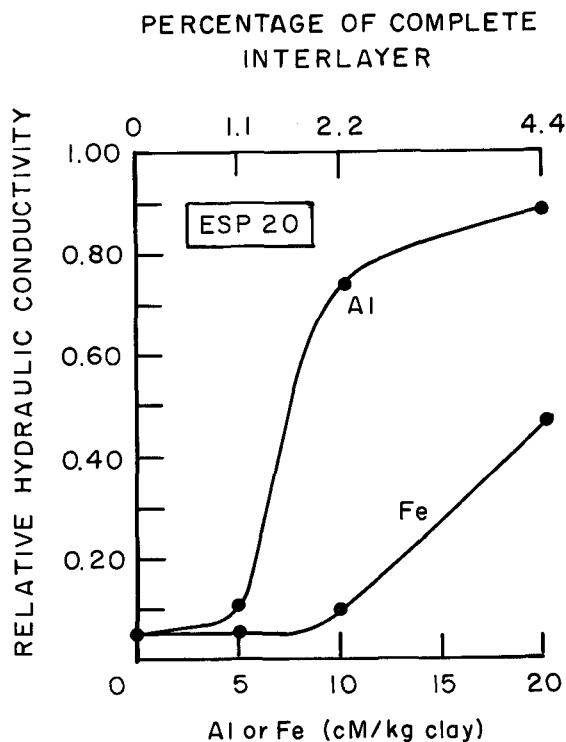


Figure 5. Effect of Al and Fe (in centimole/kg clay and percentage of complete interlayer) on relative hydraulic conductivity of montmorillonite-sand mixtures in equilibrium with 0.01 M Cl^- solution of exchangeable sodium percentage of 20.

istics between the illite and the Wyoming montmorillonite. Otay montmorillonite, with the highest charge density among the smectites examined, swelled the least, and the change in the HC curve was minimal. The limited dispersion was insufficient to change the mechanism of flow, and its HC dropped gradually to the observed final values. The Polkville clay swelled slightly more than the Otay montmorillonite, and its HC curve was below that of the Otay clay at an ESP of 10. The Polkville clay dispersed slightly more than the Otay clay; thus, at an ESP of 20 its HC curve first dropped and then increased in a manner similar to that of the Wyoming and Belle Fourche montmorillonites.

Effect of sesquioxides

The effect of the sesquioxides in countering the effect of ESP on HC response of the clay-sand mixtures equilibrated with electrolyte solutions is presented in Table 2. Sesquioxides decreased the swelling of the montmorillonite and prevented a drop in the HC of the mixtures. Similar effects of Al and Fe on the swelling of Na-montmorillonite were reported by El-Rayah and Rowell (1973) and Oades (1984). Al was also more effective than Fe in reducing clay swelling. The relative effect of the two polycations in preventing clay swelling

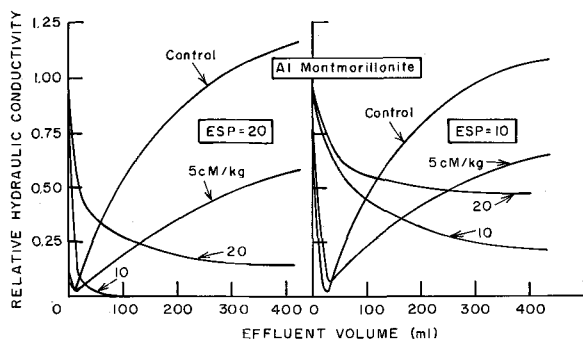


Figure 6. Effect of Al (centimole Al/kg clay) on hydraulic conductivity of sodic montmorillonite-sand mixtures.

is shown in Figure 5 along with their effect on the relative HC of the clay-sand mixtures with an ESP of 20 equilibrated with 0.01 M Cl^- solutions.

A complete interlayer of $\text{Al}(\text{OH})_3$ or $\text{Fe}(\text{OH})_3$ contains 4.5 mole Al/kg montmorillonite (Barnhisel, 1977). In a montmorillonite with an ESP of 20, less than 5% interlayer Al was needed to prevent swelling (Figure 5). In this system (ESP of 20), the amount of Al needed to prevent swelling and dispersion was $\sim 20\%$ of the amount needed for pure Na-montmorillonite (Oades, 1984). The high efficiency of hydroxy-Al in preventing swelling in this system is probably due to the fact that hydroxy-Al polymers interacted only with the external surfaces of the montmorillonite packets to form larger aggregates (Keren, 1980). Montmorillonite platelets with an ESP of 20 exist in packets with ~ 5 platelets in each packet and thus have limited ($\sim 20\%$) expandable surfaces (Oster *et al.*, 1980).

Fe-hydroxide was less effective in preventing the swelling of Na/Ca-montmorillonite. The spherical shape of the polymers and their low charge (Oades, 1984) reduced their ability to control the swelling.

