

Effect of Low Electrolyte Concentration on Clay Dispersion and Hydraulic Conductivity of a Sodic Soil¹

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ABSTRACT

The changes in hydraulic conductivity and clay dispersivity of a Fallbrook soil (fine-loamy, mixed, thermic Typic Haploxeralfs) as a function of concentration (≤ 3 meq/liter) and Na adsorption ratio (≤ 30) of the percolating solutions were measured. Both phenomena were very sensitive to the level of exchangeable Na and to salt concentration of the soil solution. When the salt concentration is 3.0 meq/liter, the hydraulic conductivity and clay dispersion decrease if the exchangeable sodium percentage (ESP) values exceed 12. Conversely, in distilled water, clay dispersion and hydraulic conductivity decrease at ESP values as low as 1 to 2%. We hypothesize that mineral soils, which readily release salt during leaching with distilled water, will not be susceptible to exchangeable Na $< 10\%$. Conversely, mineral soils with low rates of mineral dissolution, like the Fallbrook soil, should be susceptible even at lower ESP values. Also, surface soils, when leached with rainwater, will be especially susceptible at such low levels of exchangeable Na.

Additional Index Words: clay swelling.

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ONE OF THE MAJOR FACTORS affecting the suitability of a water for irrigation is its sodicity hazard. We have useful criteria to predict the steady state exchangeable sodium percentage (ESP) of a soil that will result from irrigating with the water. However, we do not have criteria as reliable for predicting how the water and the resulting ESP of the soil will affect soil structure and soil hydraulic conductivity (HC) (Rhoades, 1972). For example, Felhendler et al. (1974) measured the HC of two montmorillonitic soils (a sandy loam and a silty loam) as a function of the sodium adsorption ratio³ (SAR) and salt concentration of the percolating solution and found that both soils were only slightly affected by the SAR of the percolating solution up to SAR 20 as long as the concentration of the percolating solution exceeded 10 meq/liter. However, when the percolating salt solution was replaced by distilled water, simulating rainfall, the response of the two soils differed drastically. The HC of the silty soil dropped to 42 and 18% of the initial value for soils with ESP values of 10 and 20, respectively. The HC of the sandy loam soil dropped to 5 and 0% of the initial value for the same conditions, respectively. To explain these results, Felhendler et al. (1974) proposed that the variable HC response of soils to sodic conditions depends on the

potential of their clays to disperse. The clay in the sandy loam soil, which is very sensitive to sodic conditions, dispersed and appeared in the leachate of the column. Conversely, the clay in the silty loam soil did not disperse, nor did its HC change so drastically upon leaching with distilled water. The importance of dispersion in affecting soil permeability has also been observed by Rhoades and Ingvalson (1969), who concluded that dispersion rather than swelling was the operative process that decreases permeability in vermiculitic soils. Similarly, Frenkel et al. (1978) concluded that plugging of the soil pores by dispersed clay particles is the major cause of reduced HC in montmorillonitic, vermiculitic, and kaolinitic soils in the range of $ESP < 20$.

In spite of the importance of dispersion in reducing the permeability of sodic soils, no adequate hypothesis is available that explains why some soils are more susceptible to clay dispersion than others when leached with distilled water. This is an important problem, because under many semiarid conditions where irrigation is practiced, the irrigation season is followed by a rainy season and vice versa. During the irrigation season, the salt concentration of the irrigation water is usually high enough to prevent the deterioration of the soil physical properties. However, when the irrigation water is displaced with rain water, the upper profile soil water is diluted, increasing the likelihood of deterioration of the soil physical properties. Dispersion of soil clays is very sensitive to salt concentration of the pore water. van Olphen (1977) reported that the flocculation value of Ca-montmorillonite is 0.17 to 0.23 meq/liter and that Na-montmorillonite is 12 to 16 meq/liter. The flocculation values of the montmorillonite clays saturated with mixtures of the two cations increase rapidly with the initial increments of exchangeable Na to values of 3 and 6 meq/liter for ESP's of 10 and 20, respectively (Oster et al., 1980). Thus, we hypothesized that soils that release salt at a rate sufficient to maintain the soil solution concentration above the flocculation value of the clay at its given ESP level will not disperse, and the HC of these soils will be affected only slightly by rainfall. Conversely, soils that do not release salt upon leaching with rain water will disperse, and the HC will be very sensitive to the ESP of the soil.

