

Effect of Mineral Weathering on Clay Dispersion and Hydraulic Conductivity of Sodic Soils¹

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ABSTRACT

Three soils were chosen to test the hypothesis that differences in rates of mineral dissolution among soils may account for much of the observed differences in their susceptibilities to hydraulic conductivity decreases when leached with distilled water. Our results agreed reasonably well with the hypothesis. Differences between soils in their ability to release salt and to undergo dispersion are probably especially important in affecting crust formation under rainfall conditions.

Additional Index Words: hydrolysis, electrolyte concentration, clay swelling.

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IN ANOTHER PAPER (Shainberg et al., 1981) we reported the effect of leaching with distilled water and dilute salt solutions (0.001, 0.002, and 0.003*N*) on clay dispersion and hydraulic conductivity (HC) of a weathered mineral soil. We found that relatively low salt concentrations in the leaching water prevented clay dispersion and loss of hydraulic conductivity for ESP levels below 30 of a Fallbrook soil-sand mixture. These

observations, plus others, led to the hypothesis that a major factor causing differences among various sodic soils in their susceptibilities to HC decreases when leached with low electrolyte water was their rate of salt release by mineral dissolution properties, which determines electrolyte concentration of percolating solutions. We postulated that sodic soils containing minerals (CaCO₃ and a few primary minerals such as plagioclase feldspars and hornblende) that readily release soluble electrolytes will not readily disperse when leached with distilled water (simulating rainwater) at moderate exchangeable sodium percentages (ESP), because they will maintain high enough salt concentrations in the soil solution (> meq liter⁻¹) to prevent clay dispersion. In addition, the ESP will be reduced, because most of the released salts are Ca and Mg (Rhoades et al., 1968). Conversely, the concentration of salt in the soil solution of soils that do not contain readily weatherable minerals will be below a threshold concentration (the flocculation value), and

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the soils will be more susceptible to clay dispersion. Lodgement of dispersed clay particles in conducting pores may markedly decrease HC of such soils.

In this study, we tested the above hypotheses. Three California soils varying in their mineral weathering rates were chosen for study.

MATERIALS AND METHODS

Some properties of the three soils used in this study are given in Table 1. The rates of mineral dissolution of these soils were determined on < 2-mm fractions by extracting them (1:5, soil/water) twice with distilled water to remove excess salt and subsequently shaking them continuously and periodically determining supernatant electrical conductivity (EC).

Soil columns were prepared using both the < 2-mm fraction and the < 2-mm soil fraction mixed with 25- to 35-mesh acid-washed quartz sand in a ratio of 1:1. The soil was mixed with sand to produce high flow rates, to minimize the effect of swelling, and to maximize dispersion and clay particle movement. Columns of the soils were prepared by packing 300 g of soil into plastic cylinders 5 cm in diam to a bulk density of 1.5 g cm⁻³. Columns were initially wetted from the bottom and kept saturated. The ESP of each soil was adjusted by leaching with 0.5N NaCl-CaCl₂ solutions of a specified sodium adsorption ratio (SAR) value. Throughout this paper, SAR solutions in the range between 0 and 30 are studied, with the inherent assumption that SAR = ESP (U.S. Salinity Laboratory Staff, 1954). The HC values to the 0.5N solutions were taken as "base" values. Subsequently the columns were successively leached with solutions of the same SAR but of decreasing salt concentrations until steady-state conditions for HC and EC were successively achieved. The final solution used was distilled water, which was applied via a constant flow (peristaltic) pump. The head developed in the inflow chamber of the column was measured, and the effluent was collected using a fraction collector. Three flow rates were maintained: 5.2, 15.6, and 66.5 cm³ hour⁻¹. This corresponds to soil flux rates of 0.25, 0.75, and 3.17 cm hour⁻¹, respectively. Clay concentrations in the effluent were determined gravimetrically.

