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Stability of a Calcareous Saline-Sodic Soil During Reclamation

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ABSTRACT

General guidelines to reclaim saline or sodic soils do not adequately consider variables such as pH and the presence of organic matter that are known to affect soil stability. Poor structural stability of sodic, saline-sodic, and high-pH soils adversely influences crop yields; promotes piping, tunneling, and slope erosion; and can accelerate the failure of water conveyance systems. We evaluated six soil teats, used to measure physico-cbemical properties, for their suitability to evaluate the structural stability of a calcareous, saline-sodic soil under reclamation. The stability tests were wilting point, plastic limit, coefficient of linear extensibility (COLE,& water content at 0.03 MPa, liquid limit, and dispersion index. The range of electrical conductivity (EC) studied was 0.5 to 20 dS m^{-1}, sodium adsorption ratio (SAR) 0 to 400 (mmol $\mathrm{L}^{-1})^{0.5}$, and pH 8.4 to 10.5. The results obtained indicate that the amount of water necessary for a soil to Sow under standard conditions for the liquid limit test decreased an average of 25% when the EC decreased from 40 to 2 dS m^{-1}. The liquid limit and EC showed a linear correlation (R^2 = 0.785); therefore, the liquid limit was considered to be an appropriate index to evaluate the physical properties of a soil under a leaching process. Plasticity index and available water were more useful in the evaluation of the mechanical properties of the soil when we used amendments. Liquid limit combined with the water content of the soil at 0.03 MPa was the most useful tool for evaluating soil structural stability during reclamation.

IT IS WELL KNOWN that sodic soils are highly dispersive. Dispersion causes loss of soil structure and reduction in hydraulic conductivity and increases soil erodibility (Quirk and Schofield, 1955; McNeal et al., 1968; Rhoades and Ingvalson, 1969; Frenkel et al., 1978; Perry and Postol, 1977; Pupisky and Shainberg, 1979; Suarez et al., 1984; Yousaf et al., 1987). This dispersive effect is specially pronounced for sodic soils of high pH (>8.5). Also, clay dispersion promotes piping and tunneling erosion (Sherard and Decker, 1977). Sodic soils have an adverse effect on crop production and in the maintenance of canals and irrigation systems. Characterization of the physico-chemical soil properties to ensure a suitable state is necessary to avoid both agricultural and structural problems.

The term *alkaline* has been used in the literature in relation to soils with high alkali metal content (Na) in the exchange complex. In most cases, high pH is also associated with these soils. Allison (1964) and van Beek and van Breemen (1973) made a clear distinction between *the* terms *sodic soil* and *alkaline soil.* Alkaline soils have a pH >7 (van Beek and van Breemen, 1973) and sodic soils have high Na content (normally >15%) in the exchange complex. Sodic soils do not necessarily have alkaline pH values, and alkaline soils do not necessarily have high exchangeable Na.

Gibbs (1945) established that soils having a plasticity index <O. 1 kg kg^{-1} and liquid limit <0.30 kg kg^{-1} were erodible. The liquid limit represents the minimum amount of water that a small soil sample needs to flow under standard conditions. The plastic limit is the water content at which the soil starts to loose cohesion due to the absence of water. Plasticity index is the difference between the liquid limit and the plastic limit values. These three values are known as the Atterberg limits (American Society for Testing Materials, 1985). Sherard (1953) realized that earthen dams with a plasticity index <0.05 kg kg-' broke down in a few years; and, for a given plasticity index, the soils with higher liquid limit had more resistance to piping. Cole and Lewis (1960) reported similar observations in Australia. Aitchison (1960) proposed the use of clay dispersibility as an index to classify the susceptibility of soils to erosion. Clay dispersibility is the ratio of the weight of clay dispersed in deionized water and the weight of clay dispersed with sodium hexametaphosphate. Although the introduction of the dispersibility concept (Aitchison, 1960) changed the diagnostic criteria of most engineering recommendations, it was not universally accepted. Resendiz (1977) maintained that the clay activity index (plasticity index/clay percentage by weight) is an appropriate index to determine the stability of soil. He found that soils with clay activity index values of 0.003 to 0.01 were susceptible to piping. However, Sherard and Decker (1977) showed that most clay soils are within this range of clay activity index and a soil can go from a dispersed to a flocculated state and still stay within this range.

Agronomists and soil scientists have centered their efforts on tests such as hydraulic conductivity, aggregate stability, and clay dispersion. Many of the guidelines for the reclamation of saline and sodic soils given by various researchers during the last 50 yr (U.S. Salinity Laboratory Staff, 1954; Quirk and Schofield, 1955;

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Abbreviations: PC, electrical conductivity; ECSE, electrical conductivity of the saturation extract; SAR, sodium adsorption ratio; COLE, coefficient of linear extensibility; ESP, exchangeable sodium percentage; ESR, exchangeable sodium ratio; pIAP, negative log of the ion activity product (a_{Ca} X $a_{\mathrm{CO_3}}$); PZNPC, point of zero net proton charge; Treatment A, natural soil; Treatment B, Ca-saturated soil; Treatment C, leached soil; ζ, zeta potential; ANOVA, analysis of variance; MANOVA, multivariate analysis of variance.

Rhoades, 1982) appear inadequate without previous verification for the specific soil (Pratt and Suarez, 1990; Lebron and Suarez, 1992). Verification requires appropriate tests to determine the impact of the reclamation process on soil structure.

The importance of pH has been demonstrated for both clay dispersion (Suarez et al., 1984; Gupta et al., 1984; Goldberg and Glaubig, 1987; Lebron and Suarez, 1992) and hydraulic conductivity of soils (Suarez et al., 1984). High pH values (>8.5) are generally associated with sodic calcareous soils. However, this evidence is not normally considered because some soils with an high pH (>8.5), measured in the laboratory, show good hydraulic properties in the field. Standard procedures to measure pH in the saturation extract (or any other extract) cause a substantial CO_2 degassing compared with field conditions. The concentration of CO_2 in the root zone can be 10 to 100 times higher than in the atmosphere. Consequently the pH values are lower when measured in situ or when soil water pH is measured using extractors that minimize CO_2 degassing (Suarez, 1986).

