EFFECT OF EXCHANGE SODIUM ON THE MOISTURE EQUIVALENT AND THE WILTING COEFFICIENT OF SOILS [1]

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INTRODUCTION

Laboratory research by numerous investigators has shown that sodium adsorbed by the clay complex of soils increases dispersion, pH values, swelling, osmotic imbibition, migration velocity, apparent density of puddled soils, and the hardness of dry aggregates; and lowers heat of wetting, sticky point, and permeability.

The moisture equivalent (3, *4*)[5] and wilting coefficient (5), more than any other soil constants, have come into extensive use as reference points for the water relations of soils and plants. Sharp and Waynick (17), Joseph (10), Anderson (1), and others (20) have been in agreement in finding that adsorbed sodium markedly increases the moisture equivalent. Veihmeyer and Hendrickson (21) have concluded, however, that the change, when any, can be attributed to soil puddling. In connection with all results it can be appropriately mentioned that the magnitude of the effect that adsorbed sodium has on soil characteristics is related to the amount and character of the clay of the soil, to the extent to which other ions are replaced by sodium, and to the extent to which flocculating electrolytes are removed.

No one has reported on the effects of adsorbed sodium on the availability of moisture to plants in the wilting range, and,. so far as the writers have been able to learn, no investigations have been conducted.

In agreement with laboratory findings, it has been extensively observed that when lands are irrigated with water containing a high proportion of sodium relative to the concentrations of other bases the permeability tends to be reduced. Accompanying the effects of adsorbed sodium on permeability are other adverse consequences, such as the accumulation in the root zone of the salt constituents of irrigation waters, increased erodibility, the loss of good tilth, and consequent unsatisfactory seedbeds. It is a common observation that

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[5] Italic numbers in parentheses refer to Literature Cited, p. 424.

soils with much adsorbed sodium are less permeable to rain water than they are to saline irrigation waters.

The expression "percent sodium," as used by Eaton (7) to designate the relation

$$\text{Sodium-total base ratio} = \frac{\text{milliequivalents Na} \times 100}{\text{milliequivalents of total bases}},$$

has come to be regarded as an important water-quality characterization. Because of the diversity of factors that bear on permeability and exchange reactions and the quantitative relationships involved, it has not been possible to closely delimit the concentrations and proportions of sodium in natural waters that should be avoided or designated as undesirable.

The relationships between adsorbed sodium and moisture equivalent that are reported on in this paper were investigated for the purpose of exploring the possibility of utilizing the moisture equivalent as an index to sodium-induced dispersion. As a part of the inquiry, comparisons were made between calcium-treated and sodium-treated soils with respect to (1) the effect of the acceleration rate of the centrifuge on the moisture equivalent; (2) the migration and segregation of sand, silt, and clay in dispersed soils during centrifuging; (3) the distribution of moisture in Ca soils and Na soils after centrifuging; (4) the effect of flocculation by electrolytes on the moisture equivalent of Na soils; and (5) the quantity of sodium that significantly affected moisture equivalent values when Ca and Na soils were mixed in different proportions. Finally, moisture equivalent and hydroscopicity comparisons were made between soils saturated with calcium, magnesium, sodium, and potassium. This was done for the purpose of determining whether the effects of potassium most closely resembled those of calcium and magnesium or those of sodium.

The relationships between the adsorbed sodium and moisture availability were investigated with 12 soils, both at the wilting coefficient and at the ultimate wilting point. The resulting data, together with the moisture equivalent values, are graphically presented with the use of a pF scale.[6] (See fig. 3.)

DESCRIPTION OF SOILS, DEFINITIONS, AND METHODS

The source, classification, and certain physical constants of the 12 soils used for these investigations are reported in table 1.

MOISTURE EQUIVALENT

The moisture-equivalent values represent the percentage of moisture remaining in 30-gm. samples of soil that had been saturated for 24 hours, drained for 30 minutes, and then centrifuged for 30 minutes in standard cups in a standard moisture equivalent centrifuge drum operated at a rotational speed of 2,440 r. p. m.[7] The centrifuge came to full speed in 15 seconds. Any free water remaining on the surface of the soil after centrifuging was removed by inverting the cups for several minutes and then wiping their inside walls with blotting paper,

[6] The pF value of soils is the logarithm of the equivalent capillary tension expressed in centimeters of water column.

[7] The centrifuge drum was belt-driven from a 1-hp. polyphase induction motor following a principle of operation worked out by E. S. Babcock, of Riverside. Calif. By the use of a large motor with a low connected load, the speed of the drum is determined alone by the cycles of the alternating current and the ratio of the two pulleys. The centrifuge drum was mounted on the vertical pulley, within which were two roller bearings set on a 1¼-inch shaft anchored in a concrete pedestal. With this machine tbe acceleration rate is rapid, though it is possible to reduce it by installing an autotransformer (choke coil) in the line.

TABLE 1.—*Series, source, and certain physical constants of 12 California soils used in the investigation reported herein*

Soil No.	Soil type	Location	Moisture equivalent [1]	Xylene equivalent [2]	Wilting coefficient [3]	Apparent density [1]	Exchange capacity per 100 gm.	Mechanical analysis of composite [1,4]		
								Sand, 2–0.05 mm.	Silt, 0.05–.002 mm.	Clay, 0.002 mm.
						Gm./Cc.	*Milli-equivalents*	*Percent*	*Percent*	*Percent*
279	Gold Ridge fine sandy loam	Sonoma County, sec. 35, T. 6 N., R. 9 W	10.6	4.4	3.6	1.31	3.34	71.3	22.2	6.5
1	Sierra loam	Riverside County, sec. 22, T. 2 S., R. 5 W	8.8	4.3	3.7	1.44	4.82	60.7	33.4	5.9
4	Yolo loam	Ventura County, sec. 26, T. 4 N., R. 20 W	11.5	4.3	4.7	1.43	7.13	64.6	26.2	9.2
2	Hanford sandy loam	Kern County, sec. 8, T. 31 S., R. 30 E	11.7	4.2	5.5	1.36	8.54	72.6	17.8	9.6
6	Yolo loam	Ventura County, sec. 26, T. 3 N., R. 22 W	12.4	5.3	5.7	1.46	8.02	62.2	28.7	9.1
3	do	Ventura County, sec. 2, T. 3 N., R. 21 W	14.1	4.0	5.8	1.41	9.32	50.7	37.3	12.0
9	Antioch clay loam	Stanislaus County, sec. 31, T. 3 S., R. 7 E	18.0	7.9	10.2	1.37	14.05	38.0	36.3	25.7
5	Yolo silt loam	Ventura County, sec. 19, T. 3 N., R. 21 W	20.6	7.5	9.8	1.27	16.46	40.5	41.1	18.4
10	Antioch clay	Stanislaus County, sec. 31, T. 3 S., R. 7 E	21.0	11.1	12.0	1.40	15.83	19.4	50.5	30.1
8	Yolo fine sandy loam	Ventura County, sec. 4, T. 2 N., R. 22 W	22.4	11.6	11.7	1.22	14.82	27.5	51.5	21.0
7	Rincon loam, silty phase	Ventura County, sec. 23, T. 3 N., R. 22 W	22.9	6.0	11.4	1.38	20.00	37.1	35.6	27.3
278	Aiken clay loam	Butte County, sec. 14, T. 22 N., R. 3 E	36.2	24.7	22.0	1.09	14.77	37.6	35.8	26.6

[1] Untreated soil.
[2] Means of determinations on washed, calcium-treated, and sodium-treated soils (percentage by weight).
[3] Ca soil.
[4] The mechanical analyses were made in accordance with the pipette method of the former Bureau of Chemistry and Soils, U. S. Department of Agriculture.

XYLENE EQUIVALENT

The xylene technique was the same as that used for the moisture equivalent, except that the samples were oven-dried just before they were wet with xylene. Xylene-equivalent measurements were made on washed, calcium-treated, and sodium-treated soils. The character of the adsorbed cation, in accordance with Joseph's (10) findings for soil clays, was without effect on the percentage of xylene held against a force of 1,000 times gravity. The greatest single departure between the xylene equivalents of any soil as treated with calcium and sodium was 2.6. The average of the values of the xylene equivalents was 12.9 for the 12 Ca soils and also for the 12 Na soils.

WILTING COEFFICIENT AND ULTIMATE WILTING POINT

The exhaustion of soil water that accompanies the wilting of plants, as recognized by Briggs and Shantz (5) and subsequently by others, is progressive, and extends through what is now termed the "wilting range." The fact that wilting does occur over a range of moisture percentages for a given soil adds to the difficulties associated with the selection of a uniform end point. The wilting coefficient, as here used, represents a degree of wilting from which only about one-third of the leaves of sunflowers recovered when the plants were placed in a dark, humid chamber overnight. Except as noted in table 10, each wilting coefficient and ultimate wilting point value is the average of six determinations.