RESULTS AND DISCUSSION

The EC's of solution as a function of time of shaking after initial electrolyte removal with the three soils are shown in Fig. 1. The supernatant EC's after 4 hours of shaking were 30, 75, and 240 μ mho cm⁻¹, for Fallbrook, Pachappa, and Gila soils, respectively. The initial salt release rates are the most pertinent to the HC studies since the relatively high flow rates result in short residence times of water in the columns. The increase in EC is due predominantly to Ca and HCO₃ release, although some Na appeared in solution from ion exchange (data not given). The Gila soil contained CaCO₃ (see Table 1), whereas the Fallbrook and Pachappa soil samples were CaCO₃ free. The Fallbrook is more highly weathered than the Pa-

chappa soil, as evidenced from its mineralogical composition. Relatively unstable mafic minerals (such as hornblende) are present in the Pachappa soil but not in the Fallbrook soil (data not given). The higher content of mica and lower content of kaolinite in the Pachappa soil is also indicative of a relatively unweathered soil. Gila soil would be expected to have the fastest initial weathering rate since it contains CaCO₃, which has a faster dissolution rate than do the aluminosilicates. The dissolution rate subsequently drops off rapidly as CaCO₃ equilibrium is approached. The dissolution of the silicates produces a similar solution composition to that caused by CaCO₃ dissolution, except that some Na, K, and Mg would also appear in solution in addition to the predominant Ca and HCO₃ solutes (Rhoades, 1975). The HC of the sand-soil mixtures of the three soils in 0.5N solutions were 10.7, 12.5, and 8.0 cm hour⁻¹ for the Fallbrook, Pachappa, and Gila soils, respectively. The similarity in HC values of the three soils mixtures facilitated comparison of response to concentration and composition of percolating solutions. Also, the high porosity of the soil-sand mixtures minimized sealing due to swelling and clay lodgment when the dilute salt solutions and distilled water were added.

The EC levels of the effluents corresponding to four pore volumes of displacement (320 cm³) were approximately equal for the natural soil and the respective sand mixture (Tables 2 and 3). Consequently, subsequent discussion will deal primarily with results obtained using the soil-sand mixtures. Results obtained using the natural soil samples will be presented and compared, however.

Soil-Sand Mixtures

The effect of rate of flow on the EC's resultant from the application of distilled water at an effluent volume of four pore volumes (= 320 cm³) are presented in Table 2. For all soils (mixtures), an increase in flow rate resulted in some reduction in effluent EC. However, differences among soil mixtures were more pronounced than effects of rate of flow. The Gila soil mixture released the most electrolytes, maintaining an effluent concentration of 3.0 meq liter⁻¹ at SAR 30 and a flow rate of 15.6 ml hour⁻¹ (see Fig.

Table 1—Some physical and chemical properties of the soil used.

Soil	Sand	Silt	Clay	CEC†		CaCO ₃	Dominant clays‡
				meq/100 g			
	%					%	
Fallbrook (fine-loamy, mixed, thermic Typic Haploxeralfs)	71	13	16	13		nil	M and K
Pachappa (coarse-loamy, mixed, thermic Mollic Haploxeralfs)	69	20	11	9		nil	M and Mica
Gila (coarse-loamy, mixed [calcareous], thermic Typic Torrifuvents)	74	16	10	10		6	M and Mica

† Cation exchange capacity.

‡ M = montmorillonite; K = kaolinite. As concluded from data of McNeal and Coleman (1966) and Frenkel et al. (1978).

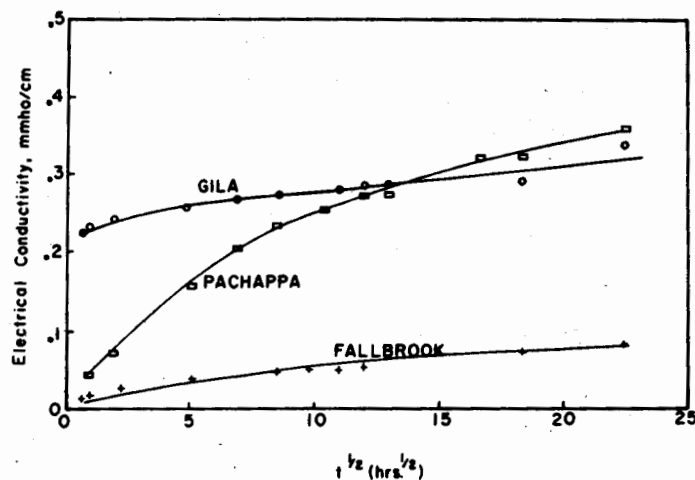


Fig. 1—The effect of time on the EC of water suspensions of Gila, Pachappa, and Fallbrook soils.