An accurate characterization of calcareous soils affected by salinity, sodicity, and high pH is lacking, in part because of the failure to properly account for the carbonate system. Saline-sodic soils under the process of reclamation undergo changes in electrolyte concentration, composition of the cations in the exchange complex, and pH. The purpose of our study was to evaluate six tests to predict the effect that salt concentration, exchangeable Na, and pH have on the physico-chemical properties of a calcareous, micaceous soil during reclamation. These tests, which reflect physico-chemical properties of the soil at different soil/water ratios, are wilting point, plastic limit, $\mathrm{COLE}_{\mathrm{rod}}$, water content at 0.03 MPa, liquid limit, and dispersion index.

MATERIALS AND METHODS

The soil samples used in this study were collected from a Tertiary basin located in the northeast of Spain. The soil is classified as saline-sodic, fine, illitic, calcareous, xeric. The predominant mineralogy is dioctahedral mica (>90%) with an abundance of amorphous Fe oxides in various degrees of hydration (U.S. Department of Agriculture, 1961). This soil contains an excess of HCO_3 with respect to Ca (in $\mathrm{mmol_c\ L^{-1}}$) and a large reserve of $CaCO_3$, thus the saturated paste pH is >8.4.

Nineteen samples from the 0- to 30-cm depth were collected from different locations. Each sample was divided into *three* equal parts. The first part was not subjected to any modification (Treatment A). The second part was washed five times with a 300 $\mathrm{mmol_c\ L^{-1}}$ $CaCl_2$ solution in centrifuge tubes (1:5 soil/solution ratio), and the excess salt was removed by washing with distilled water (Treatment B). The third part was washed with distilled water to remove the soluble salts until the EC value was <2 dS m^{-1} in a 1: 1 soil/solution suspension (Treatment C). Liquid limit, plastic limit, and plasticity index were determined according to the methods recommended by ASTM (1985).

The amounts of water retained by the soils at 0.03 and 1.52 MPa (l/3 and 15 atm) matric water pressure were determined by the porous plate and pressure membrane methods (U.S. Salinity Laboratory Staff, 1954). It was necessary to change the equilibration time of the natural (Treatment A) and washed (Treatment C) samples with water, both in the wetting and dehydration processes, due to the low hydraulic conductivity of the soil samples. It was estimated that 7 d were necessary to completely wet the soil samples in a closed chamber.

The COLE_{std} is a measure of the shrink-swell capacity of a soil. For simplicity, and because it is highly correlated with the $\mathrm{COLE}_{\mathrm{std}}$, $\mathrm{COLE}_{\mathrm{rod}}$ was calculated (Schaffer and Singer, 1976) and expressed as

$$\mathrm{COLE_{rod}} = \frac{l_m - l_d}{l_d}$$

where l_m is the length of the moist sample and l_d the same parameter for the dry sample.

To perform the dispersion test;20 g of soil were suspended in 1 L of deionized water. The same amount of soil was also suspended in 1 L of deionized water with 0.1 g sodium hexametaphosphate kg-’ added. Both samples were shaken overnight. The dispersion index was expressed as the ratio of the weight of the <2-µm particles from the soil with deionized water to that with dispersant. The same ratio was also calculated for the 2- to 6.3-µm fraction.

Particle-size distribution was determined by a pipette method (U.S. Salinity Laboratory Staff, 1954). The results are expressed in grams per kilogram of oven-dry (105°C) soil.

Saturated soil paste and saturation extracts (U.S. Salinity Laboratory Staff, 1954) were obtained for all samples. Electrical conductivity, cations, and anions were determined in the saturation extract. Concentrations of CO_3^{2-}, HCO_3^-, and Cl^- were determined by titration, SO_4^{2-} by turbidimetry (American Public Health Association, 1989), and NO_3^- by colorimetry (Keeney and Nelson, 1982). Calcium, Mg, Sr, Na, Li, and B were determined by inductively coupled plasma emission spectroscopy (Jobin-Ivon 98[1], Longjumeau, France), and K was determined by flame emission using a Perkin-Elmer/Coleman 5 1-Ca photometer (Physical Electronics Europe, Munich). Electrical conductivity was measured in a 1: 1 soil/water suspension for Treatments A, B, and C; pH in the soil paste was also measured in the three treatments.

A statistical analysis was conducted to determine if the physical properties of liquid limit, plastic limit, plasticity index, $\mathrm{COLE}_{\mathrm{rod}}$, and 0.03 and 1.52 MPa matric pressures differed significantly across the three treatments. The analysis was performed between the subsamples A-B, A-C, and B-C. The following multivariate ANOVA model was used to test for treatment effects across the six physical properties:

$$y_{ijk} = u_k + \tau_{ik} + \beta_{jk}$$

where

i = A, B, C (treatments)
$j = 1, 2, \ldots, 19$ (soil samples)
$k = 1, 2, \ldots, 6$ (corresponding to the six physical properties)

The Wilks' λ criteria was used to test simultaneously for mean differences in physical properties (to determine if at least one of the mean contrasts was significantly different from 0), and Bonferroni 95% simultaneous confidence intervals were constructed for the individual differences (Johnson and Wichem, 1988).

The statistical analysis of the <2-µm dispersion index was carried out in the following manner. All dispersion values ≥ 1 were set equal to 0.995, and then a logit transformation* was applied to the data (Myers, 1986). This transformation was

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[1] Trade names are provided for the benefit of the reader and do not imply any endorsement by the USDA.

[2] Logit transformation of $x = \ln[x/(1 - x)]$, where x is a variable with values between 0 and 1.

used to induce an approximated normality in the dispersion index data. The logit-transformed data were then analyzed using a two-way ANOVA model and Tukey's Studentized range test was used to test for differences in the mean logit dispersion levels.

RESULTS

Table 1 shows the particle-size distribution and $CaCO_3$ content for the 19 soil samples and the three treatments. A paired f-test was performed for both the $CaCO_3$ and the particle-size distribution values of the natural samples vs. those values for the samples treated with Ca or washed with deionized water. The analysis of these data indicated that the pretreatment did not significantly change either the $CaCO_3$ content or the particle-size distribution of the soils (0.005 confidence limit; Johnson, 1976).

Determinations of the liquid and plastic limits (Table

Table 1. Particle-size distribution, dispersion indexes, and calcite content for natural soil (Treatment A), soil saturated with Ca (Treatment B), and salt-washed soil (Treatment C).

