

of earth, but I question the true sine nature of the phenomenon

DR BERNHARD. Centrifugal forces excited by the oscillator itself are completely independent of the force of gravity

and therefore may be used in any direction Any modification of the sine form in soil curves has not yet been detected The gravity component (dead weight) has merely the effect of varying the position of the datum line

SURFACE-CHEMICAL FACTORS INFLUENCING THE ENGINEERING PROPERTIES OF SOILS *

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At the 1935 meeting of the Highway Research Board Professor Krynine stated the desirability of expressing the influence of various exchange ions on the engineering properties of soils in the common engineering terms and indices Today we are able to present such data The soils tested were as follows

- (1) Cecil Clay: red subsoil developed under lateritic weathering from gneiss, with an appreciable amount of mica in its larger-sized fractions and most probably also in the clay and colloid fraction Iron and alumina are present in the crystal structure as adsorbed ions and in the form of hydrous oxides The soil contains practically no organic matter Base exchange capacity of extracted clay, 13 milliequivalents per gram
- (2) Hagerstown Clay: reddish brown, sandy clay subsoil, developed from chert free limestone under podsolc type of weathering, modified by presence of limestone Base exchange capacity of extracted clay about 60 milliequivalents per gram
- (3) Putnam Silt Loam: grey-brown silty clay subsoil of mixed glacial

and loessial origin Developed by podsolc type of weathering Base exchange capacity of extracted clay 67 milliequivalents per gram

Preparation of the Homoronic Soils

Nine samples of each of the three soils were furnished for test, one representing the natural soil The other eight samples were prepared from the natural soil by satisfying its base exchange capacity with a particular ion The eight ionic species were hydrogen (H^+), sodium (Na^+), potassium (K^+), magnesium (Mg^{++}), calcium (Ca^{++}), barium (Ba^{++}), aluminium (Al^{+++}), and the ferric ion (Fe^{++}) The number of positive charges, +, ++, or +++, denotes the positive valence of the particular ionic species

The method of satisfying the base exchange capacity of the soil was as follows.

Air-dried samples were placed in percolators and each sample was treated with one of the chloride solutions, KCl , $NaCl$, $FeCl_3$, etc, and hydrochloric acid For the K , Mg , Ca , Ba and Fe soils, 0.1 normal chloride solutions were used as leachates For the Al soil aluminium sulfate was used as the leachate In the preparation of the H soil, 1/50 normal hydrochloric acid alone was used as the leachate There is little tendency for HCl of this low strength to dissolve the colloids

Leaching was continued until the leachate had the same concentration as the

* Abstract of a report on a cooperative study of the Bureau of Public Roads, the Missouri State Highway Department and the Missouri Agricultural Experiment Station The complete report will be published in Public Roads.

solution had before entering the soil, thus indicating that adsorption of the cations was complete. The excess salt and acid were then removed from the treated soil by leaching the samples with distilled water.

Attempts to leach sodium chloride solution through the podsollic soils rendered them so impermeable that it became necessary to alter the procedure by stirring the soil in large volumes of NaCl solutions, letting the soil settle and then decanting the excess solution. This process was repeated until the sodium ion had satisfied the base exchange capacity of the soil. The soil was washed with distilled water in the same manner to remove the excess salt. Some of the sodium chloride remained in the Na soil after these efforts to remove it.

After treatment, the amount of cations adsorbed was determined by chemical analysis. In general it was found that the percentage saturation of base exchange capacity was 90.

The following physical characteristics of the untreated and treated soils were studied: particle size distribution (determined by mechanical analysis), plasticity, shrinkage and moisture equivalent constants, compressibility, permeability and swell of confined samples, tensile and crushing strength of air-dried samples, slaking value of air-dried samples, swell of unconfined samples.

The mechanical analyses, plasticity, shrinkage and moisture equivalent constants were determined according to the American Society for Testing Materials tentative methods for testing subgrade soils (D 422, 424, 426, 427-35T).

The compressibility, permeability and swell of the confined samples were determined by means of the Terzaghi compression test according to a procedure discussed briefly by F. A. Robinson in the February 1936 issue of *Public Roads*. The air-dried samples were mixed with distilled water to approximately their

liquid limits, and then kept in a humidifier for 24 hours before being tested. Loads of 0.8, 1.6 and 3.2 kg per sq cm were successively applied. The load was then reduced to 1.6, 0.8 and 0.04 kg per sq cm. The consolidation or expansion of a sample under a given load was complete before the load was changed. The permeabilities were determined after the samples were consolidated in this manner under the loads of 0.8, 1.6 and 3.2 kg per sq cm.

