

## Variations in Soil Stability within and among Soil Types

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### ABSTRACT

One of the most important considerations when irrigating with marginal water or managing sodic soils is maintaining or restoring good soil structure. Recommendations developed to date have considered water quality parameters and assumed that soils behaved similarly. We examined the flocculation behavior of three different types of micaceous soils at variable electrolyte concentration, sodium adsorption ratio [SAR =  $\text{Na}/(\text{Ca} + \text{Mg})^{0.5}$ , where concentrations are expressed in  $\text{mmol L}^{-1}$ ], and pH. The variability in critical coagulation concentration (CCC) among soil types and among samples within the same soil type also was investigated. The CCC values were calculated at electrolyte concentrations of 2, 5, 10, 20, and 40  $\text{mmol L}^{-1}$  at SAR values of 5, 10, 20, 40, and 80 ( $\text{mmol L}^{-1})^{0.5}$ , and at pH values of 6.0, 7.5, and 9.0. The variability in CCC was large among soil types of similar mineralogy, and even within the same soil type. This variability was greater at higher pH, suggesting that at least part of the variation results from differences in variable charge. Increasing pH had an adverse effect on dispersion, especially when the SAR was high enough to break apart the illite domains. There was no relationship among CCC, organic matter, and Fe and Al oxide contents for the soils studied. In the range investigated (1–4 g organic C  $\text{kg}^{-1}$  soil), only the Ebro Basin soils showed increases in CCC with increasing organic matter at high pH and SAR. Aggregate stability was measured on aggregates of the soils after saturation with solutions having salt concentrations of 2 and 40  $\text{mmol L}^{-1}$ ; SAR values of 5, 20, and 80 ( $\text{mmol L}^{-1})^{0.5}$ ; and pH values of 6.0, 7.5, and 9.0. No relation was found between the flocculation test data and the aggregate stability results. Apparently the measured parameters in these two tests are governed by different soil factors. Particle-size distribution and porosity, as well as the drying and rewetting processes, exert a major influence on aggregate stability, but are not considered in flocculation tests. Regardless of the test used, differences in results for samples of the same soil type preclude the use of generalized threshold lines for soil stability.

**M**AINTENANCE OF SOIL STABILITY is an important aspect of agricultural management. Poor aggregate stability, clay dispersion, and low infiltration are often aggravated in arid soils by chemical conditions such as high exchangeable Na.

Early recommendations for maintaining good soil structure advocated reducing the ESP of soils to <15 by the application of chemical amendments (U.S. Salinity Laboratory Staff, 1954). Subsequently, stability lines including solution salt concentration as well as ESP were recommended (e.g., Quirk and Schofield, 1955; Rhoades, 1982; Ayers and Westcot, 1985), since it had been noted that increasing solute concentration increased soil stability.

Additional variables such as Fe oxides (McNeal and Coleman, 1966), organic matter (Kemper and Kock,

1966; Gupta et al., 1984), clay content and mineralogy (Frenkel et al., 1978), soluble silica (Shanmuganathan and Oades, 1983), pH (Gupta et al., 1984; Suarez et al., 1984), and soil weatherability (Shainberg et al., 1981) have also been shown to relate to soil stability. More recently, Pratt and Suarez (1990) have shown that a unique relationship considering only salinity and exchangeable Na cannot provide a general prediction of hydraulic conductivity changes for arid soils, because similar soils differ greatly in their structural stability.

The objectives of this work were to: (i) compare the stability to dispersive conditions for soils having the same mineralogy (micaceous); and (ii) examine the degree of variability within a specific soil type to determine whether a predictive relationship can be developed for soils of a specific soil series or within a given mapping unit. Soil stability was evaluated at variable salt concentration, SAR, and pH using both a dispersion test and an aggregate stability test. We examined the relationship of soil stability to differences in soil properties such as organic matter,  $\text{CaCO}_3$ , texture, and content of Fe and Al oxides. We also compared the results of the aggregate stability and dispersion tests.

### MATERIALS AND METHODS

Three micaceous soils were studied. Their classification and mineralogy are given in Table 1. Particle-size analysis was determined by x-rays, measuring the concentration of particles remaining at decreasing sedimentation depths as a function of time with a Sedigraph 5000 (ET Micrometrics, Norcross, GA<sup>1</sup>). Mineralogy was studied by XRD of the <2- $\mu\text{m}$  fraction, and by FTIR. Di- and trioctahedral mica were determined by examining XRD d spacings in the 0.15- to 0.154-nm region (Fanning et al., 1989), along with the IR absorbance resulting from octahedral cations (e.g., Mg and Fe for trioctahedral mica, Stubican and Roy, 1961).

Oxides were extracted using the method of Jackson et al. (1986). Cations were determined by ICP, and organic and inorganic C were analyzed by  $\text{CO}_2$  coulometry (UIC Corporation, Joliet, IL). A dispersion test was performed for each of the Ebro Basin, Ramona, and Clarence soils (34 soils in all). Two soils from each type were chosen for the aggregate stability test: Ebro Basin 1 and 18, Ramona 1B and 7B, and Clarence 1 and 9.

Different solution compositions also were used in an attempt to test the response of the soils in these experiments to different irrigation waters. The solutions were prepared as described below.

**Abbreviations:** SAR, sodium adsorption ratio; CCC, critical coagulation; ESP, exchangeable sodium percentage; XRD, x-ray powder diffraction; FTIR, Fourier transform infrared spectrometry; IR, infrared; ICP, inductively coupled plasma emission; C, electrolyte concentration; IAP, ion activity product; EM, electrophoretic mobility; ZPC, zero point of charge; PZNPC, point of zero net proton charge; OC, organic carbon content.

<sup>1</sup> Trade names are provided for the benefit of the reader and do not imply endorsement by the USDA.

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Published in *Soil Sci. Soc. Am. J.* 56:1412–1421 (1992).

Table 1. Soil classification and mineralogy.

Soil	Classification	Mineralogy
Ebro Basin soils, Spain	Fine, illitic, xeric, alkaline	Mica dioctahedral
Ramona soils, California	Fine-loamy, mixed, thermic Typic Haploxeralf	Mica di- and trioctahedral
Clarence soils, Illinois	Fine, illitic, mesic Aquic Argiudoll	Mica dioctahedral

### Solutions

Solutions were prepared prior to each experiment. The salts  $\text{CaCl}_2$ ,  $\text{NaHCO}_3$ , and  $\text{NaCl}$  were used to achieve different  $C$  levels and SAR values [ $C = 2, 5, 10, 20$ , and  $40 \text{ mmol L}^{-1}$ ;  $\text{SAR} = 5, 10, 20, 40$ , and  $80 \text{ (mmol L}^{-1})^{0.5}$ ]. A computer program with the equilibrium constants of Suarez (1977) was used to calculate the  $[\text{Ca}^{2+}]$   $[\text{CO}_3^{2-}]$  IAP and partial pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ) of solutions with input of solution composition and pH. By adjustment of the input  $\text{HCO}_3^-$  and  $\text{Cl}^-$  and examination of the output IAP and  $p\text{CO}_2$ , we determined which combination of pH, SAR, and salt concentration could be prepared to within 0.5 log units of calcite saturation (by bubbling with  $\text{CO}_2$  or replacing  $\text{Cl}^-$  for  $\text{HCO}_3^-$ ). Solutions were initially prepared with