Soil no.	Treatment	Particle-size distribution 200-63 pm	63-6.3 µm	6.3-2 µm	<2 µm	Dispersion indexes 6.3-2 µm	<2 µm	$CaCO_3$
		g kg^{-1}						g kg^{-1}
1	A	51	504	188	257	1.00	0.97	407
	B	46	502	189	263	1.06	0.84	401
	C	20	440	215	325	0.98	0.94	409
2	A	35	480	225	260	0.98	0.92	414
	B	35	509	217	233	1.06	0.90	405
	C	35	492	220	254	1.05	0.97	413
3	A	29	280	299	393	1.05	0.95	373
	B	29	272	287	414	1.27	0.79	373
	C	23	261	297	419	1.07	0.94	363
4	A	27	337	276	361	1.00	0.98	349
	B	29	326	263	382	1.27	0.77	373
	C	28	333	255	383	1.03	1.00	349
5	A	47	402	247	304	0.99	0.96	387
	B	43	452	218	287	1.25	0.71	381
	C	54	512	186	249	1.08	0.95	373
6	A	64	472	204	261	1.03	0.98	393
	B	59	489	195	258	1.38	0.66	397
	C	58	474	203	265	1.01	0.98	393
7	A	47	320	297	336	0.89	0.76	365
	B	46	373	240	341	1.27	0.73	393
	C	46	361	245	347	1.01	0.97	385
8	A	53	360	255	332	1.06	0.94	393
	B	56	361	268	315	1.04	0.88	377
	C	50	367	248	335	1.03	0.97	389
9	A	59	383	214	344	0.97	1.01	345
	B	66	371	214	348	1.25	0.88	385
	C	55	367	239	340	0.91	1.01	373
10	A	47	407	241	305	1.04	0.97	395
	B	38	409	249	274	1.10	0.94	377
	C	48	414	235	304	1.02	0.99	357
11	A	53	446	239	262	1.09	0.90	355
	B	59	406	242	293	1.25	0.72	365
	C	49	441	226	284	1.04	0.98	359
12	A	47	439	229	285	1.05	0.98	385
	B	54	489	225	273	1.25	0.79	357
	C	54	432	227	287	1.04	1.00	373
13	A	62	429	224	285	1.02	0.98	403
	B	62	472	207	259	1.23	0.74	353
	C	62	437	211	290	1.04	0.99	379
14	A	28	354	285	333	1.04	0.98	385
	B	28	360	285	328	1.18	0.80	371
	C	28	352	274	347	1.03	1.00	375
15	A	44	419	237	300	1.04	0.95	375
	B	37	533	229	283	0.98	0.75	379
	C	40	407	235	318	1.04	1.01	351
16	A	44	453	218	285	1.06	0.97	373
	B	43	460	213	284	1.27	0.83	365
	C	45	447	220	288	1:05	1.00	355
17	A	22	290	300	388	1.04	0.98	331
	B	21	295	306	378	1.19	0.80	359
	C	21	281	297	401	1.06	0.99	367
18	A	117	543	167	172	1.07	0.97	363
	B	114	456	163	179	1.16	0.74	393
	C	120	505	164	212	1.06	0.87	347
19	A	44	394	253	308	1.03	1.00	349
	B	39	393	250	317	1.06	0.91	363
	C	40	383	258	319	0.98	1.00	371

2) were performed for all three treatments. All determinations were duplicated. The standard error of the determinations of the Atterberg limits were less than ± 2 % water content. The measurement of COLE was triplicated and the standard error was ±0.003 % . The amounts of water retained by the soils at 0.03 and 1.52 MPa matric pressure were determined for all three fractions of each sample in triplicate. Standard errors for matric pressure determinations were ± 3 % of the water retained. The dispersion test was duplicated and the standard *error was* ±0.06 (Table 1).

Table 2. Physical properties for natural soil (Treatment A), soil saturated with Ca (Treatment B), and salt-washed soil (Treatment C).

Soil no.	Treatment	Liquid limit	Plastic limit	Plasticity index	$\mathrm{COLE_{rod}}$†	Water content 0.03 MPa	Water content 1.52 MPa
		kg kg-'				kg kg^{-1}	
1	A	0.315	0.181	0.134	0.043	0.245	0.110
	B	0.315	0.187	0.128	0.037	0.265	0.101
	C	0.240	0.158	0.082	0.029	0.249	0.133
2	A	0.335	0.198	0.137	0.039	0.270	0.110
	B	0.365	0.200	0.165	0.044	0.303	0.096
	C	0.250	0.171	0.079	0.026	0.244	0.106
3	A	0.419	0.214	0.205	0.064	0.257	0.173
	B	0.440	0.208	0.232	0.061	0.291	0.152
	C	0.284	0.182	0.102	0.047	0.270	0.167
4	A	0.370	0.201	0.169	0.057	0.243	0.162
	B	0.429	0.203	0.226	0.060	0.289	0.140
	C	0.265	0.166	0.099	0.040	0.259	0.155
5	A	0.339	0.1%	0.143	0.054	0.250	0.121
	B	0.360	0.184	0.176	0.026	0.308	0.123
	C	0.225	0.156	0.069	0.010	0.223	0.108
6	A	0.320	0.172	0.148	0.042	0.233	0.114
	B	0.343	0.182	0.161	0.035	0.270	0.102
	C	0.225	0.151	0.074	0.023	0.229	0.118
7	A	0.330	0.174	0.156	0.047	0.255	0.145
	B	0.390	0.185	0.205	0.077	0.309	0.120
	C	0.244	0.160	0.084	0.033	0.242	0.151
8	A	0.315	0.174	0.141	0.048	0.257	0.138
	B	0.389	0.186	0.203	0.045	0.302	0.133
	C	0.245	0.163	0.082	0.040	0.247	0.142
9	A	0.363	0.183	0.183	0.048	0.261	0.164
	B	0.390	0.187	0.203	0.047	0.303	0.135
	C	0.262	0.165	0.097	0.054	0.249	0.156
10	A	0.295	0.177	0.118	0.045	0.237	0.134
	B	0.375	0.192	0.183	0.060	0.274	0.115
	C	0.250	0.151	0.099	0.036	0.235	0.135
11	A	0.300	0.165	0.135	0.033	0.227	0.118
	B	0.350	0.187	0.163	0.053	0.266	0.117
	C	0.235	0.158	0.077	0.024	0.247	0.121
12	A	0.312	0.166	0.146	0.044	0.241	0.125
	B	0.355	0.176	0.179	0.039	0.2%	0.114
	C	0.239	0.152	0.087	0.030	0.250	0.125
13	A	0.250	0.154	0.096	0.038	0.234	0.126
	B	0.355	0.176	0.179	0.047	0.282	0.107
	C	0.240	0.157	0.083	0.037	0.246	0.131
14	A	0.312	0.174	0.138	0.041	0.251	0.146
	B	0.410	0.186	0.224	0.052	0.312	0.130
	C	0.260	0.169	0.091	0.035	0.264	0.147
15	A	0.275	0.164	0.111	0.045	0.233	0.124
	B	0.372	0.179	0.193	0.042	0.290	0.126
	C	0.240	0.156	0.084	0.034	0.242	0.132
16	A	0.320	0.177	0.143	0.043	0.243	0.123
	B	0.360	0.184	0.176	0.040	0.289	0.116
	C	0.230	0.161	0.069	0.043	0.231	0.131
17	A	0.380	0.199	0.181	0.052	0.275	0.159
	B	0.430	0.203	0.227	0.059	0.306	0.152
	C	0.270	0.179	0.091	0.055	0.274	0.168
18	A	0.225	0.161	0.064	0.020	0.222	0.081
	B	0.299	0.180	0.119	0.027	0.267	0.078
	C	0.215	0.160	0.055	0.020	0.211	0.085
19	A	0.349	0.190	0.159	0.041	0.258	0.113
	B	0.360	0.188	0.172	0.039	0.301	0.116
	C	0.250	0.167	0.083	0.038	0.234	0.130