The tensile and crushing strengths of air-dried natural and treated soils were determined by mixing the soil with water until plastic. This plastic mass was then tamped into cement briquette molds and into 2 by 4 in. cylinder molds. After molding, the test pieces were slowly dried until they reached apparent constant weight in the air of the laboratory. The values reported are the averages of three determinations.

The slaking specimens were made in the same manner as the tensile strength test pieces. After drying, the briquettes were protected on both ends with a paraffin coating, leaving a center stripe 0.25 in. wide for the attack of water in which they are suspended. The time required for the separation of the lower from the upper part is recorded as the slaking time. Simultaneously, the appearance of the specimens during the slaking were noted. This method was developed by the Russian pedologists. The swell of unconfined powdered samples was determined according to the methods previously described.* The principle of the determinations was the measurement of intake of liquid by powdered soil colloids through a porous plate, avoiding a positive or negative pressure head of the liquid. The amount of water adsorbed minus the amount of a non-

* Hans F. Winterkorn & L. D. Baver. Sorption of Liquids by Soil Colloids I. *Soil Science* vol. 38, pp. 291-299, 1934. II. *Soil Science*, vol. 40, pp. 403-419, 1935.

polar liquid, such as benzene similarly adsorbed, is the swell expressed in cubic centimeters per gram of soil or soil colloids. The data on heat of wetting were obtained with the Bunsen ice calorimeter

DISCUSSION OF TEST DATA

Results of the laboratory tests are recorded in Tables 1 and 2

The effect of the different ion fixations on the physical characteristics of the three natural soils is summarized in Table 3. In this table (prepared from Table 1) the relative order of activity of the various cations as estimated from the relative extents to which they increased or decreased the values, LL, PL, PI, SL, C, M E, and F M E of the natural soils is, in any instance, indicated by the order of arrangement. For examples, the barium ion increased the liquid limit of the Cecil soil more than any other ion, the increase effected by the Fe ion was less than that of barium in this case and the increase in liquid limit of the natural Cecil soils was least with the H ion. On the other hand, the Al ion was the most active in lowering the liquid limit of the Cecil soil and the K ion was least active in this respect. In any case, when one or more of the eight cations are not mentioned as having either increased or lowered a particular physical constant (Table 2) it is to be understood that those ions not listed neither increased nor lowered the physical constant of the natural soil. Thus, for example, the field moisture equivalent of the Hagers-town natural soil was neither increased nor decreased by fixation of the K, Na and Ba ions.

The cations may be rated in the order of number of times each cation is listed first in Table 2. Thus, the Na ion is listed first in ten instances in Table 2, whereas the H is not listed as first in any instance. Since the cation listed first in any instance is the most active of the cations of the group in its effect

on the given physical characteristic, the total number of times that a particular cation has first mention in Table 2 is an index to its general relative activity as compared with the other cations and these observations are tabulated as follows.

Cation	Number of times cation was most active in either increasing or decreasing the physical constants, Table 2
Na+	10
Al+++	7
K+	5
Fe+++	5
Mg++	5
Ba++	3
Ca++	2
H+	0

It must be borne in mind that this "activity rating" has no bearing on the question as to whether or not the most active ion is most beneficial or otherwise in its effect on soil properties.

This order of activity may be compared with the relative extents to which the eight different cations either increased or lowered the degree of dispersion of the colloids of the three soils. Consider the relative effectiveness of a given cation in either increasing or decreasing the *measurable* (not the absolute total) colloid content of the natural soils.

The sodium and aluminum cations were more active than all the others in influence on degree of colloid dispersion. This fact must be related to the outstanding relative activity of the Al and Na cations in their effect on the physical constants as above described. It is possible that in the treatment with Al- and Fe-, salts some colloidal hydrous oxides of iron and aluminum were formed. And again, this fact also has no relation to the question of general desirability of increasing or inhibiting the degree of colloid dispersion by ion fixation to the extents indicated.