$\text{CO}_2$ -free deionized water and  $\text{CO}_2$  was bubbled into the solution until the desired pH was achieved. Calcite undersaturation  $>0.5$  log units occurred for pH 6.0 and in some conditions at pH 7.5 and 9.0. Calcite undersaturation is only a concern for the Ebro Basin soils that contain calcite. At pH 7.5 and 9.0, calcite undersaturation occurs at low salt concentration and high SAR; in these situations Ebro Basin soils were 100% dispersed, consequently the possible reduction of the SAR (and increased stability) by Ca dissolution did not affect the CCC values reported. Ebro Basin soils (Table 2) were not investigated at pH 6.0, since an input SAR cannot be maintained for calcareous soils with a calcite-undersaturated solution. Calcite undersaturation at pH 6.0 does not result in unstable solution compositions for noncalcareous soils, so investigations at pH 6.0 remained possible for the noncalcareous Ramona and Clarence soils. Also, supersaturation values up to 0.5 log units were allowed, as these levels can be maintained in soil solutions without calcite precipitation.

### Dispersion Test

Clay concentration of the soils varied (Table 2). To compare the dispersion test results among samples, the amount of whole soil necessary to achieve a 1% clay suspension was calculated for every soil, suspensions were prepared using distilled water, and samples were then sonicated for

Table 2. Particle-size distribution,  $\text{CaCO}_3$  content, and some variable charge components of the Ebro Basin, Ramona, and Clarence soils.

Soil	Depth cm	Particle-size distribution			$\text{Fe}_2\text{O}_3$	$\text{Al}_2\text{O}_3$	Organic C	$\text{CaCO}_3$
		Clay ( $<2 \mu\text{m}$ )	Silt ( $2-50 \mu\text{m}$ )	Sand ( $>50 \mu\text{m}$ )				
		kg $\text{kg}^{-1}$			g $\text{kg}^{-1}$			
<b>Ebro Basin soils</b>								
1	0-30	0.257	0.692	0.051	19.4	3.8	1.3	406
5	0-30	0.406	0.517	0.077	18.8	4.4	4.2	387
10	0-30	0.305	0.648	0.047	20.9	4.2	4.1	395
12	0-30	0.285	0.668	0.047	19.9	4.5	3.4	385
17	0-30	0.388	0.590	0.022	23.6	4.5	3.9	331
18	0-30	0.172	0.711	0.117	15.9	3.5	3.9	363
19	0-30	0.308	0.647	0.044	20.6	4.3	3.9	349
2532	0-30	0.631	0.360	0.047	25.5	7.0	1.6	320
Mean		0.344	0.604	0.057	20.6	4.5	3.3	367
<b>Ramona soils</b>								
1A	0-20	0.148	0.313	0.540	7.5	0.8	12.1	none
1B	20-40	0.231	0.222	0.548	8.0	0.9	4.2	none
2A	0-20	0.126	0.214	0.660	6.8	0.7	6.8	none
2B	20-40	0.141	0.262	0.596	8.0	0.8	4.3	none
3A	0-20	0.088	0.214	0.698	4.9	0.7	8.7	none
3B	20-40	0.125	0.153	0.722	5.8	0.8	2.0	none
4A	0-20	0.158	0.146	0.696	9.0	0.9	2.0	none
4B	20-40	0.152	0.147	0.701	9.2	0.8	1.2	none
5A	0-20	0.186	0.228	0.586	8.9	0.8	4.3	none
5B	20-40	0.199	0.325	0.476	10.7	1.0	2.1	none
6	0-20	0.180	0.248	0.573	10.8	0.9	2.3	none
7A	0-20	0.183	0.112	0.704	5.9	0.6	4.2	none
7B	20-40	0.159	0.195	0.646	6.3	0.7	3.5	none
8A	0-20	0.175	0.273	0.552	9.0	0.9	17.0	none
8B	20-40	0.155	0.287	0.558	8.1	0.7	11.4	none
9	0-20	0.204	0.260	0.536	10.6	0.9	1.8	none
Mean		0.163	0.225	0.612	8.1	0.8	5.5	
<b>Clarence soils</b>								
1	66-109	0.735	0.207	0.058	20.2	3.0	4.5	none
2	50-79	0.689	0.242	0.069	15.5	2.3	3.3	none
3	41-76	0.660	0.296	0.044	16.2	2.2	3.0	none
4	33-66	0.796	0.187	0.017	13.8	2.5	3.4	none
5	25-51	0.762	0.215	0.023	15.7	3.1	5.3	none
6	41-61	0.635	0.285	0.080	22.5	3.8	4.7	none
7	56-91	0.618	0.348	0.034	17.1	2.8	3.2	none
8	41-61	0.750	0.237	0.013	13.7	2.7	3.5	none
9	41-69	0.680	0.265	0.055	17.6	3.3	3.0	none
10	41-66	0.679	0.264	0.057	18.6	3.5	1.1	none
Mean		0.700	0.255	0.045	17.1	2.9	3.5	

10 s at 50 W, and shaken for 30 min. Seven milliliters of each salt solution were pipetted into a 10-mL spectrophotometer cuvette, and 0.50 mL of a 1% clay suspension was added. The final dilute suspension was stirred and the transmittance read after 3 h (Goldberg and Glaubig, 1987) at a wavelength of 650 nm. After reading transmittances, electrical conductivity and pH were also measured in each cuvette. Changes from the initial solution conditions were <3% for electrical conductivity and 2% for pH. Solutions having low salt concentrations and high pH were most affected by such changes. The reproducibility of the method was evaluated by duplicating a series of experiments for each soil type. The standard error of the mean was 1.06% transmittance.

The soil sample of each soil type with clay content closest to the median value was chosen to develop the relation between transmittance and clay percentage. These soil samples were no. 19 for Ebro Basin, no. 7B for Ramona, and no. 9 for Clarence. A soil sample containing 100 mg of clay was placed into a centrifuge tube, 50 mL of a NaCl-saturated solution were added, and the suspensions were stirred for 30 min and centrifuged. After decantation of the supernatant, the procedure was repeated three times. The clay was then washed until the electrical conductivity of the solution was  $<0.1 \text{ dS m}^{-1}$ . The solutions then were made up to 10 mL with distilled water, taking the initial weight of the soil into consideration. This 1% clay suspension was used to develop the calibration curve following the methodology described above. The calibration curves for the three soils were similar. The equation for transforming transmittance to clay content was:  $y = 0.0099x^2 - 2.272x + 128.675$ , where  $y$  is the percentage of clay and  $x$  is the percentage transmittance value.