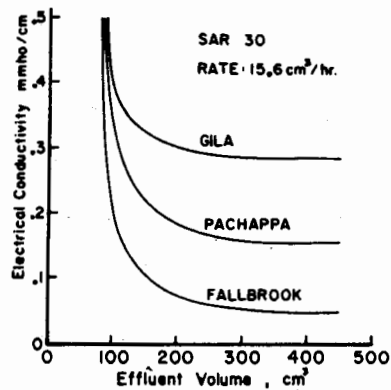


Fig. 2—The effect on relative HC's during leaching of ESP 20 and ESP 30 soil mixtures with distilled water.

2). Conversely, the more weathered Fallbrook soil mixture was able to maintain an effluent concentration of only 0.6 meq liter⁻¹ under the same conditions. The Pachappa soil mixture dissolved at an intermediate rate, resulting in an effluent concentration of 1.5 meq liter⁻¹.

The effect of flow rate on the concentration of clay in the effluent is also presented in Table 2. Rate of flow did not affect effluent clay concentration for the Pachappa and Gila soil mixtures. For the Fallbrook soil mixture, however, the amount of clay in the effluent increased with increase in flow rate. This phenomenon is readily explained, because clay can disperse only if the salt concentration is below a critical concentration—the flocculation value (Oster and Shainberg 1980). Thus, the soil solution salt concentration prevented dispersion for the Gila and Pachappa soil mixtures. Conversely, the chemical conditions for clay dispersion were favorable in the Fallbrook soil mixture. In all three soil mixtures, the effect of rate of flow on clay dispersion was small compared with differences among soils. Further discussion will deal exclusively with the 15.6 ml hour⁻¹ rate of flow.

Relative HC of the soil mixtures in 0.05 and 0.01N solutions are also presented in Table 2. When 0.05N

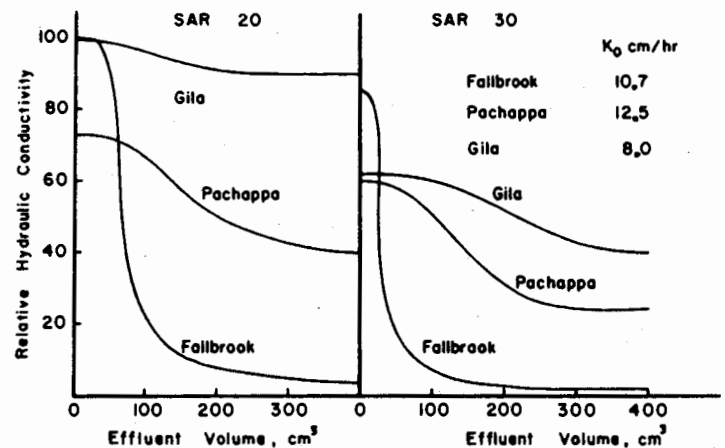


Fig. 3—The effect of effluent volume on the EC of effluents from columns of Gila, Pachappa, and Fallbrook soils during leaching with distilled water.

solutions of SAR 20 were displaced with 0.01N solutions, the HC of the Fallbrook and Gila soil mixtures did not change, and that of the Pachappa soil mixture dropped only about 30%. When the SAR 30, 0.05N solutions were displaced with 0.01N solutions of SAR 30, the HC of the Fallbrook mixture still changed only slightly, whereas for the Pachappa and Gila soil mixtures it dropped about 35%. When the 0.01N solutions of SAR 20 and 30 were displaced with distilled water, however, differences in response among soil mixtures were large (Fig. 2). The HC of the Fallbrook soil mixture dropped sharply, that of the Gila soil mixture changed only slightly, and the change for the Pachappa mixture was intermediate. For all soil mixtures, the decrease in relative HC upon displacement with distilled water was greater for solutions of increased SAR. Furthermore, the order of reduction in HC upon addition of distilled water followed the order of effluent EC (Fig. 3). Concentrations of clay in the leachate of the soil mixture columns were also affected by the degree of Na saturation and concentration of the percolating solution (Table 2 and Fig. 4).