t COLE = coefficient of linear extensibility.

Table 3 shows the results from MANOVA (Johnson and Wichem, 1988) analysis for the observed mean differences, standard errors, t scores, and Bonferroni 95% simultaneous confidence intervals for each set of contrast data for liquid limit, plastic limit, plasticity index, $\mathrm{COLE_{rod}}$, and 0.03 and 1.52 MPa matric water pressure. Wilks' λ was significant below the 0.0001 level, confirming that one or more physical properties differed significantly across treatments. The *t* scores associated with the A-B contrast indicate that the upper plastic limit, lower plastic limit, plastic index, and 0.03 and 1.52 MPa matric pressure differences were all significant at or below the 0.01 level. In the A-C contrast data, the liquid and plastic limits and plasticity index were significant at the 0.01 level, and the $\mathrm{COLE_{rod}}$ difference was significant at the 0.05 level. Finally, all six physical property differences associated with the B-C treatment contrast were significant at the 0.01 level. For the <2-µm dispersion test, every pairwise difference between the mean logit-transformed dispersion index levels was significant at the 0.05 level.

Treatment A

The data shown in Table 4 indicate that samples subjected to the A treatment exhibited saline-sodic characteristics, with EC values between 6 and 40 dS m^{-1} in the saturation extract and SAR >15. The ionic composition of the saturation extracts indicates that Na is the major cation, with very low concentrations of divalent cations and extremely high SAR values. Relating SAR to the ESP by the Gapon equation (Amrhein and Suarez, 1991), one concludes that the samples under Treatment A represent a saline-sodic soil. Also, the alkalinity of these saturation extracts (CO_3^{2-} + HCO_3^-) is much higher than the concentration of Ca^{2+} . The pIAP values for a_{Ca} X $a_{\mathrm{CO_3}}$, where a is the activity, were calculated for the A treatment at atmospheric partial pressure of CO_2, with the ionic composition from Table 4, using the program described by Suarez (1977). All saturation extracts were supersaturated with respect to calcite. Measurements of the pH under laboratory conditions gave values >8.9 for the A treatment (Table 4).

Treatment B

The addition of $CaCl_2$ in the B treatment reduced sodicity as expected (due to the exchange processes) and reduced the pH of the system to a value consistent with the pH of a pure Ca–HCO_3 solution in equilibrium with calcite at atmospheric CO;? partial pressure. Sodicity was reduced such that the SAR values ranged from 0.4 to 1. The EC in Treatment B was below the value traditionally considered in the classification of saline soils (4 dS m^{-1}

Table 3. Results from MANOVA analysis; statistics shown for A-B, A-C, and B-C treatment differences. Bonferroni 95% simultaneous confidence intervals were used for constructing intervals on pairwise treatment mean differences.

Physical property	Mean difference	Standard error	$\lvert t \rvert$ score†	Bonferroni 95% confidence interval
		Treatment contrast = A-B		
Liquid limit	−5.068	0.686	7.388	(−7.27, −2.86)
Plastic limit	−0.805	0.209	3.852	(−1.48, −0.13)
Plasticity index	−4.247	0.580	7.322	(−6.11, −2.38)
COLE_{rod}	−0.0024	0.0027	0.889	(−0.011, 0.006)
0.03 MPa water content	−4.363	0.337	12.95	(−5.45, −3.28)
1.52 MPa water content	1.124	0.219	5.132	(0.42, 1.83)
		Treatment contrast = A-C		
Liquid limit	7.658	0.686	11.16	(5.45, 9.86)
Plastic limit	1.779	0.209	8.512	(1.11, 2.45)
Plasticity index	5.895	0.580	10.16	(4.03, 7.76)
COLE_{rod}	0.0100	0.0027	3.704	(0.001, 0.019)
0.03 MPa water content	0.241	0.337	0.715	(−0.84, 1.32)
1.52 MPa water content	−0.290	0.219	1.324	(−0.99, 0.41)
		Treatment contrast = B-C		
Liquid limit	12.73	0.686	18.56	(10.5, 14.9)
Plastic limit	2.584	0.209	12.36	(1.91, 3.26)
Plasticity index	10.14	0.580	17.48	(8.28, 12.0)
COLE_{rod}	0.0124	0.0027	4.592	(0.004, 0.021)
0.03 MPa water content	4.604	0.337	13.66	(3.52, 5.69)
1.52 MPa water content	−1.414	0.219	6.457	(−2.12, −0.71)

† $\lvert t \rvert$ scores exceeding 3.212 and 3.789 are significant at the 0.05 and 0.01 levels, respectively.

in the saturation extract; U.S. Salinity Laboratory, 1954) except for sample no. 1 (4.91 dS m^{-1}; Table 4).