Exchangeable cations and those contained in the crystal structure are released from soil minerals as a result of hydrolysis and weathering. Rhoades in a series of papers (Rhoades et al., 1968) stressed the importance of soil mineral weathering reactions in offsetting the sodicity hazard of certain types of irrigation waters and the need to consider this phenomenon in water suitability evaluations. Rhoades showed that arid land soils release appreciable amounts of Ca and Mg to the solution (typically increasing the concentration by 3-5 meq/liter) and concluded that the dissolution of plagioclase feldspars, hornblende, and other common mafic minerals accounted for the salt release (Rhoades, 1968, 1972; Rhoades et al., 1968).

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³ $SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{1/2}$, where all concentrations are in meq/liter. SAR and ESP are approximately numerically equivalent for most arid land soils at values of less than 30 (U.S. Salinity Laboratory Staff, 1954).

In a more recent study, the dissolution rate of three arid zone soils has been investigated in detail (Oster and Shainberg, 1979). They found that the release of Ca^{2+} , Mg^{2+} , and K^+ from silicate minerals and the hydrolysis of exchangeable Na^+ and Ca^{2+} varied greatly among the three soils. They demonstrated that when salt-free soils were mixed with distilled water (ratio 1:5), the release of salts was rapid enough to increase soil solution concentrations from 0.5 to 4.0 meq/liter within 4 hours. The mechanism and rate of the dissolution of montmorillonite clays have been studied in greater detail than have those of soil primary minerals (Barshad, 1960; Shainberg, 1973; and Frenkel and Suarez, 1977). The dissolution of soil clays may also contribute to salt release.

The objectives of this and the subsequent paper of Shainberg et al. (1981) are to: (i) stress the importance of rainfall produced structural deterioration in evaluating sodicity hazards of irrigation water; (ii) suggest and test the hypothesis that an important factor causing different sodic soils, similar in such properties as texture and clay mineralogy, to differ in their response to exchangeable Na upon leaching with distilled or very dilute waters is their differences in ability to release salts by mineral weathering; and (iii) show that soils that can maintain soil water concentration in excess of the flocculation values of their clay minerals will remain undispersed upon leaching with rainwater.

MATERIALS AND METHODS

A soil that does not readily release soluble salts is required for study of the effect of very dilute salt concentrations on clay dispersion in soils. We used Fallbrook soil (fine-loamy, mixed, thermic Typic Haploxeralfs), which satisfies this requirement (Frenkel et al., 1978). In a preliminary study, a sample of this soil (B horizon) was extracted twice with distilled water (mixture of 1:5, soil/water) to remove excess salt by shaking for 1 hour and subsequently shaking continuously with distilled water using a reciprocation shaker (50–100 cycles/min); the electrical conductivity of the suspension was measured periodically. Within 4 hours the electrical conductivity of the suspension increased from 15 to 30 $\mu\text{mho/cm}$ and thereafter changed linearly with time at the rate of 1 to 2 $\mu\text{mho/cm}$ per hour. This represents a relatively slow rate of salt release (e.g., see the rates presented by Oster and Shainberg, 1979) as required for the purposes of this experiment. The clay and silt percentages of the Fallbrook soil are 16.2 and 12.5%, respectively, and its cation exchange capacity (CEC) is 13.0 meq/100 g. To maintain high flow rate during HC studies, the soil (< 2-mm fraction) was mixed with quartz sand in a ratio of 1:1. Thus the clay percentage in the mixed soil-sand material was 8.1%.

Columns of this soil-sand mixture were prepared by packing 300 g of material into plastic cylinders (5 cm in diam) at a bulk density of 1.5 g/cm³. (If one assumes the average density of the soil particles to be 2.65 g/cm³, the pore volume of the column was 87 cm³.) Saturated HC was determined by leaching the column with 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 (Felhender et al., 1974). The electrical conductivities of the effluent samples were determined by standard techniques (U.S. Salinity Laboratory Staff, 1954).

The HC determinations were made after each soil column had been adjusted to the desired ESP by preleaching with a 0.5N NaCl-CaCl₂ solution of appropriate SAR value. The ESP's of the soil in equilibrium with 0.01N solutions of SAR 10, 20, and 30 were approximately 9, 18, and 27, respectively. Hence, hereafter, the two indices of exchangeable Na will be used interchangeably for convenience of expression. The HC's of the soil columns obtained by using 0.5N solutions were taken as the "base" HC, K_0 . Subsequently the columns were successively leached with solutions of the same SAR but of decreased salt

concentration (0.05 and 0.01N) until steady-state flows and effluent compositions were achieved. Then the soil columns were differentially leached with solutions of the same SAR but with salt concentrations of either 0, 1.0, 2.0, or 3.0 meq/liter. Relative HC's ($K_{rel} = K_i/K_0$) and clay dispersion were recorded.