For equal colloid contents, the liquid

TABLE 1
TEST RESULTS

Source	Adsorbed Ion	SiO ₂ /R ₂ O ₃	Physical Characteristics Material Passing No 40 Sieve										Mechanical Analysis										Terzaghi Compression Test Data									
			Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Shrinkage Ratio	Centrifuge M E	Field M E	Particles Larger than 2 mm						Particles Smaller than 20 mm (% by wt)						Moisture Content	Compression ΔW per gram	Expansion ΔW per gram	Permeability K for 16 Kg Load in cm per sec	Expansion on Removal of Load—percent	Speed of Compression (mm) —percent					
										Coarse Sand 2-0 mm	Fine Sand 0.25-0.05 mm	Silt 0.05-0.005 mm	Clay Smaller than 0.004 mm	Clay Smaller than 0.002 mm	Colloids Smaller than 0.001 mm	Passing No 40 Sieve	Coarse Sand 2-0 mm	Fine Sand 0.25-0.05 mm	Silt 0.05-0.005 mm	Clay Smaller than 0.004 mm	Clay Smaller than 0.002 mm							Colloids Smaller than 0.001 mm	Passing No 40 Sieve	0 Load	3 Load	0.04 Load
Cecil	Natural	1 3	75	38	37	32	1	4	9	76	62	100	2	77	147	65	124	1	4	81	47	51	0106	00127	4	3	10 ⁻⁸	4	8	92		
"	Na		76	46	30	34	1	4	12	9	78	70	100	2	76	24	52	86	1	5	81	48	51	0103	00095	4	8	10 ⁻⁸	4	8	93	
"	Ca		76	42	34	31	1	4	13	16	70	54	100	2	79	21	51	125	1	6	79	47	51	0100	00127	4	8	10 ⁻⁸	3	0	93	
"	K		74	36	38	29	1	4	13	10	76	65	100	2	79	121	63	110	1	3	78	46	49	0100	00095	5	0	10 ⁻⁸	3	0	93	
"	H		76	42	34	30	1	4	12	10	77	68	100	2	78	122	61	73	1	5	82	49	52	0103	00095	5	4	10 ⁻⁸	3	8	95	
"	Ba		80	44	36	30	1	5	13	14	72	61	100	2	77	61	75	121	1	5	85	49	52	0112	00095	4	8	10 ⁻⁸	3	4	95	
"	Fe		78	42	36	30	1	5	12	11	76	1	100	2	76	93	60	142	1	5	76	45	47	0097	00063	5	1	10 ⁻⁸	2	7	93	
"	Al		69	38	31	29	1	5	13	14	72	1	100	2	76	65	72	147	1	6	76	46	49	0094	00095	3	8	10 ⁻⁸	3	1	89	
"	Mg		78	44	34	30	1	5	13	9	77	59	100	2	76	209	70	102	1	4	84	49	51	0109	00063	5	5	10 ⁻⁸	2	6	95	
Hagerstown	Natural	3 0	44	18	26	12	1	9	14	50	33	15	100	2	70	15	160	312	1	8	48	22	24	0081	00063	4	4	10 ⁻⁸	2	2	60	
"	Na		57	17	40	15	1	8	13	47	40	28	100	2	70	341	135	342	1	7	59	27	32	0100	00158	0	9	10 ⁻⁸	8	3	40	
"	Ca		41	18	23	13	1	9	14	53	30	11	100	2	70	23	182	357	1	0	43	21	22	0069	00032	2	3	10 ⁻⁸	1	2	65	
"	K		44	19	25	15	1	9	15	52	30	13	100	2	70	35	88	341	1	5	47	25	28	0069	00095	1	5	10 ⁻⁸	4	2	67	
"	H		40	19	21	15	1	9	13	42	42	23	100	2	70	26	105	445	1	5	40	23	28	0062	00032	3	8	10 ⁻⁸	1	4	83	
"	Ba		39	18	21	13	1	9	14	51	42	13	100	2	72	32	153	341	1	7	41	21	22	0062	00032	1	8	10 ⁻⁸	1	1	79	
"	Fe		39	23	16	16	1	9	15	41	41	27	100	2	70	15	98	302	1	2	40	22	23	0056	00032	3	6	10 ⁻⁸	1	3	92	
"	Al		40	24	16	14	1	9	12	45	43	29	100	2	70	20	93	368	1	9	39	21	22	0056	00032	4	0	10 ⁻⁸	1	8	92	
"	Mg		43	16	27	12	1	0	12	57	31	13	100	2	70	49	110	575	1	2	46	23	24	0072	00032	4	8	10 ⁻⁸	1	2	63	
Putman	Natural	3 2	35	18	17	15	1	9	11	55	33	12	100	2	69	38	188			35	20	21	0047	00032	1	0	10 ⁻⁸	0	9	75		
"	Na		48	16	32	16	1	8	10	42	47	30	100	2	70	420	202			49	24	26	0078	00063	1	1	10 ⁻⁸	0	4	40		
"	Ca		38	17	21	15	1	9	10	59	30	13	100	2	69	26	177			38	21	22	0053	00032	1	5	10 ⁻⁸	1	5	76		
"	K		37	19	18	17	1	8	11	58	30	12	100	2	69	24	113			35	22	22	0041	00032	1	3	10 ⁻⁸	0	4	75		
"	H		35	19	16	18	1	8	9	65	31	18	100	2	69	35	165			35	22	23	0041	00032	3	4	10 ⁻⁸	1	3	94		
"	Ba		37	18	19	16	1	9	9	65	26	15	100	2	69	36	218			37	22	24	0047	00063	4	0	10 ⁻⁸	3	1	84		
"	Fe		36	20	16	20	1	8	13	52	35	25	100	2	69	26	110			36	22	23	0044	00032	5	7	10 ⁻⁸	1	0	91		
"	Al		36	21	15	18	1	8	11	60	29	18	100	2	70	28	166			35	22	23	0041	00032	13	0	10 ⁻⁸	1	1	87		
"	Mg		39	17	22	16	1	8	10	55	33	16	100	2	69	31	188			36	21	22	0047	00032	3	4	10 ⁻⁸	1	3	72		