### Aggregate Stability

Aggregate stability was determined using the method of Kemper and Rosenau (1986). The salt solutions were prepared as described above. For aggregate stability, however, we selected only three SAR values [5, 20, and 80 ( $\text{mmol L}^{-1})^{0.5}$ ], two electrolyte concentrations (2 and 40  $\text{mmol L}^{-1}$ ), and three pH values (6, 7.5, and 9). Solutions were placed into the cans that accept the sieves containing the soil aggregates. Each sample in this portion of the study was duplicated. Aggregates were prepared by weighing 20-g samples of each soil into centrifuge tubes, the desired solution was added in a soil/solution ratio of 1:5, and the samples were stirred for 30 min and centrifuged. This operation was repeated three times. After removing the supernatant, the soils were mixed in order to eliminate stratification by particle size. The samples were subsequently air dried (slowly), and the soil was sieved through 2.7- and 1.0-mm screens. The 1.0- to 2.7-mm portion was selected for the aggregate stability test. Results are expressed as follows:

$$\% \text{ unstable aggregates} = (A - B - C)100/(A - C)$$

where  $A$  = initial weight of the soil,  $B$  = weight of the soil retained on the sieve after the reaction, and  $C$  = weight of the soil particles  $>1 \text{ mm}$  (the screens of the aggregate stability machine contain sieves with 1-mm size openings).

When the water evaporates in a saturated paste, the SAR increases, depending on the ratio of initial to final water content. Since the initial step of the Kemper and Rosenau (1986) procedure involves humidification of the sample, we calculated that the initial SAR would be modified by a factor of 0.97 for Ebro Basin soils, 0.70 for Ramona soils, and 1.1 for Clarence soils. If we consider the Ca-Na selectivity constants for Silver Hill illite found by Amrhein and Suarez (1991), a cation-exchange capacity of 0.10  $\text{mol kg}^{-1}$  for our soils, and the highest salt concentration used

in this pretreatment (40  $\text{mmol L}^{-1}$ ), we calculate that only very small shifts in the ESP occurred from the water content changes. The calculated ESP values in equilibrium with the external solutions are presented in Table 3. Also shown in Table 3 are the calculated ESP values after correction for changes in water content. These relatively small shifts in ESP did not affect the data interpretation. At a concentration of 2  $\text{mmol L}^{-1}$ , changes in ESP are negligible.

## RESULTS AND DISCUSSION

### Variability in Dispersibility among Soil Types

For smectites, it is well documented that the light scattering of a suspension is related to the size and shape of the particles as well as the clay concentration (Banin and Lahav, 1968). The calibration curve developed above was done with pure Na-saturated soils and salt-free suspensions; however, in this experiment we measured light transmission in suspensions at different salt concentration, SAR, and pH. In order to evaluate the influence of these variables, a set of 14 dispersion tests with Clarence no. 1 were performed; three of them varying the pH (6.0, 7.5, and 9.0) at  $C = 6 \text{ mmol L}^{-1}$  and  $\text{SAR} = 6 (\text{mmol L}^{-1})^{0.5}$ ; three of them varying the pH (6.0, 7.5, and 9.0) but at  $C = 6 \text{ mmol L}^{-1}$  and  $\text{SAR} = 40 (\text{mmol L}^{-1})^{0.5}$ ; four of them varying the salt concentration (2, 6, 8, and 10  $\text{mmol L}^{-1}$ ) at  $\text{SAR} = 6 (\text{mmol L}^{-1})^{0.5}$  and  $\text{pH} = 6.0$ ; and four at different SAR (2, 20, 40, and pure Na) ( $\text{mmol L}^{-1})^{0.5}$  and  $C = 6 \text{ mmol L}^{-1}$  and  $\text{pH} = 6.0$ .

After reading the optical transmission, the  $<2\text{-}\mu\text{m}$  clay fractions were dried and weighed. The amount of clay in suspension was calculated with the transmission data and the nonlinear regression equation given above. The relation between calculated clay amount and the amount weighed is shown in Fig. 1. Using this figure, our calibration curve is overestimating the clay dispersed by an average of 15%. Since the CCC is an arbitrary parameter, in this case it was calculated for each soil as the concentration necessary for 17% (rather than 20 or 50%, as has been used by others) of the dispersed clay to remain in suspension. This value was selected to account for the correction necessary to eliminate overestimation of the calibration curve.

The CCC values increased with increasing SAR and pH. This effect has been noted previously by several authors (Suarez et al., 1984; Goldberg and Glaubig, 1987). We evaluated the feasibility of using a general

**Table 3.** Calculated exchangeable sodium percentage (ESP) for the three soils used in this study after pretreatment with solutions at different sodium adsorption ratios (SAR) and 40  $\text{mmol L}^{-1}$  salt concentration for the aggregate stability test.

ESP	ESP		
	SAR 5	SAR 20	SAR 80
Equilibrium†	9.5	21.9	54.5
Ebro Basin soils‡	9.1	21.3	53.5
Ramona soils‡	6.5	16.7	44.4
Clarence soils‡	10.7	23.1	56.9

† Data calculated with Amrhein and Suarez (1991)  $\text{Ca}^{2+}\text{-Na}^+$  exchange selectivity values for Silver Hill illite.

‡ Data calculated with Amrhein and Suarez (1991)  $\text{Ca}^{2+}\text{-Na}^+$  exchange selectivity value for actual water content at start of aggregate stability test.

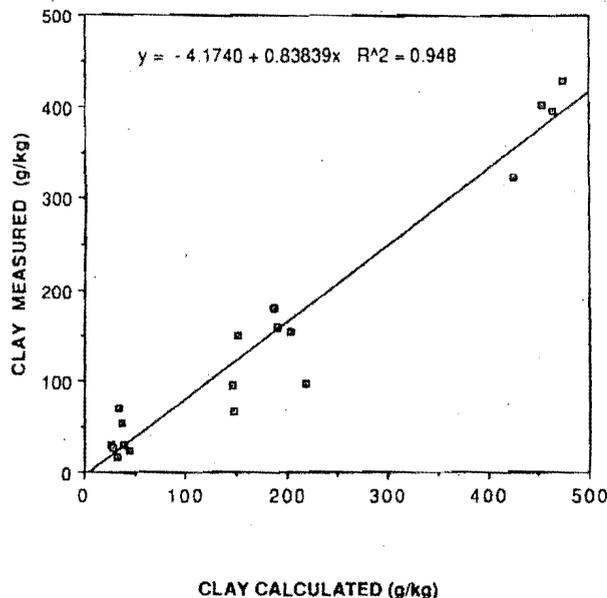


Fig. 1. Calculated clay in suspension (determined with transmission data) and the measured amount of clay with varying sodium adsorption ratio (SAR), pH, and salt concentration.