Water and soil were alternately added (washed, Ca, and Na soils alike) as the cans were filled for the wilting coefficient measurements. After germination of the sunflower seeds additional water was added to the soil surface until a plant of the desired size was developed, after which the openings in the covers of the cans were closed with cotton. After the plants had been wilted and cropped, the soils were dried at 105° to 110° C. for 4 days. The soil of each can was then broken up and passed through a 2-mm. screen and rolled in a paper to remix. One sample was withdrawn from each wilting coefficient can for moisture equivalent measurement. Any moisture equivalent determination that appeared out of line was repeated with a new sample. The soil of the six cans of each treatment was then composited as stock samples for use in other parts of the investigation.

The "ultimate wilting point," a term suggested by Taylor, Blaney, and McLaughlin (18), is used in the present work to designate the moisture content at which the rate of movement of water into a 15- to 30-cm. sunflower plant, after wilting, from a 600-gm. mass of soil was only sufficient to bring about the recovery of the terminal pair of leaves (1 to 2 cm. long) when the plant, was placed overnight in the moist chamber. As this end point was approached the loss of water was a fraction of a gram per day, or in the order of 0.1 percent of the weight of the soil mass. The atmospheric conditions in the Riverside, Calif., greenhouse where the plants were grown were conducive to high transpiration rates. After recording the pot weights at the wilting coefficient, the same plants were reexposed in the greenhouse until the ultimate wilting point was reached.

The old leaves of plants on the majority of the Na soils deteriorated somewhat more rapidly than those on the Ca soils, and the death of leaves on the former plants was sometimes accompanied by marginal burnmg. Equally good distributions of roots were observed in the Ca and Na soils. A further reference is made to the wilting measurements under soil treatments.

APPARENT DENSITY

Apparent density of untreated soils, as reported in table 1, represents the weight per unit volume of an-dry soil that had been passed through a 2-mm. sieve. The volume was measured in a 5 by 5 by 2.5 cm. box. The box was filled and lightly tapped on the desk top and leveled off before weighing; the method of filling the boxes was as nearly alike as possible for all soils.

EXCHANGE CAPACITY

For the measurements of the exchange capacity, a 20-gm. portion of soil was digested with 250 cc. of neutral normal ammonium acetate and leached free of calcium with 500 cc. of neutral normal ammonium acetate. The excess ammonium acetate was then removed by leachmg with neutral normal ammonium chloride followed by leaching with neutral methyl alcohol until the leachate was free from chloride ion. The adsorbed ammonia (NH,) was distilled! in the presence of magnesia (MgO), into a 2-percent solution of boric acid and titrated with standard sulfuric acid. The values reported in table 1 are the means of washed, sodium-treated, and calcium-treated soils; the values were in close agreement.

PREPARATION OF SOILS

Two sets of soils were prepared for these investigations. The first set-designated washed, Ca, and Na soils-provided material for the comparisons of the effects of calcium and sodium on the moisture equivalent and on the wilting coefficient and ultimate wilting point. The second set-designated Ca, Mg, K, and Na soils-was used only for the supplementary hydroscopicity and moisture equivalent measurements where the effect of potassium was of principal interest. Descriptions of the methods employed in preparation of the two sets of soils follow.

WASHED, CALCIUM-TREATED, AND SODIUM-TREATED SOILS, AND MEASUREMENT OF EXCHANGE SODIUM

Three 4-kg. portions of each of the 12 soils (table **1)** were weighed into porcelain dishpans. The washed soils were successively treated with distilled water in parallel with the soils treated with calcium and sodium. The Ca and Na soils were treated three successive times with 3-liter portions of normal calcium chloride and sodium chloride solutions, respectively. Each suspension was stirred several times during the day and allowed to settle overnight; the supernatant solution was then decanted off and additional solution was removed with filter candles. The soils were then successively washed with 3-liter portions of distilled water until, in a final washing, the solutions contained less than 10 milliequivalents per liter of chloride ion. This washing required from **15** to **18** liters of water. To each of the 4-kg. portions of soil, from which all possible solution had been removed by the filter candles, 1 liter of Hoagland's nutrient solution was added. This solution contained 5, 5, 2, and 1 millnnoles, respectively, of calcium nitrate ($Ca(NO_3)_2$), potassium nitrate (KNO,), magnesium sulfate ($MgSO_4$), and monopotassium phosphate (KH_2-PO,). The soils, still in the original pans, were then set in the sun until they had dried. After they had been passed through a 2 mm. screen, they were wet to approximately the moisture equivalent with distilled water and frozen at —10° C. for 3 days and again air-dried and screened. Freezing left the soils reasonably friable. The dried aggregates of the Na soil, though easily broken, were harder than those of the washed or Ca soils. The soils as thus treated were used for the wilting coefficient and ultimate wilting point measurements.

Replaceable sodium concentrations in the Na soils were measured after the soils had been removed from the wilting coefficient cans. Total sodium was determined by the uranyl zinc acetate method in an aliquot of the ammonium acetate extract (see section headed Exchange Capacity, p. 405) from which organic matter and silica hsd been removed. From the total sodium so determined there was subtracted the sodium in solution in the soils as wet with water to three times the moisture equivalents found for the Ca soils. Aliquots of solution for these latter determinations were obtained by centrifuging four 50-gm. portions of each soil in glass tubes. It has been shown by Eaton and Sokoloff (8) that the apparent adsorbed sodium, as calculated by subtracting the sodium of aqueous extracts from the total obtained by ammonium acetate extraction, decreases as the soil-water ratio used for extraction is increased.[8] A number of the Na soils of this series as loosely placed in centrifuge cups and wet from below (the standard procedure) absorbed approximately three times the moisture equivalent of water of the Ca soils.

Electrical-conductivity measurements made on the foregoing centrifuge extracts of five of these soils gave values between 63 X 10^{-5} and 154 X 10^{-5} reciprocal ohms at 25° C., indicating the presence of between 6 and 15 milliequivalents of salt per liter of solution at this moisture content. This salt included the residual soluble material remaining after the sodium treatments, that of the nutrient solution which was added, and any salt brought mto solution during the growth of the sunflowers, minus the salts taken up by the plants.

TABLE 2.-Exchange *capacity and exchange sodium in* Na *soils*

Soil No.	Exchange capacity per 100 gm.	Sodium in NH_4Ac extract per 100 gm.	Sodium in 3X moisture equivalent extract per 100 gm.	Exchange sodium	
				In soil per 100 gm.	Proportion of exchange capacity
	Milli-equivalents	Milli-equivalents	*Milli-equivalents*	*Milli-equivalents*	*Percent*
279	3.34	3.03	0.59	2.44	73.1
1	4.82	3.71	.69	3.02	62.7
4	7.13	5.33	1.37	3.96	55.5
2	8.54	5.54	1.10	4.44	52.0
6	8.02	6.07	1.19	4.88	60.8
3	9.32	7.12	.96	6.16	66.1
9	14.05	10.25	1.38	8.87	63.1
5	16.46	10.42	2.25	8.17	49.6
10	15.83	13.85	1.59	12.26	77.4
8	14.82	9.95	2.16	7.79	52.6
7	20.00	14.47	1.72	12.75	63.8
278	14.77	3.52	1.21	2.31	15.6

[8] Since this paper was written, Kelley (11) has published data confirming these findings of Eaton and Sokoloff. His data show for an Imperial Valley soil 5.1 m. e. of absorbed sodium per 100 gm. as determined on the basis of displaced solution, but only 0.6 m. e. on the basis of water extracts. The corresponding values for his Fresno soil 887 were 3.3 and 2.6 m. e., respectively.

As shown by table 2, the sodium chloride treatments did not saturate the soils with sodium and they were better suited, for this reason, to the purposes of the experiment. Neither Gedroiz (9) nor Ratner (13) was successful in growing plants in soils containing somewhat higher percentages of sodium. In all probability calcium was the principal base in the washed soils, since replacement proceeds in the calcium direction when soils with calcium carbonate are repeatedly treated with distilled water. 'The sequence of changes accompanying progressive leaching with distilled water of calcareous soils containing sodium (8) are (1) dilution of the aqueous phase and (2) a resultant replacement of some of the adsorbed sodium by calcium. As the process is continued, sodium of the aqueous phase is removed by leaching and new calcium comes into solution from calcium compounds, followed by further exchange of calcium for adsorbed sodium.

SOILS TREATED WITH CALCIUM, MAGNESIUM, POTASSIUM, AND SODIUM

The set of soils treated with calcium, magnesium, potassium, and sodium was given a uniform pretreatment with ammonium acetate and ammonium hydroxide to remove or reduce calcium carbonate and organic matter and thereby make possible a higher percentage saturation with the Introduced bases. One-kilogram aliquots of each of the soils were suspended twice in 4 liters of normal ammonium acetate, then in 4 liters of N/10 ammonium hydroxide, and again in 4 liters of normal ammonium acetate. Durmg each suspension the soils were recurrently stirred during the day (in the final ammonium acetate for 4 days), allowed to settle overnight, and then the supernatant solution was decanted and additional solution removed with filter candles. The foregoing trcntments did not remove all calcium but none of the final solutions contained more than 10 milliequivalents per liter. The soils were dried, ground to pass a 2-mm. sieve, and divided into five 200-gm. aliquots, only four of which were used.

