

# Stability of Soil Aggregates as Affected by Electrolyte Concentration and Composition<sup>1</sup>

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## ABSTRACT

Stability of soil aggregates was studied under different electrolyte concentration-sodium adsorption ratio (SAR) combinations. The extent of slaking of soil aggregates was found to depend upon the level of SAR and electrolyte concentration. At SAR 0, 10, and 20 and electrolyte concentrations above 3.2, 15.9, and 19.4 mol m<sup>-3</sup>, respectively, slaking into aggregates as small as 5 μm occurred without or with very little clay dispersion. At lower electrolyte concentrations, clay dispersion occurred as the fine aggregates broke down into their constituents. Slaking was attributed to the shearing stresses created by an expansion of the diffuse double layers (DDL). Dispersion was initiated as the DDL on the clay surfaces expanded to the point which permitted the clay particles to separate. Clay did not disperse from the peripheries of intact soil aggregates, rather clay dispersed at the ultimate stage of the slaking process.

**Additional Index Words:** disaggregation, slaking, clay dispersion, sodium adsorption ratio, salt concentration, diffuse double layer.

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IT IS GENERALLY ACCEPTED that both high sodium adsorption ratios (SAR) and/or low electrolyte concentrations create soil structural problems; however, we still do not have reliable criteria and standards for predicting a priori how these parameters quantitatively affect structural stability and hydraulic conductivity (HC) of soils (Rhoades, 1972). The causative mechanisms have been postulated to be: (i) swelling of soils, (ii) clay dispersion and subsequent plugging of conducting pores by the dispersed clay, and (iii) failure of soil aggregates (Quirk and Schofield, 1955). Yet a review of the literature reveals divergence of opinions about the relative importance of these mechanisms. For example, McNeal and Coleman (1966), Jayawardane and Beattie (1978) and Jayawardane (1979) concluded that swelling of soils was the dominant mechanism causing reductions in the HC of sodic soils. Rhoades and Ingvalson (1969), Frenkel et al. (1978), Pupisky and Shainberg (1979), Shainberg et al. (1981), and Yousaf (1983) upheld the view that clay dispersion was the dominant mechanism. However, Waldron and Constantin (1968) and Cass and Sumner (1982) concluded that reduced HC was caused by aggregate failure resulting from either the rupturing effect of internal swelling pressure or from shearing stresses. In addition to the above, Emerson (1964) indicated that when soil aggregates were immersed in water they broke down, to varying extents, into discrete fragments. This process is called slaking and may proceed without clay dispersion.

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The purpose of this study was to investigate the nature of the sodicity and/or low electrolyte concentration effects on the structural stability of selected California semi-arid soils and to evaluate the relative importance of slaking vs. dispersion on loss of permeability.

## MATERIALS AND METHODS

### Soil Properties

Three California soils (Arlington: coarse loamy, mixed, thermic Haplic Durixeralfs; Fallbrook: fine loamy, mixed, thermic Typic Haploxeralfs; and Pachappa: coarse loamy, mixed, thermic Mollic Haploxeralfs) were used. These soils were collected in bulk lots by the U.S. Salinity Laboratory, air-dried, passed through a 2-mm diam sieve and stored at room temperature prior to being used for this study. Some selected soil properties are given in Table 1 for Arlington soil.

Organic C was determined by modification of the Walkley-Black method (1934). X-ray diffraction analysis was carried out according to the method described by Jackson (1979). Particle size distribution was determined by wet sieving of the sand fraction followed by quantitative fractionation of the clay, fine, and medium silt fractions using 1 mol m<sup>-3</sup> NaCl solution and gravitational sedimentation. The collected clay fraction was flocculated using CaCl<sub>2</sub> solution and transferred into a volumetric flask. Samples of the clear supernatant (salt solution) and subsequently of the homogeneous suspension (salt solution and clay) were collected and analyzed gravimetrically. The amount of clay was determined by difference. The previously separated silt fractions were also determined gravimetrically.