Treatment C

The EC of samples subjected to Treatment C (Table 4) indicates a nonsaline soil with reduced sodicity and pH > 8.5. Reduced sodicity was caused by dissolution of $CaCO_3$ coupled with Ca → Na exchange. After leaching, a decrease in the pH of the soil occurs by elimination of some soluble HCO_3^-. Sodium hydrolysis was not expected since the electrolyte concentration of our samples was always above 10 $mmol_c\ L^{-1}$ (the value above which Shainberg [1973] and Frenkel and Suarez [1977] found the decomposition rate is negligible).

DISCUSSION

Determination of Colloidal Properties of Different Particle Sizes

The reduction in the hydraulic conductivity of a soil with poor structure is partially caused by the migration of fine-particle soil; this migration also induces the clogging of drainage pipes and erosive phenomena. Some researchers have attributed colloidal properties to fine silt particles, and in several dispersion indices, the fine silt is added to the clay fraction (Middleton, 1930; Volk, 1937; Downes, 1946; Ritchie, 1963; Sherar and Decker, 1977; Dong et al., 1983). Herrero et al. (1989) found, in the same soil type as used in our study, that the fine silt (2–6.3 µm) was responsible for most of the clogging problems in drainage systems.

Soil remediation depends on the cause of the dispersion. Chemical amendments will be useful only if the particles have colloidal properties. To determine if the 2- to 6.3-µm particles have colloidal properties, the dispersion index was determined for these particle sizes. Table 1 shows that the dispersion index value for the 2- to 6.3-µm size is very near 1.0. We concluded from these data that the >2-µm particles do not exhibit colloidal properties in dispersion studies. In contrast, the <2-µm particles were affected by the chemical composition of the suspension.

Dispersion Index of <2-µm Particle-Size Fraction

The dispersion status of a soil has been shown to be affected by the salt concentration, SAR, and pH, among other factors (Suarez et al., 1984; Goldberg and Glaubig, 1987). The dispersion index values for our samples, presented in Table 1, show lower values for the B treatment than for the A and C treatments, in agreement with the lowest SAR values shown for Treatment B. However, dispersion indices in the B treatment, despite being lower than the A and C treatments, still had high dispersivity values. The high dispersibility values of the B treatment may have been due to the facts that the pH of the suspension is above the PZNPC of the clay particles and that the EC is very low. Lebron et al. (1993) estimated, using electrophoretic mobility data, the PZNPC of Silver Hill illite to be at pH ≈7; above pH 7, the variable charge is negative. These chemical conditions explain the almost totally dispersed state of the <2-µm samples. This suggests that almost all of these soils will be in a dispersive state if leached with very dilute water, regardless of the ESP of the soil.

Since the particle-size distribution did not change with the treatments, we should have been able to determine the effect of the salinity, sodicity, and pH on the measured stability indices by comparing the values of these properties obtained for the natural soil samples with the same parameters measured in the B and C treatments. However, there is a range of variability in the clay content within the 19 soil samples, and clay content has already

Table 4. Electrical conductivity (EC) of the saturation extract (SE), pH SE, EC in a 1:1 soil/solution ratio, sodium adsorption ratio (SAR), saturation percentage (SP), Ca and Na SE for Treatments A, B, and C, and chemical composition of the SE for Treatment A (natural Soil).

					Ionic composition of the saturation extracts											
Soil no.	Treatment	ECSE	EC1:1	pH SE	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	Li^+	SAR	SP
		dS m^{-1}	dS m^{-1}		mmol$_c$ L^{-1}										(mmol L^{-1})$^{0.5}$	g kg^{-1}
1	A	30.7	13.2	8.9	0.0	13.2	264	68.0	4.26	2.5	6.66	358	1.20	0.12	167	355
	B	4.9	2.8	8.4						40.9		6			0.4	475
	C		1.7													
2	A	38.8	17.7	9.5	18.2	17.8	347	88.0	3.27	2.2	4.23	456	1.10	0.14	255	370
	B	2.2	1.3	8.3						15.5		4			0.5	500
	C	2.4	1.1	8.9						3.4		24			2.7	388
3	A	36.5	19.5	9.8	33.5	19.1	313	74.0	2.20	1.5	2.85	462	0.90	0.14	312	450
	B	1.2	0.7	8.4						7.5		3			0.6	575
	C		1.5													
4	A	24.8	12.4	10.0	39.4	23.8	168	64.0	5.18	1.4	1.38	278	0.55	0.10	237	395
	B	1.1	0.6	8.8						7.2		3			0.6	575
	C	2.1	1.8	9.1						2.1		22			3.2	329
5	A	40.5	19.1	10.3	113.7	32.1	297	95.0	8.17	1.6	1.46	549	1.05	0.16	442	375
	B	1.3	0.6	8.7						7.2		5			0.8	539
	C	1.6	1.2	9.0						2.3		16			2.6	525
6	A	34.9	16.3	9.8	20.6	19.9	285	90.0	10.19	8.6)	2.37	413	1.00	0.12	281	340
	B	1.3	0.6	8.7						2.7		3			0.6	450
	C	2.8	1.4	9.2								30			3.3	471
7	A	21.4	9.3	9.5	0.0	20.5	158	78.0	6.46	2.4	3.11	282	0.55	0.08	170’	345
	B	1.1	0.7	8.7								2			0.6	525
	C	1.5	1.5	9.1						1.3		16			3.5	533
8	A	16.2	6.9	10.0	24.8	23.3	94	50.0	1.07	7.0	1.89	167	0.35	0.06	133	320
	B	1.1	0.6	8.8								3			0.6	529
	C	2.3	1.6	9.2						3.4		24			3.5	342
9	A	24.0	11.6	10.5	35.5	22.9	181	36.0	1.09	1.2	2.42	265	0.20	0.10	197	375
	B	1.2	0.7	8.8						6.5		4			0.8	550
	C	1.5	1.5	9.2						1.0		17			4.1	386
10	A	14.0	6.0	95	12.9	22.4	86	32.0	1.09	2.5	2.16	146	0.20	0.06	95	330
	B	1.3	0.6	8.5						5.5		6			1.1	500
	C	1.5	1.4	9.4						1.1		17			3.9	343
11	A	17.2	6.8	9.8	9.1	27.3	103	34.0	2.70	2.5	2.41	176	0.60	0.06	112’	320
	B	1.2	0.5	8.8						6.6		5			0.8	500
	C	3.0	1.7	9.2						1.4		29			4.6	333
12	A	22.8	9.4	10.2	46.9	27.1	144	46.0	4.12	1.6	2.32	255	0.65	0.08	183	320
	B	1.3	0.7	8.3						6.8					0.8	500
	C	1.9	1.5	9.6						0.9		21			4.8	343
13	A	7.3	2.9		16.8	23.0	34	10.8	0.09	1.0	1.48	80	0.25	0.04	72	280
	B	0.9	0.5	8.3						4.8		2			0.6	500
	C		1.4	9.3								26				367
14	A	14.7	5.9	10.2	42.7	26.7	74	14.0	1.06	0.9	1.79	165	0.35	0.06	143	305
	B	1.0	0.6	8.4						5.5		2			0.6	570
	C	1.8	1.2	9.4						1.8		20			3.4	395
15	A	13.6	4.7	10.1	30.0	25.7	79	27.2	1.42	1.1	1.24	152	0.35	0.06	140	300
	B	1.1	0.6	8.6						7.2		3			0.6	540
	C	2.3	1.3	9.0						2.0		26			3.6	333
16	A	28.8	11.7		0.0	18.3	235	64.0	4.47	2.8	3.00	308	1.55	0.10	181	325
	B	1.4	0.7	a.3						10.2		2			0.4	515
	C	1.6	1.3	9.0											2.7	317
17	A	31.0	11.6	9.2	0.0	18.3	263	76.0	1.56	8.7	9.45	321	0.80	0.12	127’	360
	B	1.5	0.6	8.3						2.1		4			0.7	525
	C	1.3	1.1	9.4						1.3		13			2.5	431
18	A	6.2	2.2	9.3	0.0	16.7	37	16.0	0.11	8.7	2.91	60	0.30	0.03	41	285
	B	1.2	0.6	8.6								1			0.4	416
	C	1.6	0.8	9.0						3:o		16			2.3	296
19	A	37.4	17.1	9.7	17.0	13.8	320	80.0	5.54	1.0	3.60	420	2.10	0.14	276	388
	B	1.3	0.7	8.4						8.3		3			0.6	535
	C	1.4	1.1	9.4						2.5		13			2.3	385