RESULTS AND DISCUSSION

Hydraulic Conductivity

The HC of the Fallbrook soil-sand mixture was independent of the SAR of the percolating solution (in the range of $0 \leq \text{SAR} \leq 30$) as long as the salt concentration in the solution exceeded 10 meq/liter. However, large changes in the HC of the soil mixture occurred when the concentration of the percolating solution was reduced to less than 10 meq/liter, and the observed changes were related to the concentration of the percolating solution (see Fig. 1). Figure 1 shows that when leached with distilled water, even a low percentage of sodium on the exchange complex, such as 10, was enough to appreciably reduce the HC of the Fallbrook soil mixture. A similar study (data not presented) showed that the HC of the Fallbrook soil mixture was reduced 80% when leached with distilled water at an ESP level of only 5. Conversely, when Ca-saturated, Fallbrook soil mixture maintained the base HC even when leached with distilled water. Figure 1 also shows that an electrolyte concentration above 2 meq/liter in the percolating solution prevented the adverse effect of 10% exchangeable Na on HC of the Fallbrook soil mixture. At ESP 5, concentrations above 1 meq/liter maintained the base HC. These data showed that the ESP at which the physical properties of the Fallbrook soil mixture deteriorate depend markedly on the concentration of the percolating solution. When the soil is leached with distilled water, even ESP's of 5 may be detrimental. This marked effect of low electrolyte levels on soil permeability is especially pertinent to the surface layers of soils. During a rainstorm, the salt concentration in the surface layers may drop to a very low concentration, and even low ESP levels may enhance disaggregation, reduce the infiltration rate, and promote crust formation.

Increasingly higher concentrations of salt were needed in the percolating solution to prevent loss of HC

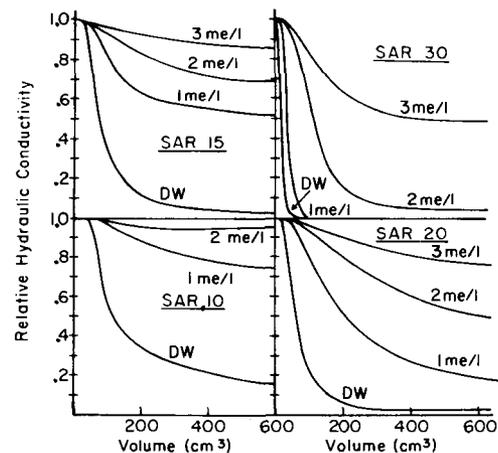


Fig. 1—Relative HC of Fallbrook soil-sand mixture, equilibrated with 0.01N solutions of SAR 10, 15, 20, or 30, and leached with distilled water (DW) or salt solutions of 1, 2, or 3 meq/liter.

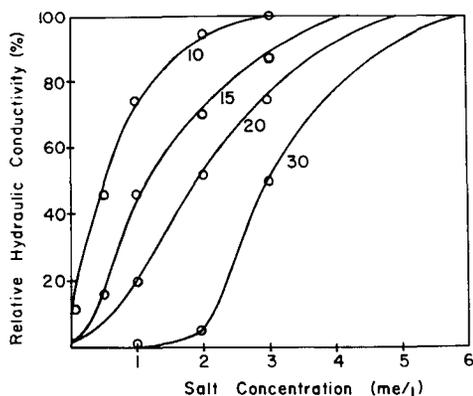


Fig. 2—Relative HC of Fallbrook soil-sand mixture with ESP's of 10, 15, 20, and 30, as a function of the soil solution electrolyte concentration.

with increasing ESP levels. This conclusion may be deduced from Fig. 1 but is more evident in Fig. 2, where the relative HC's for various SAR solutions are presented as a function of salt concentration. It is evident that for the Fallbrook soil mixture with ESP 30, percolating solution concentrations exceeding 6 meq/liter prevented loss of HC. Correspondingly, for the soil mixture equilibrated with SAR's of 20, 15, and 10, the "threshold" concentrations were about 5, 4, and 3 meq/liter, respectively.

The dependence of the HC of the soil mixture on the SAR of the percolating solution for each of the solution concentrations is shown in Fig. 3. Again, a threshold SAR (\approx ESP) existed for each salt concentration. When the percolating solution concentration was maintained at ≥ 3 meq/liter, no reduction in HC took place until the SAR exceeded 12. The threshold SAR value for solution concentrations of 2.0 and 1.0 meq/liter were 9.0 and 6.0, respectively. When the Fallbrook soil mixture was leached with distilled water and the percolating solution concentration was maintained by the soil at ~ 0.5 meq/liter, the detrimental effect of exchangeable Na started at an ESP value of about 1% (data not presented). In all cases, once the threshold ESP was exceeded, the HC was very sensitive to further increases in exchangeable Na. The more dilute the solution, the more sensitive was the soil to an incremental increase in the ESP beyond the threshold value.