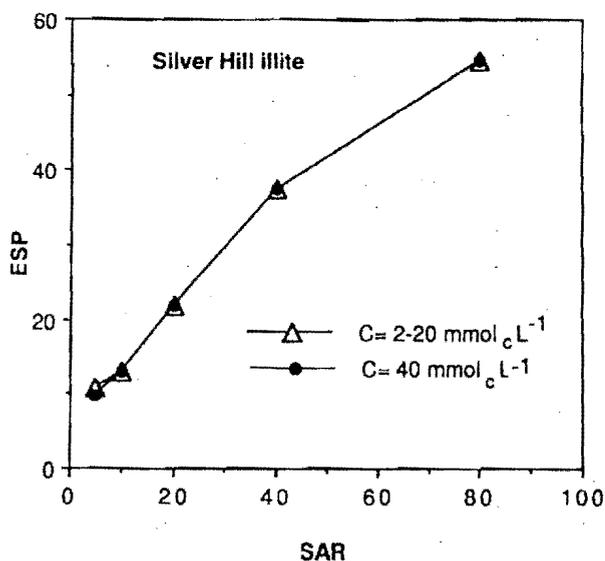


Fig. 2. Relationship between the exchangeable sodium percentage (ESP) and the equilibrium sodium adsorption ratio (SAR) of the external solution for Silver Hill illite for the salt concentration range of 2 to 40  $\text{mmol c L}^{-1}$ ; calculated from exchange data of Amrhein and Suarez (1991).

guideline for stability of micaceous soils under the assumption that different soils respond similarly to changes in pH and SAR.

The relationship between ESP and SAR may differ from soil to soil. Differences in cation affinity are not expected for samples of our three types of soils either within or among these specific soil types. The essentially pure illite clay mineralogy and the close variable-charge content makes a general ESP-SAR relationship a reasonable assumption for these soils. For Silver Hill illite, Amrhein and Suarez (1991) found no significant differences in the Gapon value in the

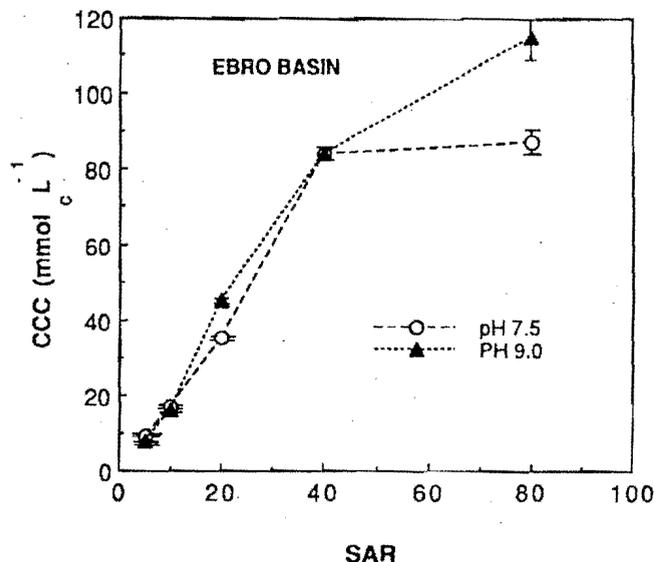


Fig. 3. Mean critical coagulation concentration (CCC) of the eight Ebro Basin soils as a function of sodium adsorption ratio (SAR) and pH. Standard errors are indicated.

range of SAR and salt concentration used in the present study. The Gapon constant ( $K_G$ ) relates the solution SAR to exchangeable Ca and Na through the formula ( $E_{\text{Na}^+}/E_{(\text{Ca}^{2+}, \text{Mg}^{2+})} = K_G \text{ SAR}$ , where  $E_i$  is the exchange fraction of cation  $i$  on the exchanger phase. The relationship between the ESP and SAR is given in Fig. 2 based on the data of Amrhein and Suarez (1991).

Median values of the CCC at each SAR for each type of soil at pH 6.0, 7.5, and 9.0 are represented in Fig. 3, 4, and 5 for the 8 Ebro Basin, 16 Ramona, and 10 Clarence soils, respectively. These lines represent the thresholds between flocculated and dispersed states.

The lines obtained for the median CCC values of each set of soils are quite different, with the Ebro Basin soils being least stable and the Clarence soils most stable. Such differences among soils were surprising, since the soils have similar mineralogy. Although flocculation behavior of the Clarence soil was relatively insensitive to changes in pH, the pH changes from 6.0 to 9.0 generally produced changes in CCC comparable to those produced by changes in SAR from 20 to 80 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> (Fig. 5). This sensitivity to pH is comparable to that observed by Suarez et al. (1984): changes in pH from 6.0 to 9.0 provided changes in hydraulic conductivity equal to those produced by changes in SAR from 20 to 40 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>. The Ramona and the Ebro Basin soils also showed a strong effect of SAR on CCC. The mica content of all soils was high (>90% of the clay fraction). The Ebro Basin and Clarence soils both contain dioctahedral mica, while the clay fraction of the Ramona soil is a mixture of both di- and trioctahedral mica. From these data we deduced that clay mineralogy cannot explain the variations in CCC among the soils studied.

The Ebro Basin soils were relatively unstable compared with the noncalcareous soils. These differences are probably caused by factors other than the  $\text{CaCO}_3$  content. In contrast to these results, Gupta et al. (1984) observed that calcareous soils were less dispersed than

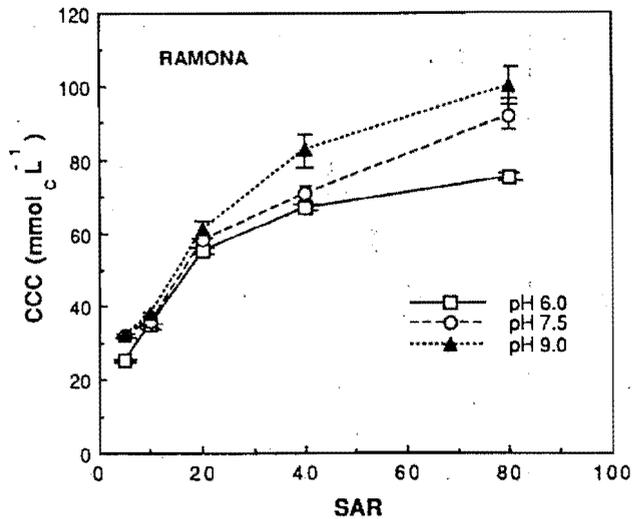


Fig. 4. Mean critical coagulation concentration (CCC) of the 16 Ramona soils as a function of sodium adsorption ratio (SAR) and pH. Standard errors are indicated.

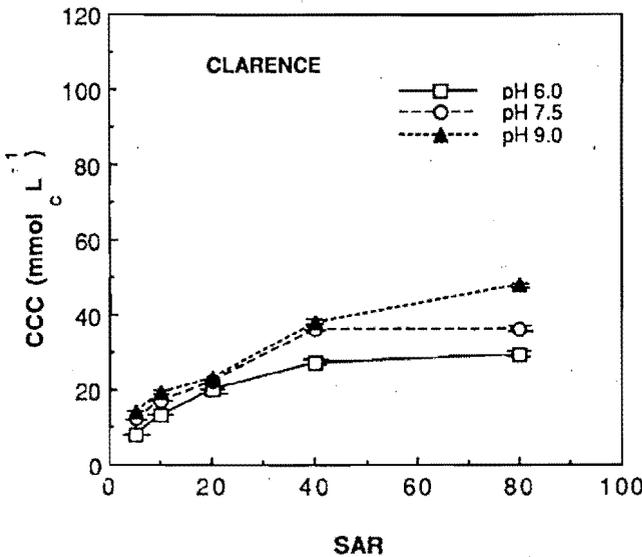


Fig. 5. Mean critical coagulation concentration (CCC) of the 10 Clarence soils as a function of sodium adsorption ratio (SAR) and pH. Standard errors were smaller than the representation of the points.

noncalcareous soils, particularly at high electrolyte concentrations and SAR values. Our observations, however, are based on solutions that were at or near equilibrium with respect to calcite, which is usually the case for irrigation waters. Failure to prevent calcite dissolution by using synthetic solutions prepared from Cl salts adjusted to different pH values with NaOH results in an increase in the Ca concentration. Thus, SAR values are lower and EC values are higher upon reaction with calcareous soils. This process may explain the apparent high stability of calcareous soils found by Gupta et al. (1984).