### Slaking and Dispersion

A modification of the method described by Yousaf (1983) was used to collect specific size particles and aggregates from soils equilibrated at various SAR-electrolyte concentration combinations. A 100.0-g sample of oven dry soil was placed in each of four 2-L glass bottles. One L of a 500 mol m<sup>-3</sup> CaCl<sub>2</sub> solution (SAR 0) was added slowly under vacuum to each bottle. The contents of the bottles were equilibrated overnight with the CaCl<sub>2</sub> solution, after which time the supernatant solutions were siphoned off. This procedure of equilibrating with CaCl<sub>2</sub> was repeated two more times. The remaining electrolyte concentration was subsequently successively diluted by addition of distilled water and then equilibrated, after which the supernatants were siphoned off. Once the supernatant solutions attained electrolyte concentrations of 5.10 mol m<sup>-3</sup>, they were replaced with fresh CaCl<sub>2</sub> solution of the same concentration. The bottles were gently inverted and then uprighted by hand and placed in a water bath at 25°C. The ≤ 1-, 2-, 5-, or 20-μm diam fractions were collected from the four bottles, respectively, by siphoning

Table 1. Selected physical and chemical properties of Arlington soil.

Sand	Particle size, g kg <sup>-1</sup>						Organic carbon, g kg <sup>-1</sup>	Dominant clay
	Silt			Clay		Total		
	Coarse	Medium	Fine	<1 μm	Total			
403	266	97	39	402	169	195	2.4	v, m, k†

† v = vermiculite, m = mica, and k = kaolinite.

Table 2. Cumulative amounts of slaked (disaggregated) and dispersed particles from Arlington soil at various SAR-electrolyte concentration combinations.

EC (dS m <sup>-1</sup> )	Concentration (mol m <sup>-3</sup> )	SAR (mol m <sup>-3</sup> ) <sup>1/2</sup>	pH	Mean diameter of slaked particles (μm)							
				≤1		≤2		≤5		≤20	
				a†	b‡	a	b	a	b	a	b
0.62	5.10	0.00	6.81	0.00	0.00	0.00	0.00	0.18	0.78	1.31	3.94
0.41	3.19	0.00	6.33	0.00	0.00	0.18	0.90	0.58	2.46	3.35	10.11
0.20	1.58	0.00	6.87	0.09	0.56	0.57	2.90	1.41	6.00	5.17	15.59
0.04	0.28	0.00	6.67	0.64	3.77	1.48	7.55	2.87	12.25	7.23	21.80
2.10	20.49	10.00	6.83	0.00	0.00	0.08	0.43	0.36	1.53	2.25	6.79
1.70	15.85	10.00	7.03	0.00	0.00	0.23	1.18	1.12	4.79	5.24	15.80
1.10	9.75	10.00	6.89	0.04	0.21	0.50	2.56	2.47	10.52	8.53	25.74
0.56	5.16	10.00	7.08	0.58	3.45	2.64	13.49	6.59	28.12	11.58	34.93
2.20	19.43	20.00	6.71	0.00	0.00	0.16	0.82	0.64	2.71	3.74	11.28
1.10	9.95	20.00	7.00	0.27	1.62	1.02	5.22	3.23	13.78	7.63	23.02
0.62	5.03	20.00	7.27	2.89	17.08	4.49	22.99	8.22	35.07	12.48	37.65

† g/100 g soil.

‡ Percent of the equivalent size fraction in soil.

off the prescribed depth of the suspensions at the times calculated according to the Stoke's law for settling velocities. The inversion/settling/siphoning step was repeated four more times with the four size fractions being composited in separate bottles. A sample of the composited solution was analyzed for pH, EC, Na, and Ca.

The soil remaining in the 2-L bottles was then subjected in the same manner as described above with successively more and more dilute CaCl<sub>2</sub> solutions (3.19, 1.58, and 0.28 mol m<sup>-3</sup>) and the various size fractions were collected as before.