Effluent Clay Concentrations

Concentrations of clay in the leachate of the Fallbrook soil mixture were also sensitive to the SAR and the concentration of the percolating solution, as Fig. 4 shows. (Because the natural soil was mixed with quartz sand, it is possible that clay mobility was unrealistically high under these conditions; however, the clay concentrations obtained in this study were similar to those obtained with natural sandy soils.) The following generalizations are evident in these clay breakthrough curves:

- 1) The concentration of clay in the effluent increased with increase in SAR provided the electrolyte concentration was ≤ 2 meq/liter.
- 2) The concentration of clay in the effluent depended very strongly on the salt concentration of the percolating solution (although some dispersion of the

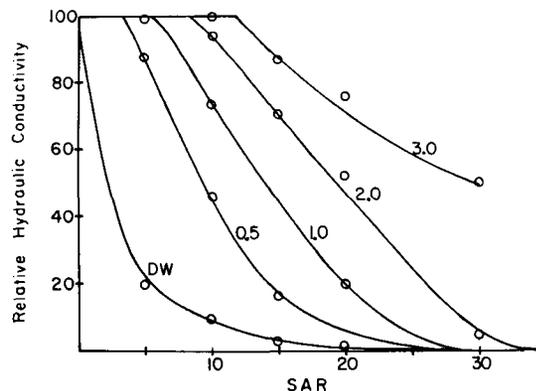


Fig. 3—The effects on the Fallbrook soil-sand mixture's HC of the ESP of distilled water (DW) and various soil solution salt concentrations.

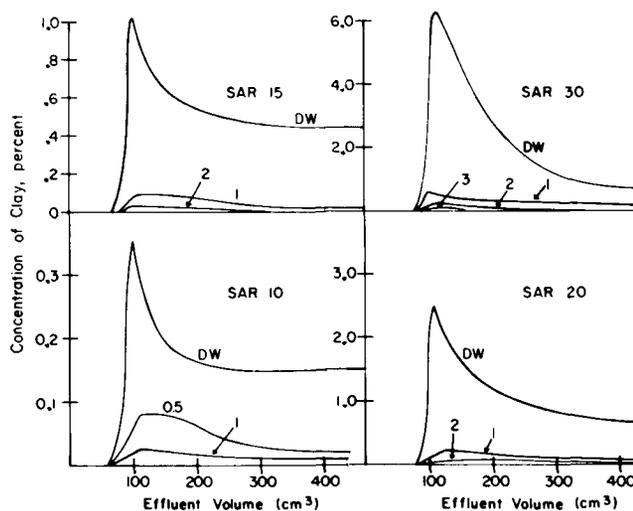


Fig. 4—The concentration of clay in the effluent of the low salt concentration and distilled water (DW) leachates from the Fallbrook soil mixture equilibrated with 0.01N solutions of SAR 10, 15, 20, and 30.

clay took place in the 1.0 and 2.0 meq/liter solutions, the clay concentration in their effluents was reduced by about an order of magnitude compared to that in distilled water). The concentration of clay in the effluent reached a maximum value at an effluent volume between 1.0 and 1.5 pore volumes (one pore volume of the column is 87 cm³), and thereafter the concentration decreased.

The peak clay concentrations as a function of the SAR and the salt concentration of the percolating solution are presented in Fig. 5. This figure shows that whereas the peak clay concentration depended on the salt concentration at a given SAR, the dependence of the dispersed clay concentration on SAR followed a similar pattern regardless of the salt concentration. Beyond a threshold ESP value, the dispersed clay concentration increased sharply with further increase in ESP. The relation was very similar to that of the hydraulic conductivity (Fig. 3) and thus suggested that the two processes are related. Figure 5 further shows that the threshold ESP for clay dispersion, with the Fallbrook soil mixture, was 0, 5, and 9 for percolating solution concentrations of 0, 1.0, and 2.0 meq/liter, respectively.