Each 200-gm. aliquot of each soil was treated three successive times with 800 cc. of normal salt solution ($CaCl_2$, $MgCl_2$, KCl, or NaCl, respectively), and then washed with distilled water, by suspension and stirring and the removal of solution with filter candles, until the chloride content of the suspending solution was less than 5 milliequivalents per liter. The potassium-trcatcd and sodium-treated soils became highly dispersed during the washing with water and certain of them liberated some additional organic matter, but by the end of the washing little came into solution. The soils were finally air-dried, ground, and thoroughly mixed by rolling.

EXPERIMENTAL RESULTS

EFFECT OF STARTING ACCELERATION ON THE MOISTURE EQUIVALENT OF CALCIUM-TREATED AND SODIUM-TREATED SOILS

Although the effect of rate of acceleration on moisture equivalent values has been recognized by others as a factor (21), cxperimentul data bearing on it have not been found in the literature. The measurement's reported in table 3 show higher moisture equivalent values when the drum is brought to full speed in 15 seconds than when full speed is attained in 4.5 minutes. The effect is especially marked only in the instance of Na soils 7 and 10. Relatively slower accelerations have been most extensively used in the past; otherwise a rapid acceleration with the resulting higher values would seem to bc desirable, since a closer packing of soil particles is more representative of field conditions.

TABLE 3.-*Effect of* starting acceleration on *the moisture equivalent of Ca and* Na soils

Time to full speed	Moisture equivalent of soil receiving indicated treatment							
	Sail No. 6		Soil No. 10		Soil No. 6		Soil No. 7	
	Ca	Na	Ca	Na	Ca	Na	Ca	Na
15 seconds	13.2	23.2	21.5	43.0	22.0	37.5	22.2	57.0
4.5 minutes	12.8	21.8	20.7	32.4	20.5	35.6	21.2	51.6

MIGRATION AND SEGREGATION OF SAND, SILT, AND CLAY IN DISPERSED SOILS DURING CENTRIFUGING

Two characteristics of certain of the centrifuged Na soils attracted attention at the outset of this investigation. At the end of the 30 minutes in the centrifuge, free water was present on the surface of the finer-textured Na soils 3, 5, 7, 8, 9, and 10. After these soils were dried the surfaces were glazed, and many times an upper layer curled away from the underlying soil (fig. 1), indicating a segregation of fine particles.

Examinations indicated that the upper layer was composed almost wholly of clay particles. Beneath this clay, silt particles tended to prcdominatc. In soil 7, there was a clearly demarked light-colored silt surface and sand particles were observed to have accumulated in the outer soil near the filter paper. These effects will receive further consideration in the section that follows.

DISTRIBUTION OF MOISTURE IN CALCIUM-TREATED AND SODIUM-TREATED SOILS AFTER CENTRIFUGING

Measurements were made of the distribution of water after centrifuging in five of the Na soils and, for comparison, in the corresponding Ca soils by the following procedure. The original screens were removed from a number of the centrifuge cups and others substituted that could bc slipped into place and readily removed. The soils were prepared for the moisture-equivalent determination in the usual way, by weighing 30 gm. of air-dry soil into the cups, allowing them to stand for 24 hours in a tray of water, and gently adding water to the surface of any that had not taken up enough water to wet the surface within half an hour. After the soils had drained for 30 minutes, the cups were placed in the centrifuge drum without jarring and centrifuged for 30 minutes. The cups were taken fromthe drum, and if there was free water on the surface they were inverted for a few minutes and the inside walls of the cups wiped with absorbent paper. The screens were then carefully slipped off the bottom of the cups and the soils placed on a block of wood slightly concave along the center line and a little smaller than the inside of the cup. By carefully pulling the cup downward, it was possible to expose portions of soil of the desired thickness above the upper edges of the cups. Succcssivc layers, roughly 2 mm. thick, were in turn sliced off with a knife and transferred to weighing cans. Four layers were taken from

each of the Na soils and three from each of the Ca soils. The bottom section of the Ca soils exceeded the mm. in thickness, but there was not sufficient for a full 2-mm. fourth layer. These methods, though not very exact with respect to the thickness of the soil layers, were regarded

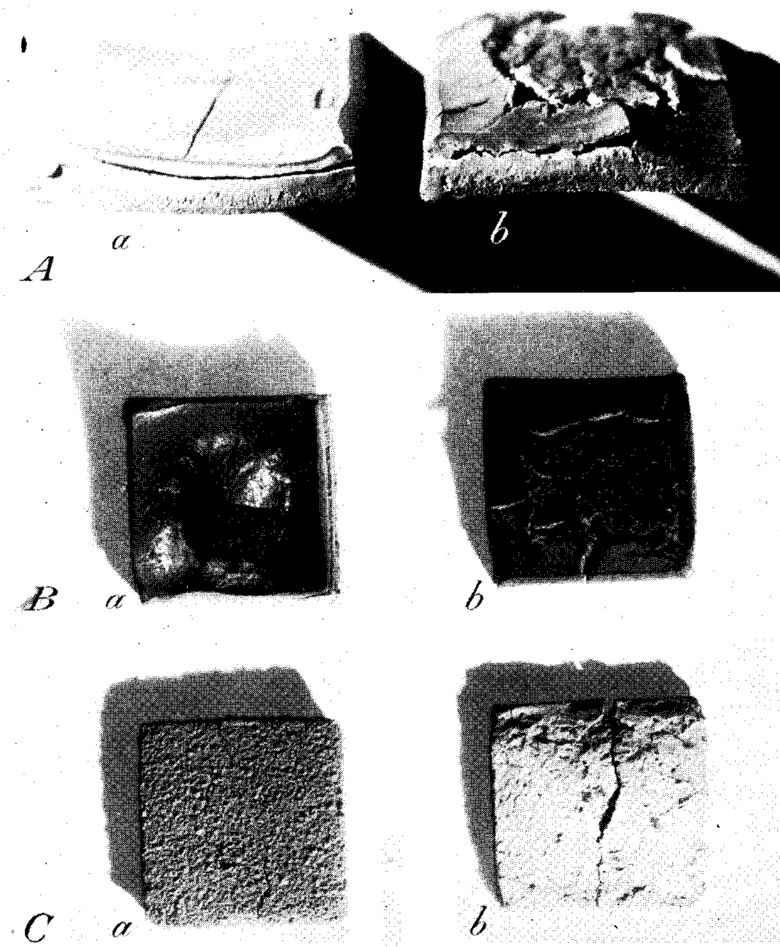

FIGURE 1.--Appearance of centrifuged Ca- and Na-treated soils after drying: A and B, (n) Na soil 10 and (b) Na soil 7 after centrifuging and drying; C, (n) Ca soil 10, (b) Na soil 7 with clay layer removed, exposing white calcareous silt layer.

as nonetheless suited to the purpose. Difficulty from crumbling, such as was experienced with Ca soil 5, would have been encountered had the measurements been undertaken with the coarser-textured Na soils.

In conformity with the findings of Veihmeyer, Israelsen, and Conrad (22), who worked with untreated soils, it was found (table 4) that the percentage of water in the Ca soils increased from the inner surface to the outer. The water distribution in each of the Na soils stands in contrast. With these the gradient was reversed. In three of the five Na soils over twice as much water was present in the inner layer as in the outer.

TABLE *4.--Effect of sodium on distribution of moisture in centrifuged samples*

Soil No.	Moisture content of successive indicated layers of soil from inner surface outward toward periphery of centrifuge in—								
	Ca soils				Na soils				
	0-2 millimeters	2-4 millimeters	Last layer	Weighted mean	0-2 millimeters	2-4 millimeters	4-6 millimeters	Last layer	Weighted mean
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
					48.4	34.4	29.6	27.8	35.1
5	(1)	(1)	(1)		53.8	38.4	32.1	28.4	36.2
					49.0	39.0	34.2	29.9	35.5
					99.5	54.3	48.0	40.4	55.0
7	19.8	21.5	22.7	20.8	94.4	55.7	50.9	44.2	55.5
					76.0	57.5	55.0	47.9	57.8
8	21.5	22.1	23.2	22.2	52.3	39.1	34.3	31.F	38.2
	21.2	22.1	22.2	21.8	52.1	39.1	34.3	31.5	3x.1
9	15.3	16.4	17.1	16.6	63.3	24.9	22.2	22.0	30.8
	16.8	17.0	17.3	17.0	------	-------	--------	------	--
10	20.0	20.2	20.5	20.2	78.4	33.9	29.5	27.2	38.3
	20.7	29.1	20.9	20.5	-------	------	-------	----	------

[1] Crumbled

In considering these effects it is necessary to take into account one of the important characteristics of the moisture-equivalent determination. The centrifugal force of 1,000 times gravity is applied not alone to the water, but also to the soil particles. As placed in the centrifugal drum, Na soils contain much water and being dispersed an excellent condition is provided in the plastic masses of the fine-textured soils for particle segregation. The large particles of Na soils, in accordance with Stokes' law, tend to migrate toward the periphery, displacing small particles toward the axis of rotation. The mass of the finer-textured Na soils being somewhat impermeable a part of the water, which has a specific gravity below that of hydrated' clays, is displaced toward the axis of rotation and collects on top of the clay. Accompanying this inward displacement of water there is a further sorting of clay and silt particles by size and specific gravity! giving rise to segregations such as are illustrated in figure 1. Continued centrifuging of Na soils beyond the 30-minute period resulted in some further loss of water, but the rate of movement of water out of the soil *was so slow* as to eliminate the possibility of removing surface water by any reasonable period of centrifuging.