The cumulative quantities of the four size fractions were determined gravimetrically. The amount of ≤2 μm clay in the ≤5- and 20-μm fractions was determined by successively dispersing these latter fractions in 1 mol m<sup>-3</sup> NaCl solution and siphoning off the clay after the appropriate settling time. Approximately 10 dispersion and siphoning treatments were required to remove the clay. The cumulative clay and the respective residual silt fractions were determined gravimetrically.

The same procedure described above for SAR 0 was also used to evaluate aggregate stability of fresh 100-g lots of soil equilibrated with the following SAR-electrolyte concentration combinations: SAR 10: 20.49, 15.85, 9.75, and 5.16 mol m<sup>-3</sup>; SAR 20: 19.43, 9.95, and 5.03 mol m<sup>-3</sup>.

## RESULTS AND DISCUSSION

### Slaking and Clay Dispersion

The term *slaking* will be used hereon to refer to the breakdown of soil aggregates into particles of >2 μm in size whereas dispersion refers to the further breakdown of fine soil aggregates and release of ≤2 μm clay.

Although the absolute amounts of each size fraction slaked or dispersed from each soil were not the same, the soils were similarly affected by a reduction in electrolyte concentration at a given SAR. Therefore, only the results of Arlington soil will be presented in this paper. Abu-Sharar (1985) may be consulted for details of the specific behavior of the other soils.

The effect of electrolyte concentration and SAR on slaking and dispersion of the Arlington soil is shown in Table 2 and Fig. 1. At SAR 0, dispersion of the ≤2 μm clay first occurred when the electrolyte concentration was decreased to 3.19 mol m<sup>-3</sup> and appreciable amounts of the ≤1 μm clay dispersed only when the electrolyte concentration was reduced to 0.28 mol m<sup>-3</sup>. This is in keeping with the finding of Emerson (1954)

that a 1 mol m<sup>-3</sup> CaCl<sub>2</sub> solution will prevent clay dispersion from Ca soils. The cumulative amount of ≤1 μm dispersed clay at the electrolyte level of 0.28 mol m<sup>-3</sup> (SAR 0) was 0.64 g/100 g soil, representing 3.77% of the total <1 μm clay content of the whole soil. On the other hand, a substantial breakdown of the original soil aggregates into aggregates of ≤5 and ≤20 μm in sizes occurred at an electrolyte concentration of 5.10 mol m<sup>-3</sup>. Under this treatment 3.94% of the original ≤20 μm size fraction broke down into smaller aggregates. Figure 1 also shows that the stability of soil aggregates was best reflected by the data for the ≤5 and ≤20 μm aggregates and not the dispersion of ≤2 μm particles. The dispersion of about 4% of the total ≤1 μm clay content was associated with a 22% slaking of the ≤20 μm fraction.

When the SAR was increased to 10, a greater electrolyte concentration was needed to prevent dispersion of the ≤1 μm clay. At SAR 10, an electrolyte concentration of 5.16 mol m<sup>-3</sup> had almost the same dispersion effect observed at SAR 0 and an electrolyte concentration of 0.28 mol m<sup>-3</sup>. Although the amounts of ≤1 μm clay dispersed were similar at these two SAR-electrolyte concentration combinations, the corresponding amounts of the ≤20 μm aggregates slaked was higher at the SAR 10 and 5.16 mol m<sup>-3</sup> combination than at SAR 0 and 0.28 mol m<sup>-3</sup> combination. At SAR 10, there was a substantial decrease in the stability of aggregates once the electrolyte concentration was reduced below 9.75 mol m<sup>-3</sup>. The greater amounts of dispersed ≤1 and ≤2 μm clay and slaked ≤5 μm aggregates occurring at SAR 10 and 5.16 mol m<sup>-3</sup> are attributed to the enhanced breakdown of the ≤20 μm aggregates under these conditions.

More slaking and dispersion occurred at SAR 20 and reduction in the electrolyte concentration below 9.95 mol m<sup>-3</sup> was sufficient to cause a marked failure of the original soil aggregates as indicated by the large increase in the amounts of dispersed and slaked particles (see Fig. 1).