Table 2—Results obtained with the < 2-mm soil fraction mixed 1:1 with 25- to 35-mesh quartz sand.

Soil	SAR†	Flow rate ml/hour	Effluent clay			Relative K			After 320 ml of distilled water	EC at four pv‡
			Peak	At four pv‡		0.5N§	0.05N§	0.01N§		
				%	g					
Fallbrook	20	5.2	1.8	0.3	2.0	1.0	1.0	1.0	0.3	0.11
Fallbrook	20	15.6	2.0	0.5	1.9	1.0	1.0	1.0	0.2	0.07
Fallbrook	20	66.5	4.0	-	-	1.0	1.0	1.0	-	-
Fallbrook	30	5.2	1.6	0.4	2.3	1.0	0.8	0.7	0.04	0.08
Fallbrook	30	15.6	1.8	0.8	3.1	1.0	0.7	0.8	0.03	0.06
Fallbrook	30	66.5	6.0	-	-	1.0	1.0	0.9	-	-
Pachappa	20	5.2	0.2	0.06	0.3	1.0	1.0	0.6	0.5	0.17
Pachappa	20	15.6	0.2	0.07	0.3	1.0	0.9	0.7	0.6	0.14
Pachappa	20	66.5	0.2	0.07	0.3	1.0	0.7	0.9	0.4	0.10
Pachappa	30	5.2	0.5	0.1	0.5	1.0	0.6	0.4	0.3	0.20
Pachappa	30	15.6	0.5	0.1	0.5	1.0	0.8	0.5	0.1	0.15
Pachappa	30	66.5	0.4	0.1	0.4	1.0	0.9	0.5	0.02	0.14
Gila	30	5.2	0.1	0.08	0.1	1.0	0.7	0.5	0.4	0.30
Gila	30	15.6	0.2	0.05	0.2	1.0	0.6	0.6	0.3	0.29
Gila	30	66.5	0.2	0.04	0.2	1.0	0.8	0.6	0.2	0.20

† SAR = sodium adsorption ratio.

‡ pv = pore volume.

§ N = normality.

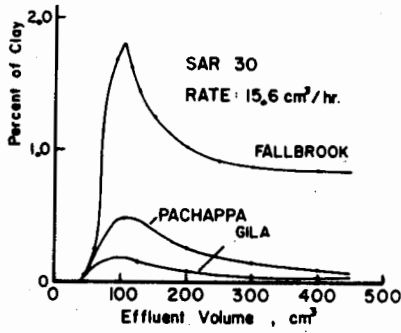


Fig. 4—The effluent clay concentration with passage of distilled water at the rate of 15.6 cm³ hour⁻¹ for the three soil mixtures at ESP = 30.

Our results for the Fallbrook, Pachappa, and Gila soil mixtures support the hypothesis that the response of a soil to exchangeable Na when leached with low electrolyte waters depends on the concentration of electrolyte in the soil solution, with this concentration in turn often greatly affected by dissolution and hydrolysis of soil minerals. The more chemically stable Fallbrook soil was the most sensitive to sodic conditions, whereas the Pachappa and Gila soils, which release more salt, were relatively less susceptible in spite of the presence of more labile montmorillonite clay in them. The Netanya soil from the coastal plains of Israel (Pupisky and Shainberg, 1979) is similar to Fallbrook soil (Frenkel et al., 1978) in its response to distilled water. Both soils were found to be chemically stable and to release salts at a similar rate (Oster and Shainberg, 1979). Both soils have been exposed to intensive weathering and have clay fractions that are enriched with sesquioxides and kaolinite. In spite of the reported stabilizing effect of sesquioxides and the inertness of kaolinite in sodicity-induced HC losses (McNeal et al., 1968), these two soils undergo marked dispersion and losses in HC upon leaching with distilled water. Thus, we may conclude that soils that release salts in greater concentration will be less susceptible to sodicity-induced clay dispersion and loss in HC when they are leached with dilute waters.