EFFECT OF ADSORBED SODIUM ON THE MOISTURE EQUIVALENT OF THE 12 SOILS

The moisture equivalents of each of the *12 Ca* and Na soils are shown in table *5*. In this table there arc also shown the clay content and exchange capacity of these soils and the adsorbed sodium of the Na soils.

The moisture equivalents of soils 279, Gold Ridge sandy loam, and 278, Aiken clay, were decreased by treatment with sodium. Soil 279 is highly siliceous, contains li ttle clay, and has a low exchange capacity. Soil 278 is of basic igneous origin, and although it has an apparent clay content of 37.4 percent it possesses few clay properties. The volume weight of this soil is only 1.09, and the ultimate soil particles are irregular in shape, porous, and easily broken. It seems probable that the indicated high clay content may be more apparent than real, since in the mechanical analysis the settling rates of many of the larger fine particles would be slow enough to cause them to be drawn off as clay. Anderson (1) found the moisture equivalent of the colloidal fraction of a lateritic soil to be unaffected by sodium treatment.

TABLE 5.-*Effect of adsorbed sodium on the moisture equivalent*

Soil No.	Moisture equivalent: Ca soil	Moisture equivalent: Na soil	Moisture equivalent: Increase in Na soil over Ca soil	Clay less than 0.002 mm.	Exchange capacity per 100 gm.	Adsorbed sodium per 100 gm.	
				Percent	*Milli-equivalents*	*Milli-equivalents*	*Percent of total*
279	10.2	9.4		6.5	3.34	2.44	73.1
1	9.2	10.2	1.0	5.9	4.82	3.04	62.7
4	11.2	15.5	4.3	9.2	7.13	3.96	55.5
2	11.9	16.6	4.7	9.6	8.54	4.44	52.0
6	13.3	23.2	9.9	9.1	8.02	4.88	60.8
3	14.5	[1] 33.0	18.5	12.0	9.32	6.16	66.1
9	18.6	[1] 34.0	15.4	25.7	14.05	8.87	63.1
5	21.9	[1] 3i. 6	15.6	18.4	16.46	8.17	49.6
10	21.4	142.9	21.5	30.1	15.83	12.26	77.4
8	22.6	[1] 43.7	21.1	21.0	14.82	7.79	52.6
7	22.1	[1] 57.4	35.3	27.3	20.00	12.75	63.8
278	33.0	30.1		26.6	14.77	2.31	15.6

[1] Free water on soil after centrifuging.

The soils are listed (278 excepted) in the order of increasing Na soil moisture equivalents (table 5). Tending to parallel this order, there are increases in the difference between the Ca soil and Na soil moisture equivalents, in *clay* content, in exchange capacity, and in adsorbed sodium. A closer parallelism would scarcely bc expected when account is taken of the variations in the size of clay particleshere grouped as less than 0.002 mm., in the hydration characteristics and exchange capacity of different clays, and the differences in soils with respect to particle segregations in the centrifuge. The conclusion obviouslv follows that the moisture equivalent of soils reflects not only mechanical composition as determined by standard analysis but also soil structure as influenced by the kind and quantity of the adsorbed cations.

The effect of adsorbed sodium on the moisture equivalent is regarded as being consequent to three coincident factors: Hydration, dispersion, and the segregation of a relatively impervious layer of clay on the surfaces of some of the soils. Hydration contributed to the results both because of the tightly held water and because of such relation as hydration may bear to impermeability. Dispersion increased the free surfaces and thereby the water retentiveness of the soils.

THE MOISTURE EQUIVALENTS OF CALCIUM-TREATED SOIL AND SODIUM-TREATED SOIL MIXTURES

When the Ca and Na soils were mixed in equal proportions by prolonged rolling in a sheet of paper; the resulting moisture-equivalent values tended to approach in magnitude the Ca soil values more nearly than the Na soil values (table 6).

TABLE 6.—*The moisture equivalent of mixtures of calcium- and sodium-treated soils*

Soil No.	Moisture equivalent of indicated percentage mixture of Ca soil and Na soil [1]										
	100/0	90/10	80/20	70/30	60/40	50/50	40/60	30/70	20/80	1 0/90	0/100
279	10. 2	--	--	--	--	10. 0					9. 4
1	9. 2	--	--	--	--	10. 1				--	10.2
4	11. 2	--	--	--	--	13. 0					15.5
2	11. 9	--	--	--	--	12. 7	--			--	16.6
6	13. 3	13. 2	13. 8	13. 3	14. 6	15 1	15. 6	17. 7	18.8	20.4	23. 2
3	14. 5	--	--	--		17. 2	--			--	[2] 33. 0
9	18. 6	--	--	--		2%. 2	--			--	34.0
5	21. 9	21. 3	21. 8	22. 5	22. 5	2:i. 4	25. 2	26. 9	30. 2	[2] 36. 2	[2] 37.5
10	21. 4	21. 6	21. 7	22. 3	24.5	[2] 27. 2	[2] 30. 5	[2] 33. 3	[2] 37. i	241.3	[2] 42.9
8	22. 6	--	--	--		27. 0	--			--	243.7
7	22. 1	21. 9	22. 8	23. 9	27.0	30. 6	[2] 38. 4	[2] 41.0	[2] 45.5	[2] 54.8	[2] 57.4
278	33. 0	--	--	--		31. 6	--			--	30.1

[1] Numerator=Ca soil; denominator=Na soil
[2] Free water on soil after centrifuging.

The fact that sigmoid moisture equivalent curves result when Ca and Na soils are mixed in the successive proportions shown in figure 2 would indicate that the relation between adsorbed sodium and either or both hydration and dispersion is not a linear one. Some of Ratner's data (13) on the dispersion of clay suspensions by adsorbed sodium also yield a graph with slightly sigmoid characteristics. Bodman and Mahmud (2) found a straight line relation between the moisture equivalents of successive mixtures of sand and clay. The migration and accumulation of clay and water on the surfaces of the soils shown in figure 1 unquestionably influenced the shape of the curves. In the soil mixtures where calcium greatly exceed sodium there was little dispersion and, without dispersion little migration. The fact that. the upper portions of the curves of soils 7, 10, and 5 are flattened is due in part to the free water. The quantity of free water was observed to increase with the proportion of the Na clay in the mixture. The upper part of the curve soil 6 is not flattened and this soil had no free water on the surface of any of the samples.

The first evidence of a significant increase in the moisture equivalent of soil 6 occurred in the 60/40 mixture, corresponding to 1.9 milliequivalents of adsorbed sodium per 100 gm. of soil. The moisture equivalents of soils 5 and 10 appear to have been increased slightly by the substitution of 30 percent of Na soil, corresponding respectively to 2.4 and 3.6 milliequivalcnts of adsorbed sodium. The moisture equivalent of soil 7 was increased by the substitution of 20 percent of the Na soil, corresponding to 2.5 millicquivalcnts of adsorbed sodium. It seems from these limited data that the moisture equivalents of soils are not measurably affected by less than 2 milliequivalents of adsorbed sodium.

The maximum effect on the moisture equivalent was approached in soils 5, 10, and 7 with, respectively, 8.17, 12.26, and 12.75 milliequivalents of adsorbed sodium, corresponding to 49.6. 77.4, and 63.8

percent of sodium in the exchange complex. The maximum effect on the moisture equivalent of soil 6 was not reached or apparently approached with the 4.9 milliequivalent of adsorbed sodium in the 0/100 mixture.