The effect of Al on the relative HC of the clay-sand mixtures when the 0.01 M Cl^- solutions were displaced with distilled water is presented in Figure 6. For the mixture with an ESP of 20 without Al (control), HC dropped slightly at first and increased sharply thereafter. Clay dispersion and the change in the mechanism of flow (from flow of solution in a clay-sand matrix to flow of suspension in a sandy matrix) are responsible for this result. Introducing 0.05 moles of Al/kg clay into the clay mixture had only a slight effect compared with the control on both swelling and clay dispersion (Figure 6) because the amount of Al was only 1.1% of the interlayer and, thus, its effectiveness was limited. When 0.10 moles of the polycation per kg of clay was present, the relative HC of the mixture (ESP of 20) in 0.01 M Cl^- solution was 73% of the base value. Thus, 2.2% of the polycation was sufficient to prevent most of the swelling of the clay. When the clays were leached with distilled water, the HC dropped to nearly zero,

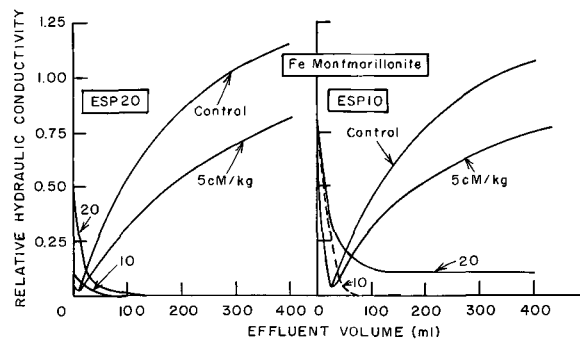


Figure 7. Effect of Fe (centimole Fe/kg clay) on hydraulic conductivity of sodic montmorillonite-sand mixtures.

indicating that sufficient dispersion, movement, and precipitation of the clay particles in the conducting pores took place to seal the clay-sand mixture completely. Preventing intensive clay dispersion also prevented an increase of the HC of the mixture, as was observed in the control and the 0.05 mole Al/kg treatments. When more Al was introduced (0.20 mole/kg clay), the swelling and dispersion of the clay were so slight that the column was not sealed, and the relative HC dropped gradually to 0.11 of the base value.

The HC curves of the mixture with an ESP of 10 are similar to those of the mixture with an ESP of 20 (Figure 6). Here, again 0.05 mole Al/kg clay was insufficient to prevent clay swelling and dispersion, and the HC curve was similar to that of the control. Conversely, 0.10 and 0.20 mole Al/kg clay decreased clay swelling and prevented clay dispersion. Thus, no clay was found in the effluent, and the relative HC curves dropped gradually to the final values determined by the degree of swelling of the clay. It is evident that a concentration of 0.20 mole Al/kg was more effective than one of 0.10 mole Al/kg in preventing clay swelling (Figure 6), and that the clay swelling increased in all Al treatments along with the ESP of the clay (Figure 6).

The effect of Fe on the HC curves of sodic clay-sand mixtures leached with distilled water (Figure 7) was quite similar to that of Al. The HC (Figure 7) and clay concentration in the effluent (not shown) were higher in the 0.05 mole Fe/kg clay system than for the corresponding Al treatments. At the two ESPs, the HC curves for the 0.05 mole Fe/kg clay treatment were between that of the Al and control curves. In the mixture with an ESP of 10, the final relative HC values in the 0.10 and 0.20 mole Fe/kg clay were near 0 and 0.10 compared to 0.22 and 0.44 for 0.10 and 0.20 mole Al/kg clay treatment. Similarly, in the mixture with an ESP of 20, concentrations of 0.10 and 0.20 mole M/kg Fe were insufficient to prevent sealing, whereas one of 0.20 mole Al/kg clay prevented sealing of the clay-sand mixture.

CONCLUSIONS

The effect of clay mineralogy on the response of clay-sand mixtures to sodic and saline conditions suggests that the mineralogy of the clay fraction in soils affected by sodium should be studied quantitatively. It is evident that in soil studies not only should the percentage of smectite be determined, but, if possible, the charge density of the smectites as well. Smectites with low charge density swell more than smectites with high charge density. The response of soils to sodic and saline conditions is affected by both the swelling and the dispersion of the clay particles; however, much less work has been devoted to the dispersion of the various clays. The importance and the contribution of each of these mechanisms to the hydraulic properties of soils depend on the ESP of the soil and the electrolyte concentration of the soil solution.

The interaction of Al and Fe polycations with montmorillonite affected both the swelling and the dispersion of the clay. Whereas exchangeable Na increased clay swelling and clay dispersion, Al and Fe polymers prevented swelling and dispersion. The hydroxy polymers with their positive charge cemented the clay platelets. The amount of Al and Fe polycations needed to prevent clay swelling depended on the ESP of the clay and the resultant external surface. Al polycations, which are planar and carry a higher charge per gram atom, were more efficient in cementing clay platelets than Fe polycations, which are spheres with low charge density.