Since the range of particle size distribution increased as the upper limit of each size fraction was increased, the smaller size fractions were included in the larger ones. Therefore, it is appropriate to subtract the amounts of slaked or dispersed smaller size fractions from the larger fraction in order to determine

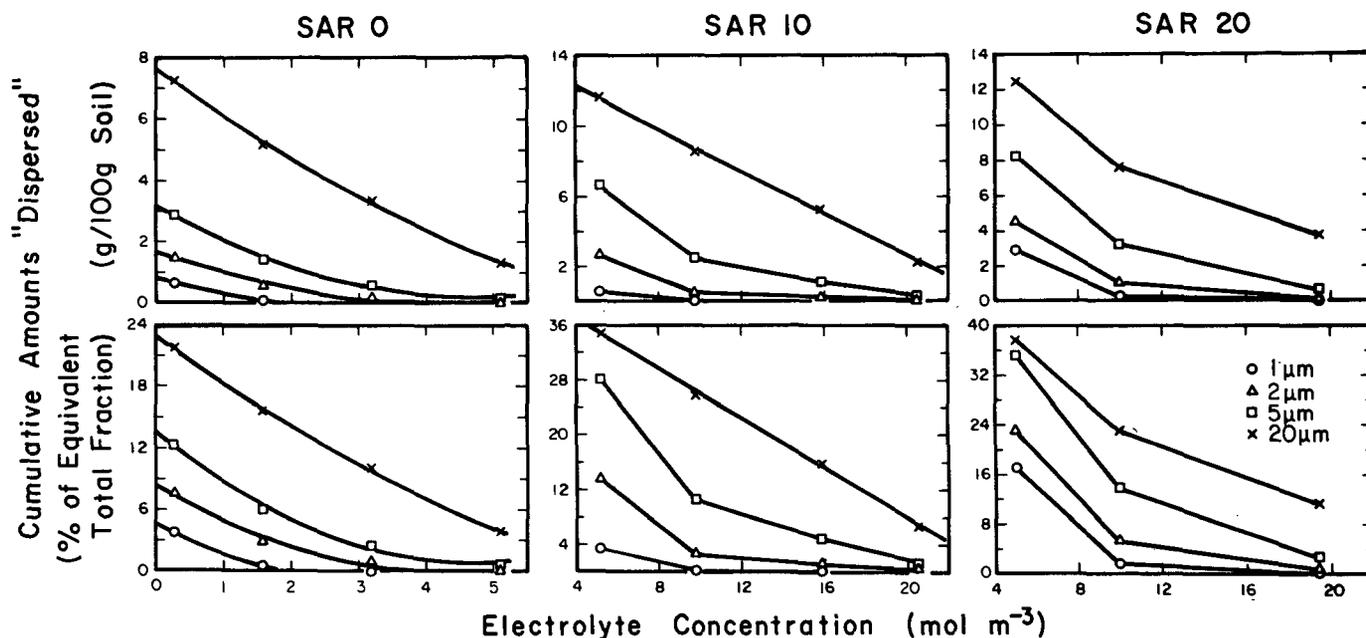


Fig. 1. The effect of electrolyte concentration and sodium adsorption ratio on the extent of slaking and dispersion of the Arlington soil.

the actual amounts of slaked and dispersed particles in the various size classes. For example, at the electrolyte concentrations of 5.10, 3.19, 1.58, and 0.28 mol  $m^{-3}$ , the differences between the amounts of the  $\leq 20$  and  $\leq 5$   $\mu m$  particles were 1.12, 2.77, 3.76, and 4.35 g/100 g soil, respectively (Table 2). The continuous increase in these differences implies a continuous increase in the amounts of  $\geq 5$  to  $\leq 20$   $\mu m$  aggregates. Differences between the  $\leq 5$  and  $\leq 2$   $\mu m$  and the  $\leq 2$  and  $\leq 1$   $\mu m$  fractions followed a similar trend.