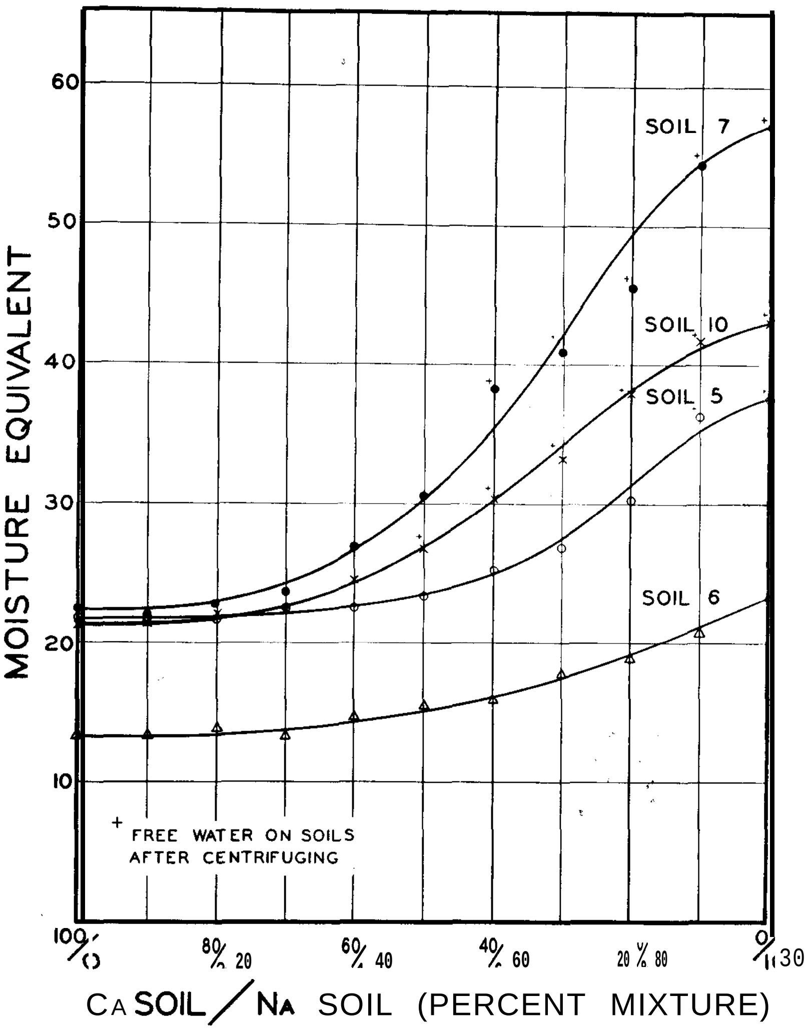

FIGURE 2.-The moisture equivalents of various mixtures of different soils that had been treated with calcium and sodium.

THE MOISTURE EQUIVALENT OF SODIUM-TREATED SOILS WET WITH STRONG ELECTROLYTES

Soil colloids, irrespective of the character of the adsorbed bases, arc flocculated when suspended in solutions of strong electrolytes. It follows that adsorbed sodium should be without effect on the moisture equivalent When samples are wet with a strong salt solution rather than with distilled water. The results of measurements made on each of the 12 sodium-treated soils as wet with normal calcium chloride, and where sufficient soil was available, with normal sodium chloride, are reported in table 7. It is to be observed that the moisture equivalents of the Na soils wet with these solutions tended to be equal to, or slightly lower than, the moisture equivalents of Ca soils wet with distilled water.

TABLE 7.—*Moisture equivalents of* Na soils wet *with normal $CaCl_2$ and NaCl solutions*

Soil No	Moisture equivalent of—			
	Na soil wet with normal—		Soil wet with distilled water in usual manner	
	$CaCl_2$	NaCl	Ca soil	Na soil
279	10.2	9.4	10.2	9.4
1	10.0	9.8	9.2	10.2
4	11.6	10.2	11.2	15.5
2	10.9	12.0	11.9	16.6
6	13.6	13.1	13.3	23.2
3	14.2	14.2	14.5	33.0
9	18.5	18.2	18.6	34.0
5	[1]20.7	------	21.9	37.5
10	21.4	21.1	21.4	42.9
8	22.9	22.6	22.6	43.7
7	20.9	------	22.1	57.4
278	29.7	29.6	33.0	30.1
Average	17.0	----------	17.5	29.5

[1] Determined an two IO-gm. samples (values. 26.6 and 25.9 percent) and interpolated after Veihmeyer, Israelsen, and Conrad (22, table 1, fig. 1) to 30-gm.,-basis.

It is suggested by these results that the moisture equivalent of field soils if determined comparatively (1) as wet with distilled water and (2) as wet with normal $CaCl_2$ or NaCl should provide an index to sodium-induced dispersion and hydration and by inference to reduced permeability from these causes. If saline, the moisture equivalents of Na and Ca soils as taken from the field should be similar. A third and companion measurement is accordingly necessary for a practical utilization of the moisture equivalent as an index to adsorbed sodium, namely, the moisture equivalent of the soil determined, after most of the readily soluble electrolytes have been removed by 'washing and extraction with filter candles. The moisture equivalent so used should provide a practical index, both to the presence of substantial amounts of adsorbed sodium in field soils and to the consequent changes in the permeability characteristics that would bc expected to accompany reclamation with nonsaline waters.

The similarity of the moisture equivalents of Ca and Na soils wet with strong electrolytes would seem to eliminate the possibility that the effect of sodium on the moisture equivalent of soils should be attributed to puddling or the mechanics of handling prior to the measurements.

An observable redistribution of soil separates did not occur when the Na soils were wet with strong electrolytes, indicating that the electrolytes increased the attractive forces between particles sufficiently to check migration and the displacement of light particles toward the axis of rotation. The surfaces of the Na samples wet with either of the normal salt solutions resembled the surfaces of the Ca samples, and in no case was free water present on the surface after centrifuging.

The laboratory measurement of the permeability of soils, even on a relative basis, has proved to be a difficult problem in many hands, but some promise of progress is afforded by other measurements wherein soils were leached with solutions of the same composition as their own displaced solutions. The use of such solutions minimizes base exchange and the associated effects on dispersion during successive leachings. By using this procedure creditable agreements have resulted between quadruplicate samples, and the hour-to-hour changes in rate of percolation so often characterizing other permeability measurements have been greatly reduced.

EFFECTS OF CALCIUM, MAGNESIUM, POTASSIUM, AND SODIUM ON THE MOISTURE EQUIVALENT AND HYGROSCOPICITY

The comparative effects of Ca, Mg, K, and Na on the moisture equivalent of soils have been studied only by Anderson (1), and he confined his work to the colloidal fraction. It seemed highly probable that Anderson's results might be applied to soils in general, but the significance of the relationships was regarded as sufficiently important to justify independent measurements. The question involved that ties in most closely with irrigation considerations was whether there was ample reason for regarding calcium and magnesium as alike in their physical effects on soils and, if so, whether such potassium as is found in irrigation waters should be classed with the calcium and magnesium or included with sodium in the calculation of the sodium-total base ratio (percent sodium).

The treatments employed in the preparation of the soils used for these experiments, as described earlier in this paper, were more drastic than those used in preparing the Ca and Na soils. Extensive predigestions were made with ammonium acetate and ammonium hydroxide, which were designed to reduce all soils to a common ammonium base and to remove calcium carbonate and humus, but these digestions were not carried to the ultimate end points. Calcium was found in the final ammonium acetate extractions of all soils and humus appeared in some of the first washings of the K and Na soils. Yresumably all of these soils approached complete saturation with the respective bases, but no measurements were made. Distilled'water washing was continued until the chloride concentrations of the final suspensions were less than 5 milliequivalents per liter.

The moisture equivalents of these soils are compared in two ways, (1) when wet with distilled water and (2) when wet with 0.02 normal chloride solutions of the bases corresponding to those adsorbed. The averages of triplicate moisture equivalent measurements are reported except in occasional instances when one of the three values was out of line with the other two.

The moisture equivalents of Ca and Mg soils arc found to be similar (table 8) and nearly always less than the K soil. The effect of the sodium ion in this experiment, as in the preceding one, is outstanding, a number of the Na soils yielding moisture equivalent values twice as great as the Ca soils. This is essentially the effect which Anderson (1) obtained, but in his series, as in this one, there was one colloid, in addition to the latcrite, upon which sodium had little or no effect.

In the presence of 0.02 normal electrolyte, tho moisture equivalents of the Ca and K soils were reduced a little, but a consistent effect is not shown in the Mg series. The effect of the 0.02 electrolyte on the

Na soils is marked, but the values are nearer to the Na soil values than to the Ca soil values. From the standpoint of considerations related to the effects of irrigation waters on soils, it seems appropriate to group calcium, magnesium? and potassium ions together and to differentiate these from the sodium ion.

TABLE 8.-*Moisture equivalents of Ca, Mg, K, and Na soils wet with distilled water and 0.02 normal electrolyte*

Soil No	Moisture equivalent of soil—							
	Wet with water				Wet with 0.02 normal electrolyte			
	Ca soil	Mg soil	K soil	Na soil	Ca soil	Mg soil	K soil	Na soil
279	9.7	10.6	9.7	10.5	9.7	10.7	9.2	10.0
1	4.4	9.8	10.1	10.6	8.9	9.3	9.2	10.8
4	11.7	11.0	11.1	15.7	11.3	11.3	10.3	15.4
2	10.9	10.5	11.0	15.5	10.6	11.3	10.3	15.2
6	12.7	12.9	13.0	18.8	12.2	12.8	11.8	16.4
3	14.0	14.2	15.2	13.6	13.2	14.2	13.9	20.6
9	19.4	19.9	20.1	[1] 33.7	19.1	20.1	18.5	[1] 30.7
5	20.8	22.0	23.7	[1] 45.0	21.1	21.4	22.8	30.4
10	23.9	23.0	26.6	[1] 52.3	23.9	22.6	24.3	[1] 47.4
8	23.3	23.8	26.6	[1] 62.5	22.6	23.8	25.2	39.5
7	22.9	23.6	24.4	[1] 85.3	21.8	23.3	22.6	154.8
278	36 I	36.1	34.6	32.4	35.2	35.2	32.7	32.6
Average	17.9	18.1	18.8	33.8	17.5	18.0	17.6	27.0
Average effect of electrolyte					—.4	—.1	-1.2	-6.8

[1] Free water on soil after centrifuging.