From an examination of the clay concentration

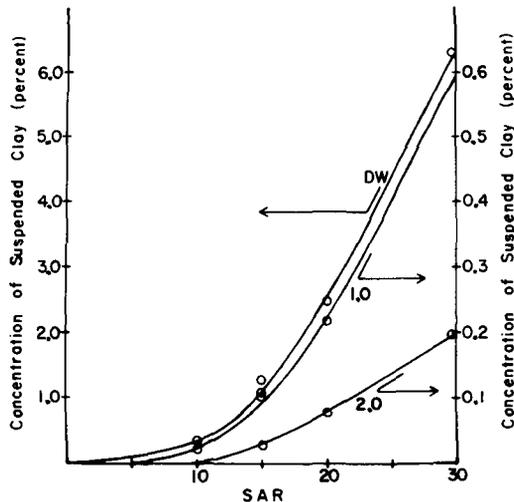


Fig. 5—The peak clay concentration in the effluent as a function of the SAR and salt concentration of the leaching solutions (DW = distilled water).

curves, it is evident that, when leaching with a dilute salt solution or distilled water, even though the salt concentration in the effluent remained constant, the clay concentration in the effluent increased rapidly with leaching to a maximum at about 1.5 pore volumes and then gradually decreased with further leaching to a near-constant low level. This shape of the clay concentration elution curve is compatible with a hypothesis of Emerson and Bakker (1973). They suggested that clay dispersion is enhanced: (i) when salt concentration in the soil solution drops below a threshold concentration (the flocculation value of the clay), and (ii) when steep salt gradients exist between the dilute solution in the soil pores and the more concentrated solution in the micropores within the aggregate. This salt gradient causes osmotic water movement into, swelling within, and the destruction of the aggregate. At the front of the displacing solution a large concentration gradient exists between the aggregate micropores and the conducting macropores, which should maximize dispersion (by the osmotic "explosion" mechanism). Thus the peak clay concentration should occur in that "frontal" percolate. With the subsequent diffusional adjustment of salt concentration between the intra- and inter-aggregate pores reducing the differential salt concentration with continued leaching. Along with the previous loss of readily dispersible clay to the "frontal" solution, clay dispersion is lessened, and less clay appears in the later percolate.

The total amounts of clay removed from the columns of the soil mixture with distilled water leaching were a function of the ESP of the soil mixture. The amounts of clay removed were 0.8, 2.5, 4.5, and 9.5 g at ESP values of 10, 15, 20, and 30, respectively. The total amount of clay in each soil column was 27 g. Thus, only a fraction of the clay initially present was dispersed and eluted from columns. Yet, the concentration of clay in the effluent decreased with leaching even though enough clay was still present in the column to sustain a higher concentration. Besides the reason given above for the reduced concentration of clay in the effluent after the maximum release, blockage of the conducting pores by lodged clay in another

likely cause, as shown by the corresponding reduced soil HC (Fig. 1) and reduced clay concentration in the effluent (Fig. 4).

SUMMARY AND CONCLUSIONS

Both the HC and clay dispersibility of the Fallbrook soil mixture were very sensitive to the level of exchangeable Na and to the salt concentration of the percolating solution. When the concentration of salt in the soil solution was 3.0 meq/liter, the HC and clay dispersion decreased only if ESP values exceeded 12%. Conversely, when the concentration of the soil solution was maintained at ~ 0.5 meq/liter (the effluent concentration when Fallbrook soil mixture was leached with distilled water), clay dispersion and HC decreased at ESP values as low as 1 to 2%. The effect of ESP on the HC of the soils that are leached periodically with rainwater should be reemphasized; even a low ESP may enhance loss of HC of the soil. Five percent Na on the exchange complex reduced the HC of the Fallbrook soil mixture to 20% of its initial value.

We hypothesize that the response of soils to low percentage of exchangeable Na (below ESP 20) and leaching with low electrolyte water depend on the concentration of electrolytes in the soil solution that the solid phases of each soil maintain. Soils with low rates of mineral dissolution should be the most susceptible to sodicity-induced aggregate deterioration from leaching with low electrolyte water. Conversely, soils that readily release salt during leaching should be less susceptible. A test of this hypothesis is the subject of the accompanying paper (Shainberg et al., 1981).

The high sensitivity of soils to low levels of exchangeable Na when leached with "high-quality water" was recently described by McIntyre (1979), who measured the HC of 71 Australian soils and concluded that an ESP much less than 15 should be accepted as the value above which soils can be adversely affected physically. He suggests that a value of 5 would be more relevant. The U.S. Salinity Laboratory has used an ESP value of 15 to designate sodic soils.

The concentration of electrolytes in the McIntyre studies was 0.7 meq/liter, whereas the salt concentration in the U.S. Salinity Laboratory studies was above 3 meq/liter. Thus, in line with the hypothesis discussed in this paper, we expect that when high-quality water is used (e.g., rainwater), an ESP of 5 can be detrimental to the physical properties of soils. However, when waters of higher salinity are used (> 3 meq/liter), an ESP of 15 is required for damage to the physical properties of soils.

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