been shown to have an effect on the physical properties analyzed.

Effect of Clay Content

The linear regression of liquid limit against clay content is shown in Fig. 1. An increase in liquid and plastic limit values with increasing clay content has long been recognized (Baver, 1940); however, there is some controversy concerning the effect of the clay fraction on the plastic limit. Remy (1971) found no effect of the clay content on the plastic limit. Mettauer et al. (1983) confirmed the effect of clay on the liquid limit but also suggested that the fine silt fraction has the same effect on the liquid limit as does the clay fraction. In our samples, we found a high correlation of clay content with the liquid limit, but the linear fit was very different for each of the three treatments (Fig. 1). Treatments B and C have similar levels of salt concentration and slightly different levels of SAR; however, their liquid limit values were very different. The different resistance to flow of Treatments B and C, with the same clay content, may

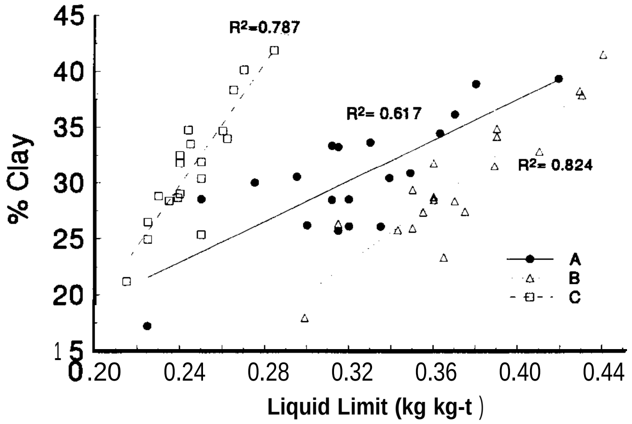

Fig. 1. **Relation between the clay content of the soil samples and the liquid limit for the natural soil (Treatment A), soil saturated with Ca (Treatment B), and salt-wasbed soil (Treatment C).**

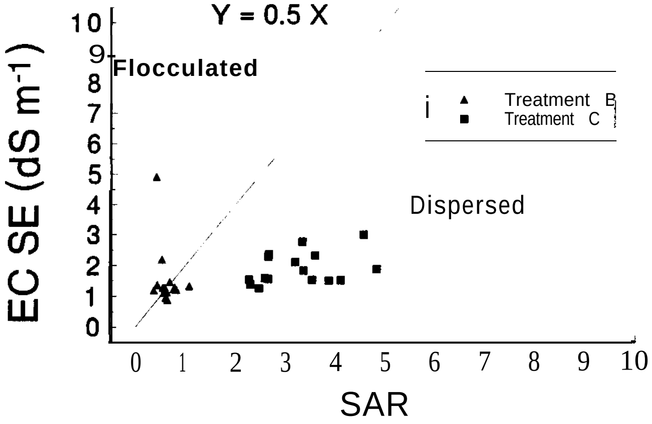

Fig. 2. Electric conductivity of saturated extract (ECSE)-sodium adsorption ratio (SAR) stability line for Ebro Basin soil (from Lebron, 1989) and Treatments B and C soil samples.

be due to the slight differences in SAR combined with the lower salt concentration and higher pH values of Treatment C. The threshold line between flocculated and dispersed for the soil used in this study is EC = 0.5 SAR (Lebron, 1989). Figure 2 shows that samples of Treatment C are below the critical coagulation concentration, consequently the samples are dispersed. Also Treatment C has higher pH values than Treatment B; the pH effect will be discussed below. We concluded that the liquid limit is indirectly related to the clay content.