¹ Flocculated

* Waterlogged—percent includes free water

TABLE 2
PHYSICAL CHARACTERISTICS (IONS NOT MENTIONED HAD NO EFFECT ON PROPERTY)¹

Soil	Liquid Limit		Plastic Limit		Plasticity Index		Shrinkage Limit		Centrifuge moisture equivalent		Field moisture equivalent	
	Increased by ions	Lowered by ions	Increased by ions	Lowered by ions	Increased by ions	Lowered by ions	Increased by ions	Lowered by ions	Increased by ions	Lowered by ions	Increased by ions	Lowered by ions
Cecil	Ba, Fe, Mg, Na, Ca and H	Al and K	Na, Mg, Ba, Ca, H and Fe	K	K	Na, Al, Mg, H, Ca, Ba and Fe	Na	Al, K, H, Ba, Fe, Mg and Ca	Mg, Al, Fe and Na	None	Mg, Na, Ca, K and Fe	Al, Ba and H
Hagerstown	Na	Ba, Fe, H, Al, C and Mg	Al, Fe, K, H	Mg and Na	Na and Mg	Al, Fe, Ba, H, Ca and K	Fe, Na, K, H, Al, Ba and Ca	None	Na, Mg and Ba	Ca, K and Fe	Fe, Al and H	Mg and Ca (equally)
Putnam	Na, Mg, Ca, K, Ba, Fe and Al (equally)	None	Al, Fe, H, K	Na, Ca and Mg	Na, Mg, Ca, Ba and K	Al, Fe and H	Fe, H, Al, K, Mg, Ba and Na	None	Na	Fe and Ca	Ba, Ca, H, Fe and Al	K and Mg (equally)

¹ The ions are listed generally in the order of the relative extents to which they increased or decreased the physical constant of the natural soil in any particular case. In several instances, however, the amount of increase or decrease effected by ion fixation was the same with two or more different ions.

limits were higher for podsolc soils having greater silica-sesquioxide ratios. Thus, the ratio between the liquid limit and the colloid content of the natural Cecil soil was found to be 1.21, for the

ficients of permeability of the three natural soil are indicated in Table 4. In this table also the cations are listed in order of decreasing activities in their influence on these properties.