Natural Soils

The HC of the three soils in 0.5N solutions were 0.99, 4.10, and 1.14 cm hour⁻¹ for the Fallbrook, Pachappa, and Gila soils, respectively. Relative hydraulic conductivities of the three soils are presented in Table 3 and Fig. 5, respectively. The clay percentages in

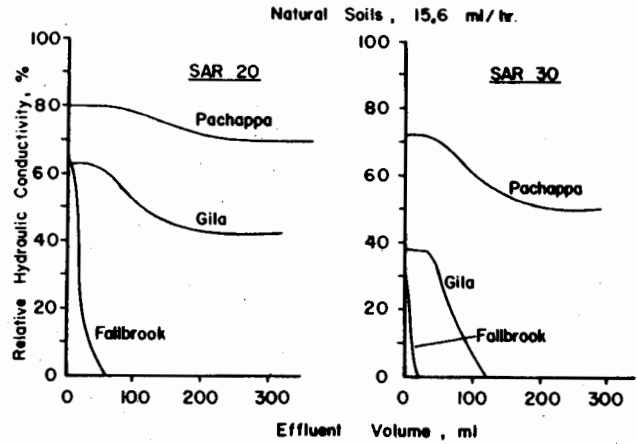


Fig. 5—The effect upon the relative HC during leaching of ESP 20 and ESP 30 soils with distilled water.

the distilled water effluent for the Gila and Pachappa soils are also presented in Table 3. At SAR 20, the Pachappa soil underwent less reduction in HC than did the Fallbrook and Gila soils, which decreased to 0.9 and 0.6 of their base hydraulic conductivities, respectively, when equilibrated with 0.05 and 0.01N solutions. Over this concentration range, swelling is the main factor causing the losses in HC (Pupisky and Shainberg, 1979). The Fallbrook and Gila soils are more sensitive to the detrimental effect of adsorbed Na over this concentration range than is the Pachappa soil. This conclusion is supported by a consideration of the effect of concentration on the HC of the soils equilibrated with SAR 30 solutions (Table 3).

When the 0.01N solution of SAR 20 was displaced with distilled water, a trend similar to that reported for the sand-soil mixtures was obtained, i.e., the HC of the Fallbrook decreased markedly within 0.5 pore volume of leaching, whereas the HC's of both the Pachappa and the Gila soils were much less affected. Similar results were obtained with the SAR 30 systems, with the Pachappa soil more stable than the Gila soil to sodicity-electrolyte effects. The EC's of the effluents of the Gila and Pachappa soil columns at 320 cm³ were 0.26 and 0.14 mmho cm⁻¹, respectively. At these solution concentrations, only limited clay dispersion and clay movement should occur. Thus, swelling effects were an additional cause of the observed losses in HC. With increase in the ESP of the soils (SAR 30 treatment) the effect of swelling was even more pronounced. Sealing of the Gila soil at this

Table 3—Results obtained with the <2-mm soil fraction.†

Soil	SAR‡	Effluent clay in distilled water			Relative K				
		Peak conc.	At four pv conc§	Σ at four pv§	0.5N¶	0.05N¶	0.01N¶	After 320 ml of distilled water	EC at four pv§
		%		g	mmho/cm				
Fallbrook	20	-	-	-	1.0	0.9	0.6	0.0	-
Fallbrook	30	-	-	-	1.0	0.8	0.3	0.0	-
Pachappa	20	0.6	0.1	0.5	1.0	1.0	0.8	0.8	0.14
Pachappa	30	0.7	0.1	0.5	1.0	0.9	0.7	0.3	0.14
Gila	20	0.2	0.04	0.2	1.0	1.0	0.6	0.3	0.26
Gila	30	-	-	-	1.0	0.8	0.4	0.0	-

† All flow rates run at 15.6 ml hour⁻¹.

‡ Exchangeable sodium percentage, assuming that SAR = ESP for the equilibrating solutions.

§ pv = pore volume.

¶ N = normality.