Effect of Salinity

Table 2 shows the values of the Atterberg limits and Table 4 the EC measured in the saturation extract for Treatments A, B, and C. Considering the Treatments A and C as a group of soils undergoing reclamation by salt leaching, Treatment A represents the beginning and the C treatment the end of this process. Both treatments together can be considered as the same soil in different stages of the leaching process. Using the combined data for the A and C treatments, the liquid limit value decreased an average of 25% in water content when the EC decreased from 40 to 2 dS m^{-1}. This decrease in the liquid limit indicates a lower resistance of the soil to flow or migration when the salinity decreases, and a lower capacity to retain water. Therefore, this soil, after a process of leaching, would be more susceptible to erosion than before. In contrast, the B treatment shows a doubling of resistance to flow relative to the C treatment. As we mentioned above, the lower liquid limit values in Treatment C with respect to Treatment B may be attributed to the combination of lower salt concentration, higher SAR, and higher pH values in Treatment C. Table 2 also shows, for the B treatment, a range in the liquid limit from 0.30 to 0.45 kg kg^{-1} of water contained at the same EC (Table 4) and similar SAR. The variability of the liquid limit values within the same treatment is probably due to differences in particle-size distribution of the soil samples. Plastic limit values decreased 10% after washing the salts from the soils (Treatment C vs. Treatment A) and did not change when the exchange complex was saturated with Ca (Treatment B vs. Treatment A). These results are in contrast to the data from Derdour and Angers (1992), who did not find any effect of salinity on mechanical properties. We believe that this disagreement is due to the lower EC values and smaller EC range (0.9-3.7 dS m^{-1}) used in their experiment. The fact that increases in EC increased the Atterberg limits of our illitic soils is explained by the aggregation of the illite crystals in the soil. As the EC increases, the electrical double layer of the particles becomes smaller; consequently, the distance between particles is smaller. Under these conditions, the attractive forces strengthen the particle bonds. A stable structure acts as a framework where the generated porosity allows a higher water content than when the structure of the soil is less stable.

The swelling or shrinking capacity of our soils, measured by the $\mathrm{COLE}_{\mathrm{rod}}$, showed no clear effect of the salt concentration. Treatments A and C showed a certain tendency to decrease $\mathrm{COLE}_{\mathrm{rod}}$ as EC decreased, but the scattering of the values, especially in the C treatment, revealed other factors affecting the swelling properties. No effect of the particle size was found in the $\mathrm{COLE}_{\mathrm{rod}}$ for our soil samples. Saturation with Ca did not change the $\mathrm{COLE}_{\mathrm{rod}}$ values with respect to the A treatment for these micaceous soil samples, thus $\mathrm{COLE}_{\mathrm{rod}}$ is not suitable for evaluating the sodicity status of a soil.

The capacity of a soil to retain water at a matric pressure of 0.03 MPa has been used historically as a standard value of the water in the soil (U.S. Salinity Laboratory Staff, 1954). The water retained by a soil at 1.52 MPa is typically chosen to represent the water content at the wilting point. The difference between the water content at 1.52 MPa and at 0.03 MPa is often called the ***available water;*** this is usually considered to be the water that plants can use. The available water depends, among other factors, on clay/sand ratio, initial compaction, and saturation of the soil, and is related to the hydraulic conductivity (U.S. Salinity Laboratory Staff, 1954). Consequently, these parameters, along with the EC, contain valuable information for planning an irrigation system, the amount of irrigation, and the timing of irrigation cycles. Considering the A and C treatments, almost no effect of EC and SAR was found on the water content at 0.03 MPa matric pressure, and there was no effect of EC at 1.52 MPa matric water pressure (Table 2).

Among the six tests analyzed, the liquid limit appears to best predict the effect of the leaching process in this soil.

Effect of Sodium Adsorption Ratio

Sodium chloride was the dominant salt in the natural soils in this study; therefore, SAR values were high and directly correlated with the EC. The fact that the SAR increases when EC increases, and the fact that ESP values should be close to 100% (SAR > 100) prevents the use of SAR values to study the effect of sodicity on the physical properties of these soils in their natural state. To determine the effect of sodicity on the physical properties of our soils, we compared the results of Treatment B with Ca saturation to Treatment C with slightly higher SAR values and similar EC. The values of the liquid limit, plastic limit, and water content at 0.03 MPa matric water pressure were higher for the B treatment than for the C treatment. Liquid limit and plastic limit for the B treatment were higher than for the A and C treatments, as expected (Table 2). Moreover, the C treatment had a plasticity index <0.10 with a liquid limit <0.30 kg kg^{-1}. This corresponds to an erodible soil, according to U.S. Bureau of Reclamation criteria (Gibbs, 1945). The A treatment was marginally stable, according to this classification, and only the B treatment shows stability. The fact that a soil retains more water when Ca is the predominant cation in the system indicates a structure where large pores are present, resulting in more space available for water. This is also shown in Table 2, where the available water for the mean of the values of the B treatment was 70% higher than for the mean of the values of the C treatment. The slightly higher SAR values of the C treatment with respect to the B treatment, together with high pH values in the C treatment, makes the porosity in C treatment samples very unstable and reduces the capacity to hold water (Fig. 2). The SAR values in Treatment C are between 2 and 5; these values seem very low, especially compared with the traditionally critical point found for many different soils (SAR $\approx$ 15) (U.S. Salinity Laboratory Staff, 1954) but Northcote and Skene (1972) found the limiting value for Australian soils at ESP = 6. The sodic soils examined by Northcote and Skene (1972) were mainly nonsaline and many of them were calcareous. Lebron (1989), for the same type of soil as used in this study, found a threshold line similar to that found by Oster et al. (1980) for Fithian illite.

The water contents at 1.52 MPa matric pressure were higher for the C treatment than for the B treatment, which agrees with results from other soils (El Swaify et al., 1970; Russo and Bresler, 1977a,b) and clays (Dufey and Banin, 1979; Tessier, 1984). This is related to the water bound by the specific ions; monovalent cations cause more swelling and thus more bound water than divalent cations. This water, however, is not available for plant uptake, as shown by the available water data in Table 2.