The influence of the kind of adsorbed base on the hygroscopicity of soils was investigated as an incidental feature of the inquiry by the following procedure. The three oven-dried moisture-equivalent samples of each ofthe soils of the experiment reported in table 8 were ground and mixed. From each of these, two 25-gm. samples were weighed out and placed on 4 inch watch glasses and exposed on open shelves in a closed concrete basement vault for **15** days. The atmospherc in this vault was humidified by a fan directed into a group of wet towels suspended from a vessel of water. The same fan maintained a good circulation of air throughout the 'room and over the soils. The average temperature in this vault, as recorded by a thermograph during the period of the experiment, was 20.3' C. (during the 15-day period the maximum was 21.1° and the minimum 18.8°). The average relative humidity during the first 7 days was about 72 percent and during the last 8 days it was 84.1 percent (lowest 81.0 and highest 90.0) as determined twice daily with a sling psychrometer. The partial pressure of water in an atmosphere of 84 percent relative humidity at 20.3' C. is 1.9 cm. Each soil was stirred daily and left ridged to give as great a surface as possible. Starting on the 12th day, selected samples were weighed twice daily until the 15th day by which time the variations were negligible and the gains equaled the losses. The samples were then placed in bottles, and their moisture content was determined by weighing them before and after *oven*-drying at 105°-110° C. In considering these data, account should be taken of the fact that they are wetting data in contrast with the drying curves represented by the wilting coefficient and ultimate wilting-point results presented in figure 3.

TABLE 9.-*Hygroscopicity of ocen-dried Ca, Mg, K,* and Na *soils when in. equilibrium with an atmosphere of 84 percent relative humidity at 20.3°* C.

Soil No.	Hygroscopicity of oven-dried soil--							
	Previously wet. with distilled water				Previously wet with 0.02 normal electrolyte			
	Ca soil	Mg soil	K soil	Na soil	Ca soil	Mg soil	K soil	Na soil
	Percent	*Percent*	Percent	*Percent*	Percent	*Percent*	Percent	Percent
279	0.93	1.02	*0. RI*	*0.* x7	0.94	1. 14	0.93	0. 86
1	.90	1.04	.81	92	.99	1. 07	.80	.98
4	1.63	1.65	1. 28	1.30	1.65	1. 73	1.17	1.54
2	1.75	1.81	1. 27	1.46	1.78	1.91	1. 35	1. 77
6	2.24	2.14	1.63	1.95	2.15	2.23	1.68	1. 97
3	2.41	2. 31	1.78	2.22	2.34	2.42	1.91	2 24
9	3.75	3.90	2.98	3. 15	3.87	4.18	3.02	3. 75
5	4.23	4. 37	3. 15	3.90	4.27	4.52	3.23	3.94
10	4.74	4. 70	3.80	4. 53	4. 98	4.94	3.97	4.85
8	3.94	4. 12	3. 13	4.20	4. 24	4.16	3. 20	4.25
7	5.18	5.42	3. Xl	4.67	5. 29	5.02	3.73	4.76
278	7.42	8.06	7.51	7. 86	7. 50	8. 14	7.82	7. 57
Average	3.26	3.38	2.66	3.09	3.33	3. RI	2. 73	3. 21
Average effect of electrolyte	......	......			+.07	+. 13	+.07	+.12

At the end of the absorption period the theoretical concentration of electrolytes in the moisture held by the soils previously treated with 0.02 normal salt solutions is represented by the relation: Moisture equivalent÷hygroscopic moisture × 0.02. Solution concentrations are indicntcd as high as 232 millicquivalents per liter in Na soil 279 and as low as 82 millicquivnlrnts in Ca soil 7.

The clcctrolytc increased hygroscopicity in nearly every comparison (table 9), and its average effect though small, was nearly the same for each of the four bases with which the soils had been treated.

Calcium-treated soils, in keeping with the findings of Anderson (1) and with those of Thomas (19) at the latter's higher vapor pressures, adsorbed more moisture than did sodium-treated soils. Except for a few determinations (table 9), the magnesium values are slightly higher than the calcium values. Potassium is the low member of the series. Na soils adsorbed less moisture than did Ca or Mg soils but more than K soils. The order both with and without clcctrolytc is K<Na<Ca<Mg. These results will be referred to again in the final section.

AVAILABILITY OF SOIL MOISTURE IN CALCIUM-TREATED AND SODIUM-TREATED SOILS

The wilting-cocfficicnt and ultimate wilting-point measurements (tables 10 and 11) show that the moisture in Na soils is less available to plants than that in Ca soils, and in nearly all instances the differences are substantial. The differences between the Ca soils and Na soils decrease as the moisture content is reduced from the wilting coefficient to the ultimate wilting point.

The wilting coefficients and ultimate wilting points of soils *278* and 279 were not changed appreciably by the sodium treatments, and these soils, which adsorbed little sodium, showed no positive sodium effects in the moisture-equivalent comparisons. Through the remainder of the series there is a strong positive relation between the effect of sodium in increasing the moisture equivalent and in increasing the

TABLE 10.—*Effect of exchange sodium on the wilting coefficient and ultimate wilting point of Ca and Na soils*

Soil No.	Washed soil in can No.—							Ca soil in can No.—							Na soil in can No.—						
	1	2	3	4	5	6	Average	1	2	3	4	5	6	Average	1	2	3	4	5	6	Average
WILTING COEFFICIENT (PERCENTAGE OF MOISTURE)																					
279	3.8	3.6	3.3	3.4	3.5	3.8	3.6	4.0	3.4	3.7	3.4	3.3	3.9	3.6	—	4.3	4.3	3.8	3.9	4.9	4.2
1	3.5	3.5	3.3	3.5	3.8	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.6	3.7	3.7	5.2	4.6	5.4	4.4	4.5	4.6
4	5.3	5.0	4.9	5.2	5.2	5.0	5.1	4.4	4.5	4.9	5.0	4.6	4.7	4.7	8.2	—	10.2	—	—	7.2	[1] 8.5
2	6.7	5.1	5.1	4.9	4.8	5.2	5.3	5.8	4.8	5.7	5.6	5.1	5.7	5.5	9.5	7.2	8.1	8.1	8.0	10.1	8.5
6	5.5	5.4	5.6	5.8	5.4	5.4	5.5	5.8	5.5	5.6	5.6	5.9	5.6	5.7	7.0	7.0	7.6	9.0	7.6	8.8	7.8
3	6.0	6.2	6.7	6.5	6.1	5.8	6.2	5.7	5.6	6.2	5.7	5.9	5.8	5.8	9.7	8.1	9.0	11.9	9.3	10.0	9.7
9	10.2	10.0	9.8	10.1	10.1	10.0	10.0	10.4	10.2	10.5	9.8	10.3	10.2	10.2	11.4	12.9	12.5	10.7	11.7	11.6	11.8
5	9.3	10.4	10.1	10.1	9.6	9.8	9.9	9.5	9.5	9.5	9.9	10.0	10.1	9.8	13.8	15.6	14.9	13.6	14.7	15.1	14.6
10	11.9	12.1	13.0	12.3	12.3	12.3	12.3	11.4	12.8	11.7	11.8	12.6	11.5	12.0	14.7	15.8	16.2	16.6	15.9	14.1	15.6
8	10.7	10.3	10.3	10.5	9.7	9.8	10.2	12.7	11.4	10.7	12.1	12.0	11.0	11.7	13.9	15.1	13.7	13.9	12.8	12.6	13.7
7	11.2	11.7	11.2	12.2	12.1	10.9	11.6	11.4	11.2	11.2	11.1	11.9	11.5	11.4	15.9	16.2	15.8	15.8	15.4	15.8	15.8
278	22.2	21.4	22.3	21.5	—	—	21.9	21.2	21.6	22.7	22.3	—	—	22.0	21.8	21.8	22.9	22.9	—	—	22.4
Average	—	—	—	—	—	—	8.8	—	—	—	—	—	—	8.8	—	—	—	—	—	—	11.4
ULTIMATE WILTING POINT (PERCENTAGE OF MOISTURE)																					
279	3.4	3.2	3.0	3.0	3.3	3.2	3.2	3.3	3.0	3.1	2.8	2.9	3.4	3.1	—	3.2	3.2	3.3	3.6	3.4	3.3
1	3.3	3.3	3.1	3.3	3.3	3.5	3.3	3.6	3.5	3.6	3.4	3.6	3.3	3.5	3.6	3.9	4.3	4.2	3.8	4.1	4.0
4	4.6	4.6	4.8	5.0	4.6	4.4	4.7	4.4	4.5	4.6	4.4	4.4	4.7	4.5	5.2	—	5.6	—	—	5.2	[1] 5.3
2	4.9	5.0	4.6	4.8	4.7	4.7	4.8	4.6	4.8	4.8	4.9	4.9	4.8	4.8	6.0	5.9	5.8	6.3	6.6	5.7	6.1
6	5.1	5.2	5.0	5.4	5.1	5.3	5.2	5.3	5.2	5.1	5.1	5.0	5.4	5.2	6.8	6.9	7.4	6.6	6.4	6.5	6.8
3	5.5	6.1	5.6	6.0	6.0	5.6	5.8	5.4	5.6	5.7	5.5	5.5	5.5	5.5	6.6	6.5	7.4	7.2	6.9	7.5	7.0
9	9.2	9.1	9.1	10.0	10.0	10.0	9.6	10.0	10.0	9.7	9.0	10.2	9.7	9.8	11.2	10.4	9.6	9.9	10.6	10.3	10.3
5	8.8	9.8	9.3	9.0	8.9	9.2	9.2	9.0	9.5	8.7	9.2	9.0	9.5	9.2	10.2	11.2	10.1	9.9	12.1	11.7	10.9
10	11.4	11.2	11.6	11.5	11.5	12.0	11.5	10.9	10.8	11.2	11.3	11.1	11.0	11.1	12.9	12.5	13.8	12.8	11.8	12.6	12.7
8	10.0	9.6	10.3	10.1	9.2	9.5	9.8	9.8	10.8	10.3	10.9	9.7	11.0	10.4	11.2	12.8	11.0	12.2	12.1	11.4	11.8
7	10.8	10.8	11.2	11.0	10.8	10.7	10.9	11.1	11.1	10.7	10.7	10.9	11.3	11.0	13.2	14.4	14.1	13.0	12.9	13.3	13.5
278	21.3	20.5	21.2	20.8	—	—	21.0	20.6	21.0	22.1	20.9	—	—	21.2	21.1	21.3	22.0	21.6	—	—	21.5
Average	—	—	—	—	—	—	8.3	—	—	—	—	—	—	8.3	—	—	—	—	—	—	9.4