TABLE 3
COLLOID DISPERSION OF NATURAL SOILS (FROM TABLE 1)

Soil	Increased most by Cations	Decreased most by Cations	Changed least by Cations
Cecil	Na, H and K	Al, Fe, Ca, Mg and Ba	Ba, Mg and K
Hagerstown	Al, Na, Fe and H	Ca, K, Mg, Ba	Ba, Mg and K
Putnam	Na, Fe, H, Al, Ba, Mg and Ca	None	Ca and K

TABLE 4
RELATIVE ACTIVITIES OF CATIONS AS INDICATED BY THEIR EFFECT ON COMPRESSIBILITY, PERMEABILITY AND EXPANSIVITY OF SOILS. CATIONS ARE LISTED IN ORDER OF DECREASING EFFECT¹

Soil	Total Consolidation		Expansion on Load Removal		Speed of Compression		Coefficient of Permeability	
	In-creased by ions	Decreased by ions	Increased by ions	Decreased by ions	Increased by ions	De-creased by ions	Increased by ions	Decreased by ions
Cecil	Ba	Al, Ca, H, K, Fe and Na	None	Mg, Fe, K, Al, Ba, H and Ca	Mg, Ba and H to an equal extent Na, Ca, K and Fe also to an equal extent	Al	Na, K, Fe, H, Ba, Mg and Ca	Al
Hagerstown	Na	H, Fe, Al, Ba, K and Ca and Mg equally	Na and K	Ba (Ca and Mg equally) Fe, H, and Al	(Al and Fe equally) H, Ba, K, Ca and Mg	Na	None	Na, K, Ba, Ca, Al, H, Mg and Fe
Putnam	Na	Mg, (K and H equally) Fe, Ba, Al and Ca	Ba, Na, Ca (H and Mg equally), Al and Fe	K	H, Fe, Al, Ba, Ca, K and Mg	Na	Mg, Fe, H, Ba, Al and K	Na and Ca

¹ Cations not listed had no effect on the properties mentioned in this table.

natural Putnam soil the corresponding value as determined was 2.92 and for the natural Hagerstown soil, 2.93.

The relative effects of the eight different cations on the total consolidations, speeds of compression, the expansions of the soil on release of load and the coef-

According to the theory of soil consolidation the speed of compression increases with the permeability of a soil. Since the various layers of adsorbed water around a mineral particle are held with forces, which decrease with increasing distance from the mineral sur-

face, the pore space available for the movement of water varies with the acting hydraulic forces. Therefore, also the permeability of a soil should be dependent upon the method used for its measurement. That this is the case is indicated by the data in Table 5 where the cations, Al, Fe, H, Ba, K, Ca and Mg which increased the speed of compression of the Hagerstown soil, lowered the permeability of this soil if determined by a different method. The Na cation is the only exception in this case. With the Cecil and Putnam soils, however, it is seen from Table 4 that, for the most part, those cations which increased the

Cation	Order of Activity
Na	8
Al	5
Fe	0
Mg	3
Ca	0
Ba	2
H	3
K	2

Obviously, this "rating" is only approximate since it is obtained without regard to the relative order in which cations, as listed in Table 1, succeed or follow the first cation listed. For present purposes, however, and until

TABLE 5
DATA ON THE FACTORS INFLUENCING THE SLAKING TESTS

Putnam Soil	Slaking Time in Min	Shrinkage Limit	Swelling of Extracted Clay in cc/gm	Heat of Wetting of Extracted Clay in cal/gm	Swelling Heat of Wetting	Remarks
H	35	18	0.81	13.6	0.06	The high value for the slaking time of Na-Putnam is obviously directly connected with its "osmotic" swelling
Na	420	16	4.02	12.0	0.34	
K	24	18	0.50	9.5	0.053	
Mg	31	16				
Ca	26	15	0.91	15.0	0.061	
Ba	36	16	0.85	13.9	0.061	

speed of compression also increased the permeability, the calcium ion in the Putnam soil being another exception. The converse also holds, the Al and Na ions which appreciably lowered the speeds of compression of the Cecil and Putnam soils lowered the coefficients of permeability of these two soils. Obviously, the effect of any particular cation on a given soil depends both on the cation and on the soil and this simple fact must be appreciated and borne in mind.

Summarizing the data of Table 4, the order of activity of the eight different cations in their effect on compressibility, speed of compression, permeability and expansivity is as follows.

considerably more is known about this entire subject, a more exact rating of activities would be superfluous. It is important to know the general trend of conditions following chemical treatment of soils.