However, at SAR 10, reduction in the electrolyte concentration below 9.75 mol  $m^{-3}$  resulted in a substantial reduction in the stability of the  $\geq 5$  to 20  $\mu m$  aggregates. At electrolyte concentrations of 20.49, 15.85, 9.75, and 5.16 mol  $m^{-3}$ , the differences between the amounts of  $\leq 20$  and  $\leq 5$   $\mu m$  aggregates were 1.89, 4.11, 6.07, and 4.99 g/100 g soil, respectively.

The deviation in the trend for the 5.16 mol  $m^{-3}$  treatment suggests a sudden reduction in the stability of the  $\leq 20$   $\mu m$  aggregates and that most of these aggregates had slaked into particles as small as 5  $\mu m$ . Slaking of the  $\leq 20$   $\mu m$  fraction also resulted in corresponding increases in the quantities of the finer fractions.

For the above electrolyte concentrations, the differences in amounts of  $\leq 5$  and  $\leq 2$   $\mu m$  fractions were 0.27, 0.89, 1.97, and 3.96 g/100 g soil, respectively; the corresponding differences in the  $\leq 2$  and  $\leq 1$   $\mu m$  fractions were 0.08, 0.23, 0.47, and 2.05 g/100 g soil, respectively. The sharp increase in the value corresponding to the most dilute electrolyte solution was the result of slaking of the  $\leq 20$   $\mu m$  aggregates. A similar trend in particle size distribution with decreasing electrolyte concentration was also observed at SAR 20.

These observations suggest that slaking preceded clay dispersion and that aggregate slaking will occur with a reduction in the electrolyte concentration below the threshold value. At SAR 0, Arlington soil aggregates

were somewhat stable even when the electrolyte concentration was as low as 0.28 mol  $m^{-3}$ .

#### Size of the Dispersed Aggregate

The relationship between the size and the amount of particles slaked or dispersed is of two types depending upon electrolyte concentration (Fig. 2). At high electrolyte concentration, the relationship is approximately linear, whereas at lower electrolyte concentrations, the relationship is curvilinear. The linear relationship suggests that a mechanical effect is being exerted on the soil aggregates which is proportional to the size of the aggregates. Soil aggregates may breakdown (slake) as a result of the development of internal swelling pressure or of local shearing stresses which deform the weakened aggregates (Waldron and Constantin, 1968). According to the Vant Hoff equation, the development of internal swelling pressure depends on the difference between the concentration within the soil aggregate and the bulk solution (Shainberg et al., 1971; Emerson, 1967). In our study, the gradual reduction in the electrolyte concentration and the overnight period of equilibration minimized the development of swelling pressure. Thus, the breakdown of Ca-saturated soil aggregates due to swelling of clay should not be significant (Emerson, 1954). The linear relationship could be attributed to the slight expansion of the DDL on the clay surfaces. Such expansion may be large enough to increase the repulsive forces between the clay particles and to create sheer stresses within the aggregates causing their breakdown. The linear relationship between the size of aggregates and the amount of each size fraction slaked or dispersed is consistent with the observation that there was no dispersion of the  $\leq 1$   $\mu m$  and no or very little dispersion of the  $\leq 2$ - $\mu m$  clay fractions. This observation indicates that slaking can occur in the absence of clay dispersion.