[1] 3 plants in Na soil 4 died before wilting and the remaining 3 were in poor condition.

wilting coefficient and the ultimate wilting point. The coefficient of correlation between differences at the moisture equivalent and ultimate wilting points of Ca and Na soils for soils numbered 1 to 10 is 0.76 ± 0.09, which can be regarded as an indication of the operation of at least some of the same causal factors in the two moisture zones.

TABLE II.--Summary of *moisture equivalents, witting coefficients, and ultimate wilting points* of washed, *Ca,* and Na soils

Soil No.	Moisture equivalent			Wilting coefficient			Ultimate wilting point		
	Washed soil	Ca soil	Na soil	Washed soil	Ca soil	Na soil	Washed soil	Ca soil	Na soil
	Percent	*Percent*	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
279	10.1	10.2	*9.4*	3.6	3.6	4.2	3.2	3.1	3.3
1	10.1	9.2	10.2	3.5	3.7	4.6	3.3	3.5	4.0
4	11.2	11.2	15. b	5.1	4.7	[1] 8.5	4.7	4.5	[1] 5.3
2	11.5	11.9	16.6	5.3		8.5	4.8	4.8	6.1
6	13.1	13.3	33.0	5.5	5.3	7.8	5.2	5.2	6.8
3	13.9	14.5	34.0	10.0 6.2	5.8	9.7	5.8	5.5	7.0
9	18.1	18.6			10.2	11.8	9.6	9.8	10.3
5	21.2	21.9	37. b	9.9	9.8	14.6	9.2	9.2	10.9
10	22.2	21.4	42.9	12.3	12.0	15.6	11.5	11.1	12.7
8	23.3	22.6	43.7	10.2	11.7	13.7	9.8	10.4	11.8
7	23.9	22.1	57.4	11.6	11.4	15.8	10.9	11.0	13.5
278	32 9	33.0	30.1	21.9	22.0	22.4	21.0	21.2	21.5
Average	17.6	17.5	29.5	8.8	8.8	11.4	8.3	8.3	9.4
Average **of soils 1 to 10, omitting 4**	17.5	17.3	33.2	3	8.4	11.3	7.8	7.8	9.2

[1] 3 **of the 6 original plants of Na soil 4 died before wilting and the remaining** 3 on **which the average is based were in poor condition.**

Before continuing the analysis of the results from the standpoint of tbe soil, the possibility of differences between the plants grown in Ca soils and those grown in Na soils that might affect their ability to utilize soil moisture should be canvassed. McGeorge and Breazeale (12) have considered oxygen deficiency as a factor responsible for the wilting of plants in puddled soils. Some support for the idea that puddling, as ordinarily considered, was not an important factor contributing to the results of the present work is provided'by the facts: (1) That whether measured in the dry state, in the moisture equivalent cups after centrifuging, or in the wilting coefficient cans, the volumes of the Na soils were greater than the volumes of the Ca soils; and (2) that when the Na soils were wet with strong electrolytes, the moisture equivalent values were nearly the same as those of the Ca soils.

The distribution and the abundance of roots were examined with considerable care both in representative cans before oven-drying and afterwards as the successive cans were emptied for grinding and mixing. Differences were not found, but no examinations were made of the comparative abundance of root hairs. If there had been fewer roots, or a poorer distribution of roots in the Na soils than in the Ca soils, wilting would be expected to have occurred at a higher moisture content in the Na soils.

It may be assumed that the solutions of the Na soils contained substantially higher concentrations of sodium ion than did the solutions of the Ca soils. It is accordingly possible that physiological distinctions should be drawn between the two sets of plants, but so little is known about sodium effects on tissue structure that discussions cannot be carried far in this direction. As distinct from the Ca roots grown on Ca soil, roots grown on Na soil may have been more highly hydrated and water uptake by them conceivably could have been impeded, but such an effect has never been demonstrated. In some earlier sand-culture experiments in which plants were grown on nutrient solutions high in calcium chloride and high in sodium chloride, respectively, the plant material from the sodium solutions when placed on a Biichner funnel, after ‘drying and grinding, took up and held relatively large quantities of water and could be leached only with difficulty, whereas the calcium plant material behaved m a normal way. The question of whether sodium affects the uptake and movement of water in living plants must be regarded as speculative and there is no present basis for a conclusion.

CAPILLARY POTENTIAL

The term "availability" as phrased by Richards *(14)* involves two notions, namely, (1) the ability of the plant to absorb and to use water with which it is in contact and (2) the readiness or velocity (6, *14)* with which the soil moisture moves in to replace that which has been used by the plant. At any given point in the soil water, the capillary potential is numerically equal to the hydrostatic potential and below saturation the quantity is negative. The tension of the soil water at a given capillary potential may be expressed as the length of the suspended water column necessary to produce that tension. The rates of water movement through a soil for a given potential difference will not be the same in different soils, in the same soil at different capillary potentials, or in the same soils as here differentially treated with calcium and sodium. Furthermore, the moisture at the wilting coefficient cannot be regarded either as being uniformly distributed throughout the soil mass or as being in static equilibrium with the plant at wilting. In the wilting range, the plant-soil system is a dynamic one and water withdrawal is continuous, though at a decreasing rate, to the death point.

The present experiments were so conducted as to yield values for each Ca and Na soil at each of three moisture levels,, and to each of these moisture levels it is possible to assign at least an approximate capillary-potential value. Schofield and Botelho daCosta (16), from freezing-point-depression measurements of their own and calculations from vapor pressures and seed-absorption measurements of others, have computed the pF value of soils (the logarithm of the equivalent capillary tension expressed in centimeters of water column) at the moisture equivalent and at the wilting coefficient. These values ranged from 2.5 to 3.3 for the moisture equivalent and from 4.02 to 4.40 for the wilting coefficient. From the foregoing data, the writers elected to assume an intermediate value of 3.0 for the moisture equivalent and to take Schofield's average value, 4.24, for the pF value at the wilting coefficient. The problem remained of obtaining a suitable value for the ultimate wilting point By relating the average change in moisture content between the wilting coefficient and the ultimate wilting point of the writers' calcium soils to the corresponding average changes in pF values for like moisture changes in the Schofield and DaCosta Botelho graphs, a pF increment of about 0.16 was indicated. If this is added to the pF value of the wilting coefficient! approximately 4.40 is obtained for the pF value of the ultimate wiltmg point. For the purposes here served it is not necessary to assume that pF 3.0 represents the best moisture equivalent value for any soil or for the writers' soils as differentially treated with calcium and sodium. The moisture content values of certain Na soils that have been centrifuged by standard moisture equivalent procedures are not representative of the moisture tension conditions corresponding to a pF value of 3. If other pF values had been used for the moisture equivalent, the wilting coefficient, or the ultimate wilting point, the slopes of the curves (fig. 3) would have been altered but not their general characteristics.