The data obtained for the Ebro Basin and Ramona soils are more similar to each other than to the data for the Clarence soil, despite the fact that the Ramona soil has the lowest and the Ebro Basin soil the highest oxide contents (Table 2). Organic matter differences

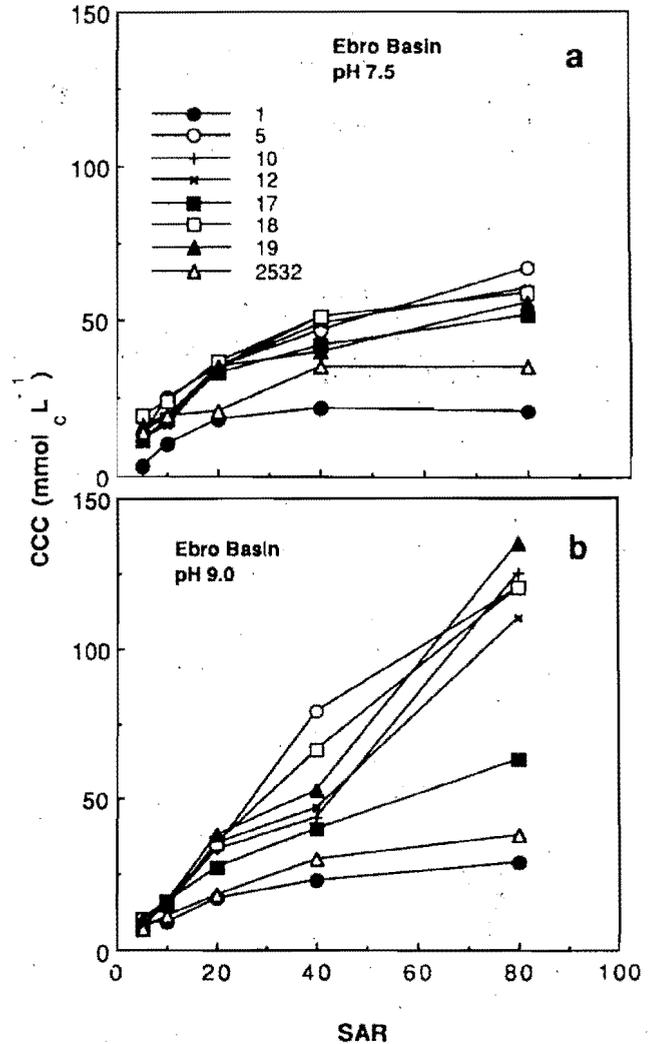


Fig. 6. Critical coagulation concentration (CCC) as a function of sodium adsorption ratio (SAR) for each of the eight Ebro Basin soils at (a) pH 7.5 and (b) pH 9.0.

among the three soil types also cannot explain the differences in CCC. The Ramona soil has 60% more organic matter in the upper horizon than does the Ebro Basin soil, and 20% more organic matter in the lower horizon (Table 2). The composition of this organic matter may be as important for soil stability as the soil organic matter content (Smith and Elliot, 1990).

The detrimental effect of high pH on clay dispersion was more evident at SAR values  $>20$  ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> (for the Ramona and Clarence soils) or 40 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> (for the Ebro Basin soils). This result is in agreement with the interactive effect of pH and SAR on flocculation-dispersion behavior as reported by Goldberg and Forster (1990). They concluded that the pH dependence of the CCC values at SAR 0 to 80 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> for kaolinitic, montmorillonitic, and illitic soil clays was much less pronounced than at infinite SAR (pure Na solutions).

For the Ebro Basin soils, CCC increased with increasing SAR up to SAR 40 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>, Fig. 3, and no significant CCC differences were found between pH 7.5 and 9.0. Above SAR 40, changes in pH resulted in changes in the CCC value. Similar

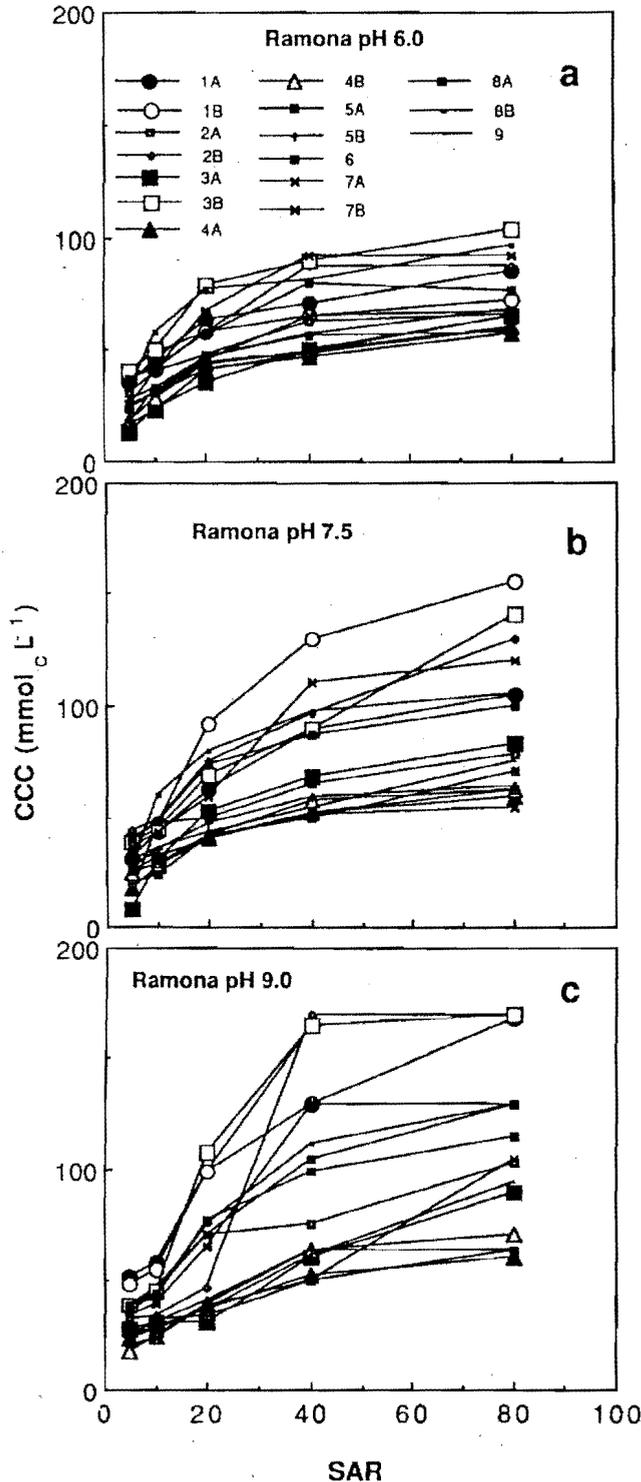


Fig. 7. Critical coagulation concentration (CCC) as a function of sodium adsorption ratio (SAR) at (a) pH 6.0, (b) pH 7.5, and (c) pH 9.0 for each of the Ramona soils.

behavior was found for the Ramona and Clarence soils (Fig. 4 and 5). The synergistic effect between SAR and pH, however, was evident even at SAR 20 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> for the Ramona and Clarence soils.