TENSILE AND CRUSHING STRENGTH OF AIR-DRIED SAMPLES

As shown in Table 1, the tensile and compressive strength of the natural soils is greater for higher $\text{SiO}_2/\text{R}_2\text{O}_3$ ratios. With the Cecil soil, the greatest tensile strength was obtained when barium was adsorbed by the soil and the lowest compressive strength was observed on the hydrogen Cecil. In the Hagerstown series, calcium produced the highest

tensile strength and magnesium the highest compressive strength. The lowest tensile and compressive strengths in the case of Hagerstown soil were obtained with the potassium and iron ions respectively. The tensile strength of iron Putnam was lowest and that of the barium

SLAKING VALUE OF AIR-DRIED SAMPLES

The slaking values are not representative of a single phenomenon, but rather are complex functions of the pore space and of the swelling behavior of the soil. The influence of the hydration of the soil on the numerical slaking values

TABLE 6
SWELLING OF SOILS IN ELECTROLYTE SOLUTIONS IN CC PER GM OF SOIL

Ca-Putnam			Na-Hagerstown		
Conc CaCl ₂	Intake	Swelling	Conc NaCl	Intake	Swelling
0 (Water)	618.	096	C (Water)	775	165
7187 N	630	082	3375 N	710	150
1 4375 N	630	080	675 N	715	125
2 875 N	595	030	1 35 N	675	115
5 75 N	559	017	2 70 N	689	130
11 50 N	500	- 075	5 40 N	645	095
Shrinkage Limit of the Ca-Putnam = 15			Shrinkage Limit of Na-Hagerstown = 15		

TABLE 7
THE EFFECT OF ELECTROLYTE CONCENTRATION ON CONSISTENCY INDICES OF PUTNAM SOIL (200 SIEVE)

Salt	Milli Equiv of salt per gm of Soil	Lower Liquid Limit	Lower Plastic Limit	Plastic Index	Volume Change at Field Moisture Equiv	Shrinkage Limit	Shrinkage Ratio	Vacuum Moisture Equivalent
None	0	32.8	16.2	16.6	37.3	13.0	1.89	28
NaCl	15	32.8	15.6	17.2	38.4	12.9	1.93	32.6
"	30	31.6	15.6	16.0	34.3	13.7	1.92	35.4
"	75	28.7	15.2	13.5	26.1	14.7	1.86	31.7
"	1 50	25.8	12.7	13.1	11.9	18.9	1.72	32.3
KCl	15	31.9	21.1	10.8				23.6
"	30	30.8	21.0	9.8				26.3
"	75	30.8	21.4	9.4				25.4
"	1 50	27.7	20.3	7.4				23.2
CaCl ₂	15	30.9	14.3	16.6	34.6	12.9	1.92	26.1
"	30	31.7	15.3	16.4	36.8	12.8	1.95	25.9
"	75	30.7	13.7	17.0	36.5	12.2	1.97	25.1
"	1 50	28.8	11.0	17.8	30.4	12.8	1.90	23.4

Putnam was highest. The crushing strength test pieces of the Putnam samples on drying developed large shrinkage cracks so that they could not be tested.

The moisture content of the test pieces reported in Table 1, was determined at the time of test

varies according to its hydration or osmotic character. (Hydration swelling is associated with a considerable amount of heat of "wetting" and is practically proportional to it, osmotic swelling is not related to evolution of heat, but is defined by the extent of the

ionic atmosphere surrounding the soil particle) The following are three of the types of slaking which may occur:

(1) When soil has small pore space and hydration but no osmotic swelling capacity, the slaking is normal, that is the soil is corroded from the outside. The outside grains separate and settle out. The slaking of a soil with large pore space and small hydration energy is similar but proceeds more rapidly.

(2) When the soil has small pore space and great osmotic swelling capacity, the swelling closes the pores and impedes the influx of water. The soil is slowly dispersed on the outside and settled slowly.

(3) Where soil has great pore space and great energy of hydration, the water rushes to the interior and reacts with the internal surface with resulting swelling and faulting by disruption.

Because of its effect on pore space and hydration capacity a varying water content can change the slaking time and slaking appearance enormously. To obtain data comparable with actual behavior on the road, air-dry test specimens were used. It was realized, however, that samples dried at a higher temperature might give more simple relationships between slaking and other soil data. The relative influence exerted by pore space and hydration on the slaking data is illustrated by the data in Table 5.