The curvilinear relationship corresponds to condi-

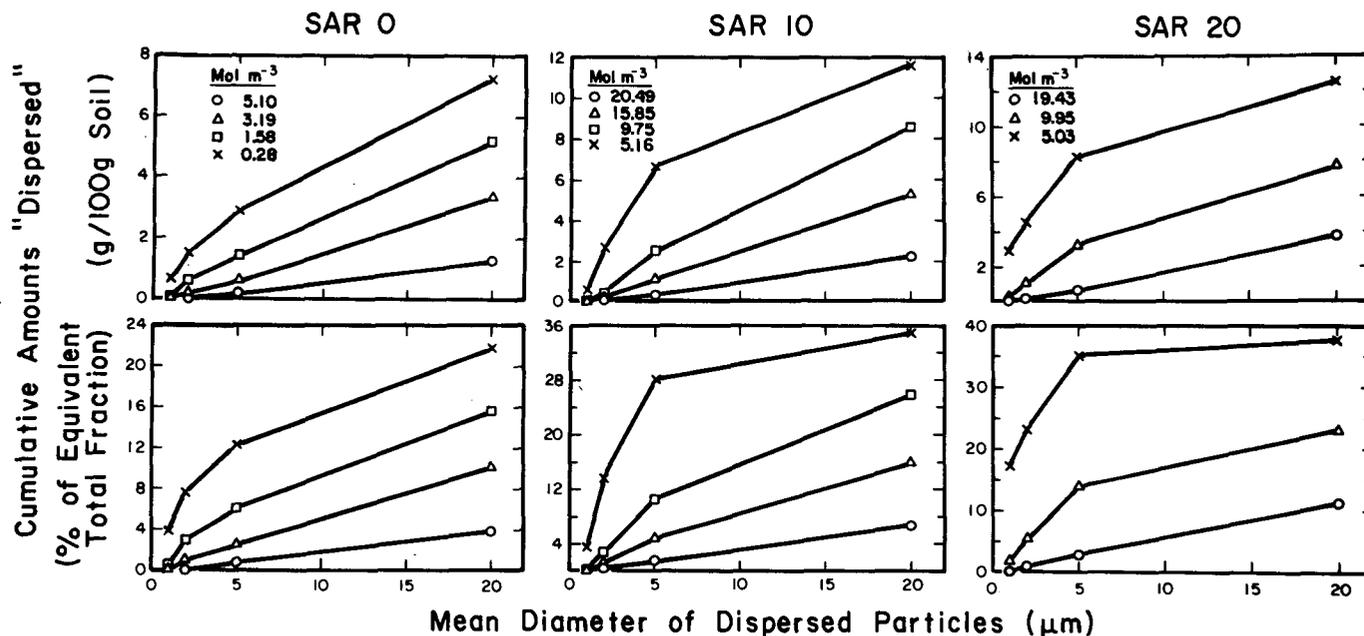


Fig. 2. The effect of electrolyte concentration and sodium adsorption ratio on the amounts and size of slaked and dispersed particles of the Arlington soil.

tions under which dispersion had occurred. Emerson (1954, 1967) likewise observed a significant effect of clay dispersion on aggregate stability. The further expansion of the DDL at low electrolyte concentration may cause an increase in the extent of the repulsion forces between clay particles to the point that clay disperses and soil aggregates break down into smaller sizes. The curvilinear relationship between the size of slaked and dispersed particles and the respective amounts of slaking or dispersion of each size fraction is taken as evidence of the enhanced role of chemical dispersion. Slaking of soil aggregates into smaller sizes may result from the weakening of clay bridges between subaggregates, causing a continuous increase in the amount of small aggregates at the expense of larger aggregates. For example, at SAR 0 and an electrolyte concentration of  $5.10 \text{ mol m}^{-3}$ , the ratio of the  $\leq 5$  to the  $\leq 20 \mu\text{m}$  aggregates was 0.14 (Fig. 1). When the electrolyte concentration was reduced to  $0.18 \text{ mol m}^{-3}$  the ratio increased to 0.4. Similarly, the ratio of the  $\leq 2\text{-}\mu\text{m}$  to the  $\leq 5\text{-}\mu\text{m}$  dispersed aggregates increased from 0 to 0.5 under the same treatment. As mentioned above, the  $\leq 20\text{-}\mu\text{m}$  aggregates were less stable to reduction in electrolyte concentration at SAR 10 compared to SAR 0. At SAR 10, the 0.16 ratio of the  $\leq 5$ - to  $\leq 20\text{-}\mu\text{m}$  slaked aggregates at electrolyte concentration of  $20.49 \text{ mol m}^{-3}$  increased to 0.57 when the electrolyte concentration was reduced to  $5.16 \text{ mol m}^{-3}$ .