Results from electron microscopy (Greene et al., 1978) and EM data (Lebron and Suarez, 1992) support the theory of domain formation for Ca-illite. According to the ion demixing theory (Bar On et al., 1970),

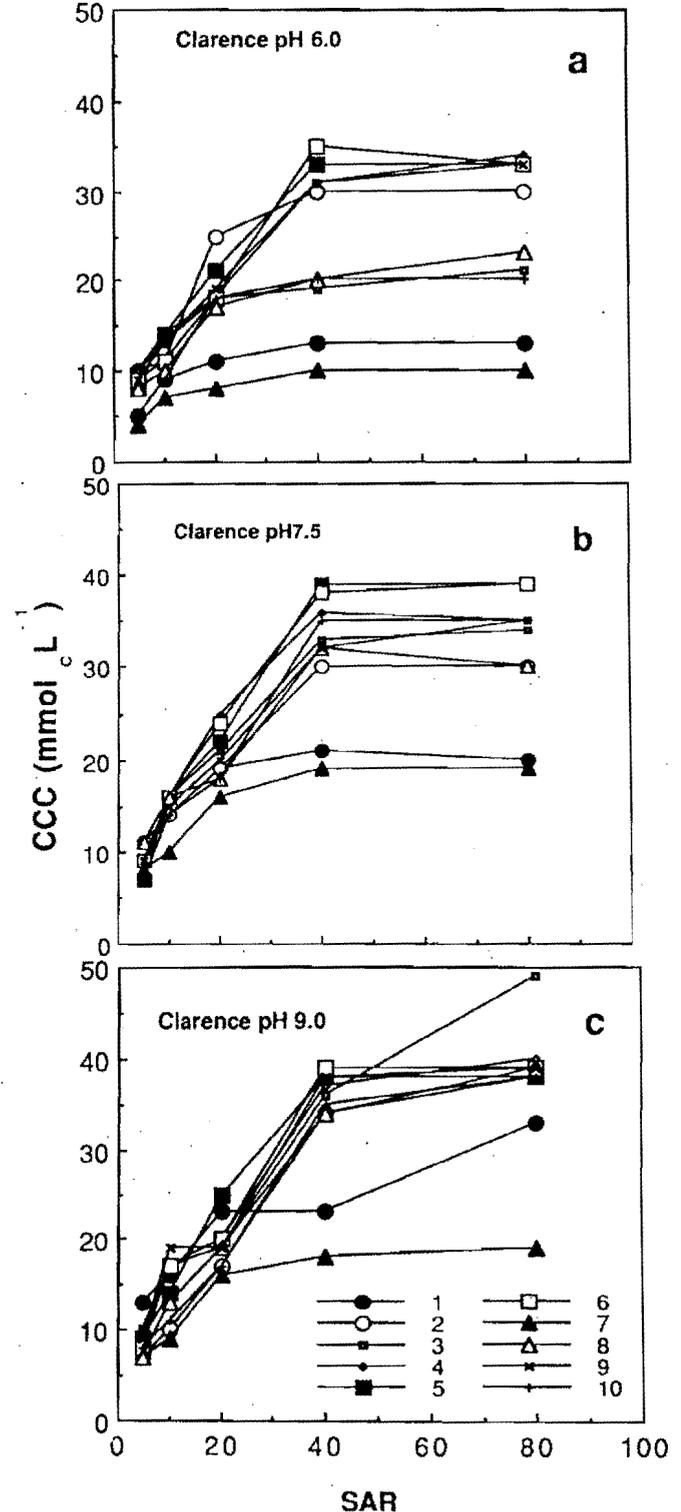


Fig. 8. Critical coagulation concentration (CCC) as a function of sodium adsorption ratio (SAR) at (a) pH 6.0, (b) pH 7.5, and (c) pH 9.0 for each of the Clarence soils.

at low exchangeable Na values a rapid increase in CCC is expected with increasing exchangeable Na because Na is exchanged preferentially on the external surfaces sites. The domains begin to be broken only after the exchangeable Na reaches a critical value, which should be at about SAR 20 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup> (ESP

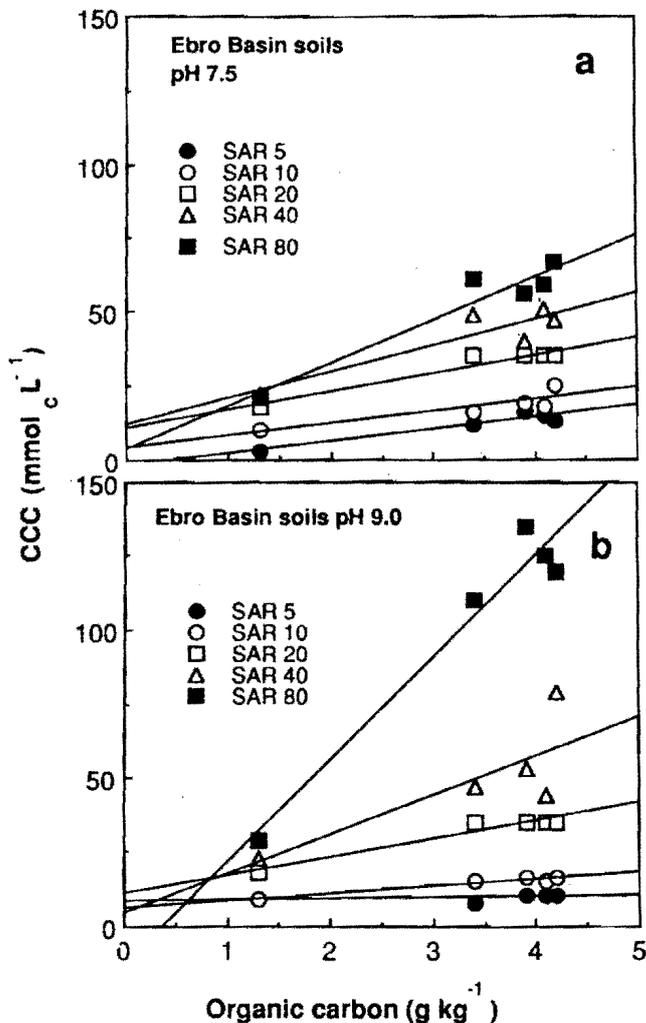


Fig. 9. Relationship between critical coagulation concentration (CCC) and organic C contents for Ebro Basin soils at different sodium adsorption ratio (SAR) values and at (a) pH 7.5 and (b) pH 9.0.