INFLUENCE OF FREE ELECTROLYTES ON THE PROPERTIES OF SOILS

The data discussed in the foregoing expressed the behavior towards water of homoionic soils from which the excess salt used in their preparation had been leached out as far as possible. These data, therefore, are representative of what may be called the permanent effect of a salt treatment; that means the behavior of the soil after the excess salt has been washed away by precipitation water. Although these data are of prime theoretical and practical interest they need to be supplemented by data

on the character of soils in the presence of free electrolytes. In view of the necessity of obtaining such data, but being unable to undertake an extensive study at this time, a few exploratory experiments were made by George W. Eckert of the University of Missouri, on the swelling of homoionic soils in the solution of various electrolytes and also by R. C. Schappler of the Missouri State Highway Department, on the influence of electrolyte additions on various soil indexes. The results of Eckert's work are shown in Table 6. The liquid intake was measured with the Winterkorn-Baver apparatus. All the soils tested show a decrease of swelling with increasing electrolyte concentration. Changes in the structure of the soil system, caused by the concentrated electrolyte solutions are indicated in the slope of the swelling-concentration curves. If the exchange ions on the soil are different from the ions in solution, the swelling-concentration relation follows no definite form. This fact is of practical importance in predicting the effect of salts on soils which vary in the amount and kind of their base saturation.

The results of Schappler's investigations concerning the effect of electrolytes on the values of the soil indexes are in general accord with the results of the swelling experiments and with the general understanding of the factors influencing the numerical values of the soil indexes. The data are given in Table 7.

SUMMARY

(1) The test data showed that the physical character of natural soils especially as pertaining to stability at varying moisture contents can be changed to a great extent by a change of the adsorbed ions.

(2) It is proposed that the experimental data be used to examine the soundness of the theoretical foundations of soil mechanics particularly the part dealing with cohesion and internal friction in soils.

DISCUSSION ON ENGINEERING PROPERTIES OF SOIL

MR C A HOGENTOGLER. I want to emphasize one point that may not be entirely clear. The data presented by Dr Winterkorn showed the effects of completely saturating clays with metallic ions. Those effects should not be confused with treatments with the salts from which the ions are derived.

What I have reference to is this. That in treatments with a particular chemical, sodium hyposulphite, for instance, the effect as shown for the sodium ion in the data, is not in any way related to the behavior of that clay so long as it contains the solution of sodium hyposulphite.

In like manner in every other instance so long as the initial treatment lasts, and the solution of the chemical introduced remains in the soil, these ionic effects as shown do not apply. We do not know today just what they mean with respect to our road construction.

I am going to pass on another question having to do with the practical application of the principles of surface chemistry. What would be the procedure for finding out how to correct the trouble if stripping of bituminous films occurred?

DR WINTERKORN. The effects of these ions should not be confused with the effects of concentrated salts which are still in the soil. The soils discussed have been treated with salt solutions such as are usually applied on earth roads. On the other hand, excess salt was washed out as far as possible, but we could not always do it completely. For instance, with potassium chloride we had water-logging so that even when we tried different methods of removal, we could not get rid of all the metallic salt. Although the results are not exactly those which you find with application of concentrated salt solution to a soil, they are comparable to the effect you will have after rain has had a chance to wash out most of the material. With sodium chloride

treated soils, very little of the excess salt could be washed out, therefore, the data reported should represent quite closely the behaviour of a *salt treated binder soil on the road*.

Now as to the second question, if one finds that bituminous films are stripped from soil particles, then the soil itself should be treated if it can be done so economically. It should be treated with iron or aluminium ions which usually give the best results. Ionic treatments may improve or decrease the affinity of the natural soil for bitumen. Distinctly unfavorable to the adhesion of bitumen is the treating of the soil with sodium ions.

MR L C STEWART *Dow Chemical Company*. In treating soils, do you use chloride throughout?

DR WINTERKORN. In all cases except with aluminium salt, where we used the sulfate.

MR HOGENTOGLER. In this program today we tried to cover as far as possible the different phases of stabilization but we lack one, that is, any possible effects produced by straight chemical combinations, and I wonder if you would care to say anything about the introduction of various materials into the soil.