Hydroxy-Al and hydroxy-Fe interlayers are abundant in soils, and their effect on soil structure is important not only under the extreme conditions of soils with high ESPs but also in soils with low sodium content. A systematic study of their effect on soil structure and aggregate stability is overdue.

REFERENCES

- Alperovitch, N., Shainberg, I., and Keren, R. (1981) Specific effect of magnesium on the hydraulic conductivity of sodic soils: *J. Soil Sci.* **32**, 543–554.
- Barnhisel, R. I. (1977) Chlorites and hydroxy interlayered vermiculite and smectite: in *Minerals in Soil Environment*, J. B. Dixon and S. B. Weed, eds., Soil Sci. Soc. Amer., Madison, Wisconsin, 331–356.
- Carstea, D. D., Harward, M. E., and Knox, E. G. (1970) Comparison of Fe and Al hydroxy interlayers in montmorillonite and vermiculite: I. Formation: *Soil Sci. Soc. Amer. Proc.* **34**, 517–521.
- Deshpande, T. L., Greenland, D. J., and Quirk, J. P. (1968) Changes in soil properties associated with the removal of iron and aluminum oxides: *J. Soil Sci.* **19**, 108–122.
- El Rayah, H. M. E. and Rowell, D. L. (1973) The influence of Fe and Al hydroxides on the swelling of montmorillonite and the permeability of a Na-soil: *J. Soil Sci.* **24**, 137–144.
- Felhendler, R., Shainberg, I., and Frenkel, H. (1974) Dispersion and hydraulic conductivity of soils in mixed solution: in *Trans. 10th Int. Congr. Soil Sci., 1974, Moscow*, Nauka Publ. House, Moscow, 103–112.
- Frenkel, H., Goertzen, J. O., and Rhoades, J. D. (1978) Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity: *Soil Sci. Soc. Amer. J.* **42**, 32–39.
- Frenkel, H. and Shainberg, I. (1980) The effect of hydroxy Al and Fe polymers on montmorillonite particle size: *Soil Sci. Soc. Amer.* **44**, 624–628.
- Keren, R. (1980) Effects of titration rate, pH and drying process on cation exchange capacity reduction and aggregate size distribution of montmorillonite hydroxy-Al complexes: *Soil Sci. Soc. Amer. J.* **44**, 1209–1212.
- Low, P. F. (1980) The swelling of clay: II. Montmorillonites. *Soil Sci. Soc. Amer. J.* **44**, 667–676.
- Low, P. F. and Margheim, J. F. (1979) The swelling of clay: basic concepts and empirical equations: *Soil Sci. Soc. Amer. J.* **43**, 473–481.
- McNeal, B. L. and Coleman, N. T. (1966) Effect of solution composition on soil hydraulic conductivity: *Soil Sci. Soc. Amer. Proc.* **30**, 308–312.
- McNeal, B. L., Layfield, D. A., Norvell, W. A., and Rhoades, J. D. (1968) Factors influencing hydraulic conductivity of soils in the presence of mixed-salt solutions: *Soil Sci. Soc. Amer. Proc.* **32**, 187–190.
- Oades, J. M. (1984) Interactions of polycations of Al and Fe with clays: *Clays & Clay Minerals* **32**, 49–57.
- Oster, J. D., Shainberg, I., and Wood, J. D. (1980) Flocculation value and gel structure of Na/Ca montmorillonite and illite suspension: *Soil Sci. Soc. Amer. J.* **44**, 955–959.
- Pupisky, H. and Shainberg, I. (1979) Salt effects on the hydraulic conductivity of a sandy soil: *Soil Sci. Soc. Amer. J.* **43**, 429–433.
- Quirk, J. P. and Schofield, R. K. (1955) The effect of electrolyte concentration on soil permeability: *J. Soil Sci.* **6**, 163–178.
- Rhoades, J. D. (1972) Quality of water for irrigation: *Soil Sci.* **113**, 277–284.
- Shainberg, I. and Letey, J. (1984) Response of soils to sodic and saline conditions: *Hilgardia* **52**, 1–57.
- Shainberg, I., Rhoades, J. D., and Prather, R. J. (1981) Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil: *Soil Sci. Soc. Amer. J.* **45**, 273–277.
- U.S. Salinity Laboratory Staff (1954) Diagnosis and improvement of saline and alkali soils: *U.S. Dept. Agric. Handbk.* **60**, 160 pp.
- Velasco-Molina, H. A., Swoboda, R., and Godfrey, C. L. (1971) Dispersion of soils of different mineralogy in relation to sodium adsorption ratio and electrolyte concentration. *Soil Sci.* **111**, 282–287.
- Yaron, B. and Thomas, G. W. (1968) Soil hydraulic conductivity as affected by sodic water: *Water Resources Res.* **4**, 545–552.

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