Consequently, the replacement of Na with Ca in the exchangeable complex favors the linkage of the particles by reducing the thickness of the double layer, and enhances the water available for plant uptake. The above findings suggest that liquid limit, plasticity index, and available water appear to be adequate indexes to measure the improvement of the physical conditions of a soil during reclamation with amendments.

Effect of pH

A calcareous saline-sodic soil, during a leaching process, undergoes the following changes: reduction of salts, substitution of exchangeable Na by Ca supplied by calcite dissolution, and accumulation of alkalinity. The increase in alkalinity in the soil solution will increase the pH. This circumstance together with a low electrolyte concentration confers very poor stability to the soil particles (Treatment C).

The effect of pH on the stability of clay particles has been analyzed in previous studies. Lebron and Suarez (1992) and Lebron et al. (1993) found no significant pH effect on either dispersion or ζ potential in clay particles when the SAR is below the value at which the aggregation of micaceous clays (quasi-crystals) break down. Up to this point of aggregate breakdown, the main effect on dispersion and ζ potential were due to SAR and electrolyte concentration. But once the particles were apart, increases in SAR (above SAR 15 and pH 6) did not significantly increase the dispersion or the electrophoretic mobility of micaceous clays. In contrast, the pH effect became important once the particles were apart.

According to the data in Fig. 2, the disaggregation of the quasi-crystals for this soil may occur at SAR > 2 when ECSE is < 3 dS m^{-1}. The presence of single platelets together with high pH is probably the reason for the lower values for liquid limit, plastic limit, and COLE$_{rod}$ in the C treatment compared with Treatments A and B.

Relation between Physical Parameters

Resendiz (1977) related the presence of piping to a clay activity index between 0.003 and 0.01. These index values are generally associated with illitic soils or mixtures of kaolinite and smectite. Smectitic soils generally have a clay activity index X.01. The relevance of this index results from its relation to the permeability and swelling potential of a soil. Consistent with this relationship, a soil with a high clay activity index has less susceptibility to piping due to swelling potentials higher than soils with a low clay activity index.

Figure 3 shows that the A and B treatments were in the clay activity index range of 0.01 to 0.003, where soils are susceptible to piping, while the C treatment clay activity indices were ≤ 0.003, which classifies the samples as erodible.

The liquid limit can also be defined as the minimum distance between particles or between aggregates at which the interaction between the particles is weak

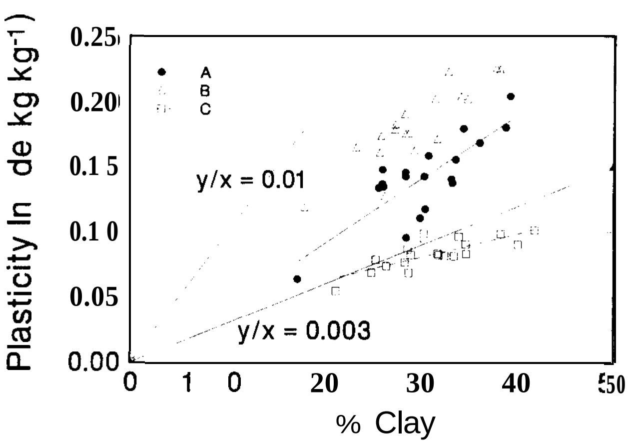

Fig. 3. **Relation between the plasticity index (liquid limit minus plastic limit) and the clay content of the soils for the natural soil (Treatment A),** soil saturated with Ca (Treatment B), **and salt-washed soil (Treatment C).**

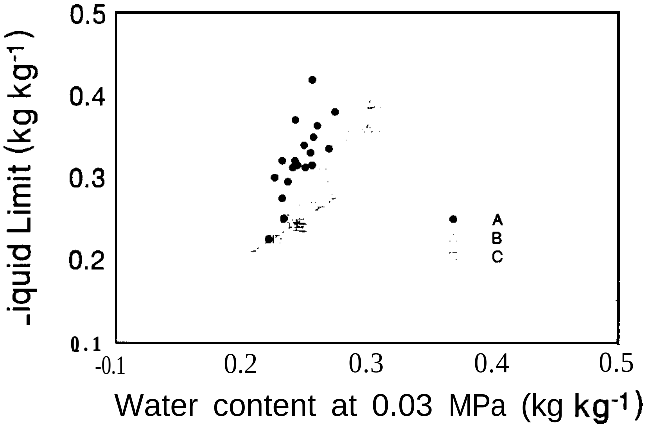

Fig. 4. Relation between the water content at 0.03 MPa and the liquid limit for the natural soil (Treatment A), soil saturated with Ca (Treatment B), and salt-washed soil Treatment C).

enough to allow the particles to move (Warkentin, 198 1). Figure 4 shows that the water content at 0.03 MPa is equal to the water content at the liquid limit for Treatment C. Soils with these characteristics flow easily, even at 0.03 MPa, due to the absence of internal cohesion. Natural leaching of the salts in the A treatment can put the soil in the same condition as represented by the C treatment.

CONCLUSIONS

The use of classical engineering techniques, such as Atterberg limits, combined with traditional soil science determinations, such as the water content at 0.03 MPa, gives us valuable information. In soil reclamation, especially in calcareous saline-sodic soils, the physical properties of the soils must also be considered.

Liquid limit is a suitable test to evaluate the ability of the soil to flow when under a leaching process. Liquid limit together with data on water content at 0.03 MPa can be used as a diagnostic tool to avoid unfavorable conditions, such as weakness of the bonding between particles to the point of loss of cohesion.

The elimination of soluble salts in a calcareous saline-sodic soil decreases the available water content and increases the tendency to flow in the washed soil, thus making the soil easily erodible. This is caused by accumulation of alkalinity in the soil solution due to the substitution of exchangeable Na by calcite Ca. When amendments are used, an increase in the exchangeable Ca content of the soil increases the liquid limit values and increases the amount of water available for plants. Therefore, liquid limit, plasticity index, and available water can be used to evaluate the improvement of the physical conditions of a soil under a process of reclamation with amendments.

The elimination of salts in a calcareous saline-sodic soil without addition of amendments may cause an irreversible loss of soil structure. This potential hazard can be evaluated by comparing the liquid limit to the water content at 0.03 MPa. The reason for the loss of structure is the combination of a low salt concentration, the presence of Na in the exchange complex, and the accumulation of alkalinity due to dissolution of calcite.

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