#### Mechanism of Slaking

Our results showed that the initial breakdown of soil aggregates associated with a reduction in electrolyte concentration took place without clay dispersion. A further reduction in electrolyte strength resulted in an extensive slaking of larger into smaller aggregates along with release of clay. Hence, these observations indicate a mechanism of slaking that is different from that proposed by Emerson and Bakker (1973). They

assumed that initially the periphery of the aggregates releases clay (disperses), with the remainder of the aggregates being unchanged. This process was assumed to continue until the dispersion of the outer layers ceased, then the remaining core of the aggregates gradually broke down.

Our results indicate that slaking of aggregates into sizes comparable to those of medium silt took place prior to clay dispersion. It is unlikely that such large aggregates originated from the periphery of larger aggregates. Rather, it is more plausible to consider a random breakdown of soil aggregates at planes of weakness prior to clay dispersion.

The random breakdown concept is supported by the ratio of total clay to total silt fractions in the  $\leq 20\text{-}\mu\text{m}$  aggregates slaked at different electrolyte concentrations at SAR levels of 0 or 10 (Fig. 3). The ratios remained relatively constant as the electrolyte concentration was varied. Actually, the ratios were 1.28 and 0.98 for electrolyte solutions adjusted to SAR 0 and 10, whereas that for the whole soil was 1.44.

The ratio of total clay to silt reflects the relative importance of the slaking and clay dispersion processes. If clay disperses from the peripheries of the intact soil aggregates, then the ratio would increase as more clay and less silt disperse as a result of the limited slaking. To the contrary, it appears that with each additional amount of the total clay found in the slaked  $\leq 20\text{-}\mu\text{m}$  aggregates, a random slaking occurred in proportion to that amount of clay. Russel (1971) indicated that soil aggregates may break down completely or partly. Our data suggest that soil aggregates may break down without clay dispersion when the repulsion forces attain a level that allows only the shearing stresses to become operative.

In contrast to the relatively constant clay/silt ratio for  $\leq 20\text{-}\mu\text{m}$  aggregates, the ratio for the  $\leq 5 \mu\text{m}$ -aggregates increased upon reduction in electrolyte concentration (Fig. 3). Slaking of aggregates  $\geq 5 \mu\text{m}$  led

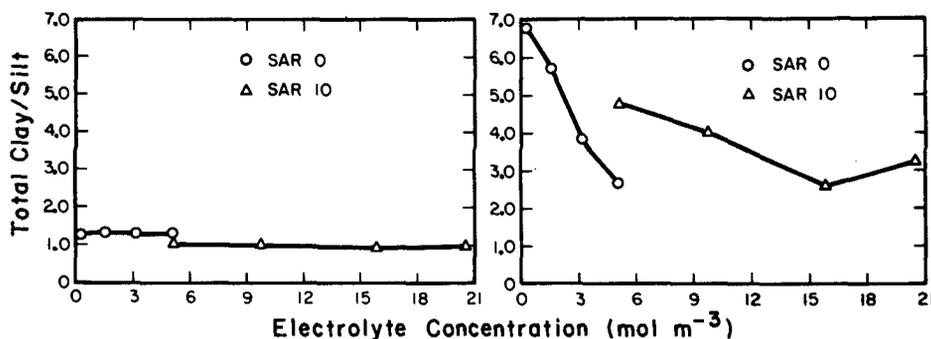


Fig. 3. The effect of electrolyte concentration on the ratio of total clay to silt obtained from the  $\leq 20\text{-}\mu\text{m}$  (left) and  $\leq 5\text{-}\mu\text{m}$  (right) aggregates slaked from the Arlington soil.

to the release of the medium silt particles ( $5\text{--}20\ \mu\text{m}$ ) and thus to a differential enrichment of the  $\leq 5\ \mu\text{m}$  fraction in clay.