= 22) for soils such as those of this study (Lebron and Suarez, 1992).

In agreement with the demixing theory, the CCC of the Ebro Basin soils at pH 7.5 increased from 9 to 84  $\text{mmol}_c \text{L}^{-1}$  when the SAR was changed from 5 to 40  $(\text{mmol}_c \text{L}^{-1})^{0.5}$ , but the CCC increased only from 84 to 87  $\text{mmol}_c \text{L}^{-1}$  as SAR increased from 40 to 80  $(\text{mmol}_c \text{L}^{-1})^{0.5}$ . Differences in CCC were not as large for the Ramona and Clarence soils, but similar trends were seen.

When domains predominate, changes in edge charge with increasing SAR apparently are not as important as exchange of Ca with Na on the external surfaces. This is probably because the number of edges involved in new linkages is much less for domains (packets of particles) than for individual platelets. The dominant mechanism for linkages between particles, especially at low concentrations, is probably face-face flocculation, this is particularly true if we consider the spillover effect (Secor and Radke, 1985). According to this theory, at low salt concentrations, the negative electric field from the clay faces spills over onto clay edges, so that the edges exhibit negative charge even

Table 4. Results from aggregate stability tests for selected Ebro Basin, Ramona, and Clarence soils.

pH	SAR	Unstable aggregates		Standard error	
		2 $\text{mmol}_c \text{L}^{-1}$	40 $\text{mmol}_c \text{L}^{-1}$	2 $\text{mmol}_c \text{L}^{-1}$	40 $\text{mmol}_c \text{L}^{-1}$
%					
<u>Ebro basin no. 1</u>					
7.5	5	11†	27	4	4
	20	43†	38	3	10
	80	72†	72	6	11
9.0	5	59	42	4	13
	20	95†	53	<1	8
	80	72†	53	13	<1
<u>Ebro basin no. 18</u>					
7.5	5	66†	60	11	6
	20	73†	73	18	6
	80	91†	78	5	14
9.0	5	56	74	3	1
	20	97†	70	<1	13
	80	97†	81	1	9
<u>Ramona no. 1B</u>					
6.0	5	50	56	7	2
	20	57	66	1	2
	80	57	60	1	<1
7.5	5	59	52	<1	1
	20	61	56	1	1
	80	48	52	1	<1
9.0	5	54	55	4	1
	20	52	58	<1	1
	80	56	62	1	<1
<u>Ramona no. 7B</u>					
6.0	5	50	48	<1	7
	20	43	—	3	—
	80	56	50	1	1
7.5	5	35	56	1	4
	20	46	52	7	2
	80	58	46	—	1
9.0	5	56	49	3	<1
	20	55	54	<1	7
	80	57	45	2	<1
<u>Clarence no. 1</u>					
6.0	5	6	6	1	<1
	20	7	12	<1	1
	80	8	8	<1	<1
7.5	5	8	6	1	<1
	20	7	5	<1	1
	80	6	6	<1	2
9.0	5	7	7	<1	2
	20	6	5	1	<1
	80	7	5	1	<1
<u>Clarence no. 9</u>					
6.0	5	7	6	1	1
	20	8	9	1	1
	80	6	13	1	2
7.5	5	10	10	<1	1
	20	13	8	4	1
	80	14	10	<1	4
9.0	5	14	6	<1	<1
	20	13	10	<1	<1
	80	10	7	1	1

† Data obtained in  $\text{CaCO}_3$  undersaturation conditions.

at low pH. As a result of this effect, edge-face bonds do not occur at low concentrations. Thus, the hydration radii of the predominant cations in the double layer become the most important factor, because attractive van der Waals forces fall off exponentially with the one-half distance between particles (van Olphen, 1977).

When the domains separate at high SAR, the elec-

trolyte concentration needed to flocculate the particles once more is higher than the salt concentration required to flocculate the particles at low SAR. Concurrently when the salt concentration is higher, the amount of variable charge increases and the spillover effect is reduced; in this situation differences in CCC should be more dependent on pH at higher SAR, which is what we also observed experimentally. At high electrolyte concentration when the spillover effect is negligible, edge-face linkages are possible if the pH is lower than the ZPC of the edges (also called point of zero net proton charge or PZNPC).

The Ramona soils increased in CCC from 75 to 100  $\text{mmol}_c \text{L}^{-1}$  when the pH was elevated from 6.0 to 9.0 at SAR 80 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>. For the Clarence soils, the CCC increased from 29 to 48  $\text{mmol}_c \text{L}^{-1}$  across this same change in pH. There are discrepancies in the literature about the value of PZNPC for illites but pH 6.0 may be below the PZNPC in our micaceous clays. At pH 6.0, positive charges in the edges and an increase in variable charge with increased salt concentration promotes flocculation. At pH 9.0, if we assume this value is above the PZNPC, negative charges in the edges and an increase in variable charge with increasing salt concentration depresses flocculation and more electrolyte concentration is needed to compress the double layer of the clays and allow the attractive forces to act.

#### Variability in Dispersibility within Soil Types

The data presented above demonstrate substantial differences in CCC among soil types having the same clay mineralogy and similar organic matter and oxide contents. In this section we evaluate the variability of CCC even within a given soil type. Individual representations of the CCC values vs. SAR are shown in Fig. 6, 7, and 8 for each sample of the Ebro Basin, Ramona, and Clarence soils, respectively. These figures show that there are large differences in CCC even among soils of the same type and from the same locality. The two pH values tested for the Ebro Basin soils (Fig. 6a and 6b) show greater variability in CCC at higher pH. For SAR 80 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>, the range in CCC among samples was 50  $\text{mmol}_c \text{L}^{-1}$  at pH 7.5 and 108  $\text{mmol}_c \text{L}^{-1}$  at pH 9.0. For the Ramona soils at pH 6.0, 7.5, and 9.0, these ranges were 50, 100, and 110  $\text{mmol}_c \text{L}^{-1}$ , respectively (Fig. 7a, 7b, and 7c). In contrast, pH did not greatly affect CCC variability for the Clarence soils (Fig. 8a, 8b, and 8c). Such differences are remarkable considering the similar mineralogy, texture, and oxide and organic matter contents for each group of soils. Such variations in CCC, if truly manifest in the field as differences in soil stability, preclude the use of predictive soil stability relationships even for specific soil types. Earlier, Pratt and Suarez (1989) indicated that a generalized predictive relationship was certainly not satisfactory to represent the stability of all arid-zone soils.

The increased differences in flocculation values at high pH suggest that at least some of the variations in CCC may be related to differences in the variable-charge components of these soils. In order to separate the effects of the different components, we chose soils having relatively constant Fe oxide contents for ex-

amination of the relationship between CCC and OC. Similarly, we selected soils of relatively constant organic matter content in order to examine the relationship between CCC and Fe oxide content. We also examined the relationship between Al oxide content and CCC.