Figure 3 shows moisture percentage (dry basis) plotted against pF for Ca and Na soils: soil 6, a sandy loam; soil 7, a clay; and the average of the nine soils that showed sodium effects on the moisture equivalent, excluding soil 4, the wilting data for which were not regarded as very accurate. The Ca and Na graphs of corresponding soils are widely separated at the moisture equivalent, but approach each other as the moisture content is decreased, and intersect at a moisture content somewhat lower than the permanent wilting percentage.

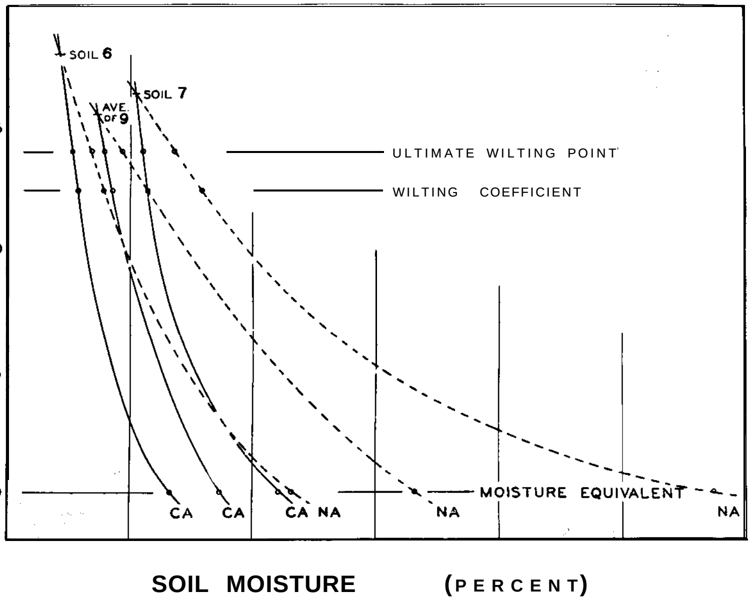

FIGURE 3.-Soil-moisture and pF values of different soils that had been treated with calcium and sodium.

From the fact that the Ca and Na graphs intersect, it follows that Ca soils should have higher hygroscopic coefficients than the Na soils in atmospheres substantially below saturation. This finding is in accord with the writers' results (table 9) and those of others.

In keeping with these measurements, it is to be observed that Thomas' (19) vapor pressure curves of Ca- and Na-treated soil materials intersected; his Na-treated materials having had a higher moisture-absorbing capacity than his Ca-treated materials from very moist atmospheres and lower from the drier atmospheres. Freezing-point data in a paper by Schofield (15) on the penetration of diffuse double layers may likewise be construed as anticipating the findings of the writers. Those data when extrapolated into the lower moisture range beyond that over which freezing-point measurements are possible also indicate that water is more closely held by an Na soil than by a Ca soil. If extended yet farther the two curves would intersect.

MOISTURE EQUIVALENT-WILTING COEFFICIENT RATIOS

Conclusions with respect to the effect of sodium on the ratio of moisture equivalent to wilting coefficient are made difficult by the fact that free water on the surface of many of these soils after centrifuging caused the observed values to exceed what might be regarded as the true values. For Ca soils **1,** 2, and 4 these ratios are 2.5, 2.2, and 2.4, respectively, and for the same Na soils 2.2,2.0, and 1.8. This suggests that sodium tended to narrow the ratios by raising the wilting coefficient relatively more than the moisture equivalent.

Treatment with sodium increased neither the moisture equivalents nor the wilting coefficients of soils 279 and 278. These soils are of interest, however, for other reasons. The Gold Ridge sandy loam, 279 untreated, has a moisture equivalent-wilting coefficient ratio of 3.9, whereas the Aiken clay has a ratio of **1.6.** In the opinion of the writers much of this divergence can be accounted for on the basis of the properties of the ultimate soil particles. The Gold Ridge soil is highly siliceous and the faces of most of the soil particles tend to be smooth? indicating that a large part of the water retained by the soil is exterior to the crystalline surface. A sample of Exeter sandy loam supplied by J. C. Johnston from near Visalia, Calif., had a moisture equivalent nearly four times as great as its wilting coefficient. The siliceous crystalline character and smooth faces of the particles of this soil were more outstanding than in the Gold Ridge soil. The particles of the lateritic Aiken clay, on the other hand, are highly porous and much water is retained, both against gravitational force and plant uptake, as closely held interstitial water, i. e., water within capillary pores. It is obvious that interstitial water retained by a soil both at the moisture equivalent and wilting coefficient would reduce the proportion of moisture-equivalent water available to the plant. The interplanar water of a number of soil colloids represents a third type of retention, but the question of availability of such water to plants and its relation to sodium is obviously complex. Much of it is released to the soil atmosphere as the moisture content of the soil is reduced.

DISCUSSION

Whether the consequences of the state of aggregation or dispersion of the ultimate soil particles are more important in terms of water retention against centrifugal forces and plant uptake than forces involved in the hydration of Ca and Na clays cannot be concluded from these data. Both are probably involved, and the combined soil-water tensions produced are reflected in the water-retention measurements. Dispersion may be consequent to hydration; if so, the two go hand in hand.

The possibility cannot be eliminated that the differences in the availability of moisture in Na soils and Ca soils to plants represent a slower rate of movement through the former soils than through the latter. In such case it would presumably follow that the soil zones away from the roots were relatively more moist in the Na soils than in the Ca soils, but with equally dry zones in Ca and Na soils at the root surfaces. The distances through which moisture must move to plant roots are relatively great in terms of the thickness of the moisture films at the wilting coefficient. In a soil in which a root or a root hair is situated at intervals of **1** mm,, the average distance of water movement is eauivalent to 50 times the diameter of a 0.005-mm. silt particle.

If water, in the wilting range, moves primarily by vapor flow, the pertinent distinction between Ca and Na soils in the present connection becomes one of size of capillary pores through which diffusion must take place rather than thickness of water films. Ca soils are characterized by a crumb structure with particle aggregates and voids that are large as compared with those of dispersed Na soils. Vapor diffusion through the Ca soils should accordingly proceed more rapidly than through Na soils.

If moisture movement in the wilting range is primarily movement of film water, it follows likewise that such movement should be slower at a given moisture content in the thinner films covering dispersed particles than in those covering aggregates of closely adhering particles. Water of hydration *as* such is probably not subject to movement except as it is vaporized into the soil atmosphere.

Irrespective of possible explanations, the finding of immediate significance is that water in dispersed Na soils is less available to plants than that in Ca soils.

SUMMARY

The moisture equivalents of soils partially saturated with sodium were substantially higher than those of the same soils treated with calcium provided most of the soluble electrolyte was removed.

The average moisture equivalents of **12** well-leached Ca, Mg, K, and Na soils were Ca, 17.9; Mg, **18.1;** K, 18.8; and Na, 33.8. The average moisture uptake by these soils when exposed: (after oven drying) in an atmosphere with a relative humidity of 84 percent at 20.3' C. was K, 2.66; Na, 3.09; *Ca,* 3.26; and Mg, 3.38 percent

A close parallelism *was* found for 10 soils between the effect of sodium on the moisture equivalent and the percentage of clay, the exchange capacity, and the quantity of adsorbed sodium.

Adsorbed sodium had negative effects on the moisture equivalent of a soil high in silica and a negative effect on an Aiken clay which is lateritic; both soils had low cation exchange capacities.

The moisture in centrifuged Ca soil samples increased from the inner toward the outer surfaces. An opposite gradient was found in Na soils.

Some migration and segregation of sand, silt, and clay particles occurred when the finer-textured Na soils were centrifuged, a higher proportion of large particles being observed in the outer portions with well-defined clay layers on the inner surface. In certain of the soils water was also displaced toward the axis of rotation and remained on the surface after centrifuging.

Rapid starting acceleration of the centrifuge gave higher moisture-equivalent values than slow acceleration.

Wetting Na soils with normal calcium or sodium chloride solutions gave moisture equivalent values that were nearly the same as those of Ca soils. The moisture equivalent may therefore provide a measure of sodium-induced dispersion of field soils if comparisons are made between leached and unleached soils and soils wetted with a strong electrolyte.

The moisture equivalent of mixtures of Ca and Na soils in successive proportions gave sigmoid graphs. The moisture equivalent was not significantly affected by less than 2 milliequivalents of adsorbed sodium per 100 gm. of soil and values approaching maximum were found when there were 12 milliequivalents or more of adsorbed sodium.

Adsorbed sodium caused soil moisture to be less available to plants. The calcium and sodium averages of nine soils were, at the moisture equivalent, 17.5 and 29.5; at the wilting coefficient, 8.4 and 11.3; and at the ultimate wilting point, 7.8 and 9.2 respectively.

Plotting moisture content against a pF scale, the Ca and Na soil graphs intersect at moisture percentages below the ultimate wilting point. This result confirms earlier work showing lower hygroscopicity of Na soils than of Ca soils in drier atmospheres.

It is suggested that interstitial water held within soil particles against both centrifugal and plant-uptake forces may account for the differences observed in the moisture equivalent-wilting coefficient ratios observed in different soils,

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