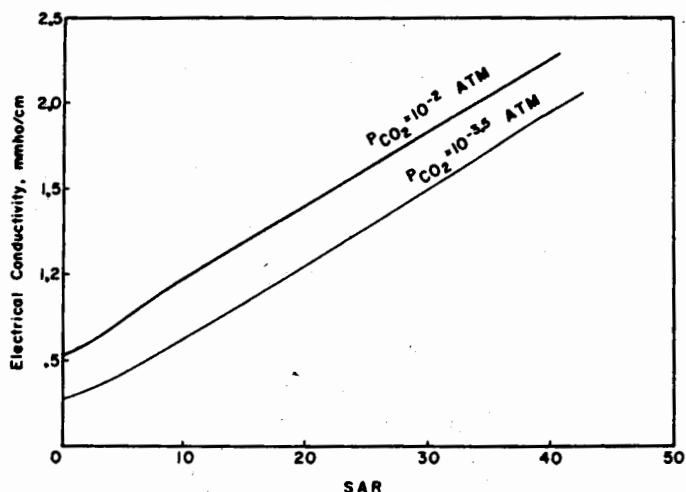


Fig. 6—Theoretical relation between SAR and EC of calcareous soil solutions at partial pressures of CO_2 of $10^{-3.5}$ and 10^{-2} .

SAR, for example, was probably a consequence of increased swelling. Hence, separation of the effects of dispersion and swelling becomes much less clear cut in undiluted (sand-amended), highly montmorillonitic soils.

The potential effect of mineral weathering on soil solution composition can be most simply calculated for the CaCO_3 case. If a calcareous soil at a given ESP were placed in contact with distilled water, it would dissolve CaCO_3 and exchange Na from cation exchange sites until the solution was at simultaneous equilibrium with exchange sites and with the CaCO_3 solid phase. Since the absolute amount of cations in the solution phase is usually small compared with those associated with the exchange phase, however, the exchange phase buffers the solution SAR over the short term. If we use the apparent CaCO_3 solubility product value of $10^{-8.0}$ (Suarez, 1977) and solve for different equilibrium SAR values, we obtain the SAR/EC relationship shown in Fig. 6. This relationship should result upon equilibration of a salt-free soil of that ESP (= SAR) with distilled water. These values represent the EC values that would occur at equilibrium for a calcareous soil equilibrated at a given SAR for two different P_{CO_2} levels. Near-surface soil P_{CO_2} conditions are likely to be between $10^{-3.5}$ atm (atmospheric) and 10^{-2} atm. It is evident from the figure that water equilibrated with a calcareous sodic soil can never be at very low salinity. For example, at SAR = 30 and $\text{P}_{\text{CO}_2} = 10^{-3.5}$, the EC would $1.52 \text{ mmho cm}^{-1}$. The presence of other salts, for example, chloride, would of course increase the EC above the values shown. Upon continued application of distilled water the ESP, SAR, and equilibrium EC would all decrease. At $\text{P}_{\text{CO}_2} = 10^{-3.5}$ the solution composition would follow that curve down to SAR = 0 (with continued leaching) and remain at EC = $0.28 \text{ mmho cm}^{-1}$.

The flow rate of $15.6 \text{ cm}^3 \text{ hour}^{-1}$ used in our column studies was probably too fast to allow the attainment of equilibrium during leaching. The kinetics of dissolution would effect the actual EC achieved during leaching. Although the Pachappa and Fallbrook soils do not contain CaCO_3 , a similar argument could be made for aluminosilicate minerals, except that their

dissolution rates appear to be slower. In any case the behavior of these soils during leaching qualitatively agrees with this hypothesis.

SUMMARY AND CONCLUSIONS

The clay dispersivity, HC, and mineral weathering properties of three California soils were studied. The chemically stable Fallbrook soil was the most sensitive soil to exchangeable Na effects on clay dispersion and loss in HC in spite of the presence of sequioxides and kaolinite in its clay fraction. The Gila and Pachappa soils, which have higher mineral dissolution rates, were less affected by exchangeable Na. These findings support the hypothesis that the response of soil to exchangeable Na during leaching with distilled water depends on the concentration of electrolytes that the solid phase of the soil maintains. Clay dispersion, movement, and possible lodgment in conducting pores is caused by low levels of electrolytes even at low levels of exchangeable Na.

The differences among soils in their capacity to release salt and to undergo dispersion is probably especially important in affecting crust formation under rainfall conditions. Soils that have moderate ESP levels may maintain reasonable physical properties through most of the profile and yet still be susceptible to dispersion near the surface. This is because the soil solution electrolyte concentration may be insufficient there to maintain physical structure.

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