The relation between OC and CCC for the Ebro Basin soils at pH 7.5 is shown in Fig. 9a. Increasing OC in the range of 1.3 to 4.3  $\text{g kg}^{-1}$  was related rather uniformly at all SAR values to increasing CCC values for these soils. At pH 9.0, the SAR also affected the OC dependence of the CCC value (Fig. 9b), with an effect greatest at high SAR. The adverse effect of organic matter on CCC was also much greater at pH 9.0 than at 7.5.

The Ramona and Clarence soils showed no clear relationship between CCC and OC at constant oxide content. The OC varied from 3.0 to 17.0  $\text{g kg}^{-1}$  for the Ramona soils and from 3.0 to 5.2  $\text{g kg}^{-1}$  for the Clarence soils. Stratification of the curves with increasing SAR and pH was similar to that for the Ebro Basin soils. The CCC increased regardless of OC content with increasing SAR.

When soils with OC content near 4.0  $\text{g kg}^{-1}$  were selected, Fe oxide content showed no relation to CCC at low SAR for the Ebro Basin soils (Fe oxide content varied from 16.0–26  $\text{g kg}^{-1}$ ). There appeared to be a significant trend of decreasing stability with increasing Fe oxide content when SAR was >40 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>. Study of more soils, however, would be necessary to generalize such a conclusion. There was not a significant trend in CCC with variation in Al oxide content (the Al oxide content varied from 3.4–7.0  $\text{g kg}^{-1}$ ).

For Ramona soils two populations were chosen to identify the effect of Fe oxide on CCC: one having  $\approx 2.0 \text{ g kg}^{-1}$  OC and the other  $\approx 4.0 \text{ g kg}^{-1}$  OC. In neither case did the results show any clear trend with Fe oxide content. Also no trends were found for either of these two populations when we examined the variation of CCC as a function of Al oxide content (in both data sets, Al oxide content varied from  $\approx 0.6$ –1.0  $\text{g kg}^{-1}$ ). The Clarence soils also showed no relationship in CCC as a function of either Fe or Al oxide content. With the exception of Ebro Basin soils above SAR 40 ( $\text{mmol L}^{-1}$ )<sup>0.5</sup>, variations in oxide content did not affect differences in CCC for the three groups of soils examined.

#### Aggregate Stability

Significant differences in aggregate stability among the three soil types were observed despite the large standard errors obtained for the Ebro Basin soils. The Ebro Basin soils were the most unstable, while the Clarence soils were remarkably stable. Apparently, high  $\text{CaCO}_3$  content did not confer any measurable stability to aggregates of the Ebro Basin soils, as is shown in Table 4, even when the samples at 2  $\text{mmol}_c \text{L}^{-1}$  were almost all calcite undersaturated and thus likely to reduce the ESP. Since the aggregate stability test was performed simultaneously for all soils, and Ebro Basin soils at 40  $\text{mmol}_c \text{L}^{-1}$  are in equilibrium with calcite, the high standard errors in Ebro Basin soils must be attributed to their high dispersibility.

Sloughing of Ebro Basin soil aggregates began even in the humidification phase, before the start of the test itself. This illustrates the extreme instability of the Ebro Basin soil aggregates.

Results of the aggregate stability test are shown in Table 4. No substantial differences in aggregate stability with variations in salt concentration, pH, or SAR were observed within the same soil group. As expected, however, increases in SAR generally decreased aggregate stability and increases in salt concentration did not give any clear trend. The lack of a trend can be due to all physical processes that occur during the drying and humidification cycles as well as the effect that Fe and Al oxides have on the cementation between particles, and the behavior of OC at different water contents (Kemper et al., 1987). For the Ebro Basin soils, aggregate stability decreased with increasing pH. Clear trends in aggregate stability were not evident for the other soils.

We did not observe any correlation between aggregate stability and the CCC data. This is probably due to differences in particle-size distribution for these soils, as indicated by the data of Table 2. The wide variation in particle-size distribution for these three groups of soils is not accounted for by the dispersion test, which measures clay dispersion at constant clay/solution ratio. The Ebro Basin and Ramona soils have a mean clay content of 0.2 to 0.3 kg kg<sup>-1</sup>, while Clarence soils contain a mean of 0.7 kg kg<sup>-1</sup> clay. Higher clay contents results in greater aggregate stability (Kemper et al., 1987); this indicates that clay provides more contact points between the larger soil particles and helps bond the soil together. Kemper et al. (1989) compared the aggregate stability of two soils with different textures, one fine and the other coarse, at different water content. They concluded that the coarse soil had a low soil water tension and a consequent reduction in the force pushing particles into contact. Particle size is also related to porosity, which is an important parameter for aggregate stability.

The lack of correlation between dispersion and aggregate stability tests raises the issue of which test is preferred for predicting soil behavior in the field. Aggregate stability relates to the initial processes determining field stability. On the other hand, the physicochemistry of the colloids and the clay particles is the likely dominant process affecting field behavior after disaggregation has occurred.

These stability tests provide information about different aspects of soil stability. Even after considering the results from both tests, however, information is insufficient to provide a satisfactory prediction of field behavior. For example, a soil with poor aggregate stability could still have good hydraulic conductivity regardless of the results of its flocculation test. This is the case, for example, for a sandy soil or for laboratory experiments with clay-sand mixtures (Shainberg et al., 1987, 1988; Levy et al., 1991) where dispersion results in a washing out of the clay and increased hydraulic conductivity. For this reason, a combination of aggregate stability, flocculation behavior, and hydraulic conductivity, possibly coupled to texture, may be required to define soil structural behavior. Also, other factors such as biological

processes may need to be considered with respect to macroaggregate stability, because organisms are involved in maintaining the integrity of aggregates during wetting and other disturbances (Oades, 1990).

The large variability among soil types with the same clay mineralogy, or even among samples within a given soil type, shows that general guidelines are not precise enough to quantify soil reclamation requirements. In addition, pH values above the ZPC of the edges promote clay dispersion and higher variability among soils. This is especially important when the exchangeable Na is high enough to maintain individual clay particles and when the CCC represents a high electrolyte concentration. High electrolytic concentrations reduce the spillover effect and increase the quantity of variable charge. The fact that variability in CCC was greater at higher pH also suggests that variable-charge particles are responsible for differences in CCC. Correlations between CCC and OC or Fe and Al oxide contents, however, were not significant, with  $r^2$  values <0.3 for the Ramona and Clarence soils. Therefore, the interaction between differing variable-charge particles is not clarified, and additional research remains necessary to understand the role of variable-charge particles in soil stability.

#### ACKNOWLEDGMENTS

Gratitude is expressed to Dr. F. Alberto and Dr. W.D. Nettleton for providing the Ebro Basin and Clarence soil samples, respectively. We also wish to thank the Spanish Ministry of Education and Science for the fellowship that provided funding for I. Lebron for part of this research.

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