On the other hand, total clay fractionated from the  $\leq 20\text{-}\mu\text{m}$  or  $\leq 5\text{-}\mu\text{m}$  slaked aggregates were essentially in two forms, the clay dispersed to sizes  $\leq 2\ \mu\text{m}$  (dispersed clay) and the clay incorporated in aggregates  $\geq 2\ \mu\text{m}$  (aggregated clay). The latter fraction was calculated by subtracting the experimentally determined amounts of dispersed clay ( $\leq 2\ \mu\text{m}$ ) from the total clay fractionated from the  $\leq 5\text{-}$  or  $\leq 20\text{-}\mu\text{m}$  slaked aggregates at the respective SAR-electrolyte concentration combination. It appeared that a ratio of the aggregated clay to silt would give an estimate of stability of soil aggregates. A greater silt content and/or smaller aggregated clay content (extensive slaking) would decrease the above ratio.

The ratio of aggregated clay to silt fractions obtained from the  $\leq 20\text{-}\mu\text{m}$  aggregates slaked at successively more and more dilute electrolyte concentrations adjusted to SAR 0 or 10 is germane. At SAR 0, the ratio decreased with decreasing electrolyte concentration because of the decreasing stability of the  $\leq 20\text{-}\mu\text{m}$  aggregates. At SAR 10, the ratio remained relatively constant until the electrolyte concentration decreased to  $9.75\ \text{mol m}^{-3}$ . Below that level, the aggregated clay became less stable and dispersed into  $< 2\text{-}\mu\text{m}$  sizes (data not shown). Similarly, Fig. 4 shows that with decreasing electrolyte concentration at SAR 10 or 20, the ratio of dispersed to aggregated clay remained relatively constant at or above  $9.8\ \text{mol m}^{-3}$  electrolyte concentration and thus reflected a certain degree of equilibrium between slaking and clay dispersion; but when the electrolyte concentration was reduced below  $9.8\ \text{mol m}^{-3}$ , a sharp increase in the ratio of dispersed to aggregated clay was observed. The increase in this ratio indicates that the failure of soil aggregates and consequently a substantial release of dispersed clay occurred at the expense of aggregated clay. The continuous increase in the ratio at SAR 0 indicated a similar though less extensive trend.

### CONCLUSIONS

When the electrolyte concentration, at a given SAR, is high enough to prevent clay dispersion, slaking of soil aggregates into sizes as small as  $5\ \mu\text{m}$  occurred in the California soils studied. A further reduction in electrolyte concentration caused the fine soil aggregates to break down and the clay to disperse. Clay did

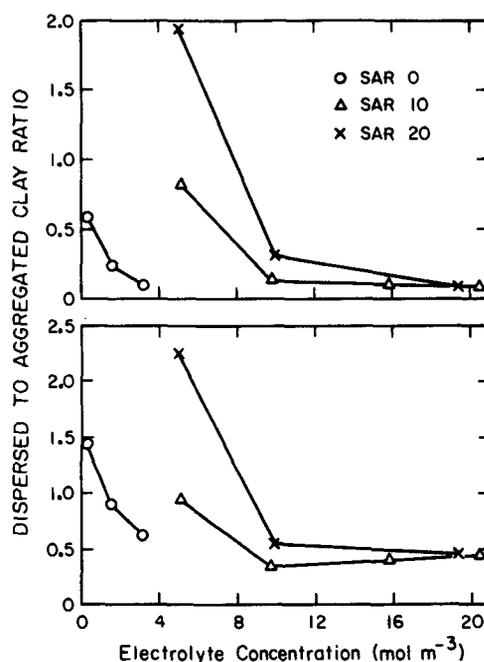


Fig. 4. The ratio of dispersed to aggregated clay in relation to electrolyte concentration and SAR. Both clay fractions were obtained from aggregates slaked from the Arlington soil (top:  $\leq 20\text{-}\mu\text{m}$  aggregates, and bottom:  $\leq 5\text{-}\mu\text{m}$  aggregates).

not appear to disperse from the peripheries of intact soil aggregates, instead it dispersed concurrently with aggregate breakdown.

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