DR WINTERKORN. Stabilization of a soil without addition of aggregate implies a reduction of the water affinity and a cementing together of the soil grains. Permanent reduction of the water affinity of the soil can only be procured by chemical means, that is, by the exchange of bases for those that can become part of the crystal lattice of the soil mineral, thereby changing the surface properties of the soil, by substances which form insoluble compounds with the available valencies of di- or poly-valent ions on the

surface of the soil grain and by resin forming organic compounds which undergo exchange adsorption as a result of their basic nature and which are afterwards condensed to resins by the addition of other substances. This latter method of synthesizing resins in situ on mineral grains can give good water-protecting properties even if no chemical reaction between the artificial resin or its components with the mineral surface has taken place. It is being utilized in the priming of minerals before bituminous treatment.

The cementing can be accomplished by the same substances used in surface coating, by the addition of an organic or inorganic cement with affinity for the surface, or by a chemical synthesis of a cement in situ. For this synthesis a combination of two or more of any organic or inorganic materials can be used—at least one of which wets the surface—and which together form a water-insoluble compound.

MR HOGENTOGLER. In your last year's paper you mentioned something about the formation of certain definite cements.

DR WINTERKORN. The formation of certain definite cements falls in the lines of the statements I just made. In nature we find silica grains cemented together by hydrous iron and aluminum oxides and by calcium carbonate. The sesquioxides possess a chemical and electrical nature opposite to that of the silica, consequently, in this mutual adsorption there is a linkage at least by chemical "rest" valencies. If these substances have been in contact for a long enough time (millions of years) even chemical reaction may have resulted on the interface. *Mutatis mutandis*, the same holds with the cementing of sand by calcium carbonate. This process for which nature needed geological time and which was enacted at low temperature, is duplicated

in the modern manufacture of sandstone bricks with lime binder in an atmosphere of superheated steam.

Other natural cements are the humates of bi- and trivalent ions formed by the precipitation of soluble humates in horizons rich in these ions. These cements are active in the hardened alluvial horizons of the hardpans, "ortsteins" and "padas," and in the more stable crumbs of soils rich in calcium and in organic matter. The setting up of limestone and limestone dust in clay may serve as another example in this connection.

PROF W S HOUSEL, *University of Michigan*. It seems to me that anyone listening to Dr Winterkorn's paper cannot fail to appreciate the fundamental importance of his discussion of the forces acting between various particles—the linkage and the sources of cohesion and internal resistance. In that connection I would like to emphasize one point. As I understand it, Dr Winterkorn in some experiments has demonstrated that the water films around the soil particles have a very important effect on this thing which we have been used to calling internal friction. It appears that the soil particles in a saturated clay are not actually in contact but are surrounded by water films of varying thickness. More important than that, the forces which link these particles together are molecular in character, either adhesion or cohesion and probably both. Nevertheless engineers attempt to apply to such soils the conventional conception of internal friction when in all probability the character of the interfacial boundaries are such that true frictional forces are eliminated. In the light of what these forces may be I cannot help but wonder how much longer practicing engineers and investigators are going to hang on to this internal friction, and express internal resistance of such materials in terms of a conception which obviously is so far from being in agree-

ment with the phenomenon which Dr. Winterkorn has described.

MR STEWART I am a little confused on one point As I understood it, Dr Winterkorn said that in a clay, as the moisture evaporates cohesion decreases Is that right?

DR WINTERKORN: It depends upon the kind of clay If the clay is a lateritic clay, as the moisture evaporates the cohesion will increase to a certain point, but when the moisture is completely evaporated there is nothing left which induces cohesion With podsolc soil, it is practically impossible to dry out the water entirely, therefore, in this case cohesion increases continuously with decreasing moisture content You always have to consider the kind of soil This is a point I have tried to put over for three years, that the various clays are different from each other in their properties The character of a clay depends upon the kind of material it is derived from, and upon the weathering agents which produced it

MR STEWART. In other words, we must not only define clay as to size, but chemical composition.

DR WINTERKORN. And, possibly, shape and electrical structure.

MR W B WORSHAM, *Illinois State Highway Department*: We know that soils near industrial plants have a tendency to absorb certain chemicals from the air, and that these chemicals have certain influences upon materials such as culvert pipe, concrete, etc. Have you ever made any studies of the absorption and influence of these chemicals or attempted to prevent such damaging influences as might be present?

DR WINTERKORN: No, we have not done any such work ourselves, but I re-

member some experiments by Wiegner in Switzerland on the influence of chemical solutions, especially in peat and bog, on culvert pipes made of portland cement concrete He found that the best way to fight the destruction is to make as good concrete as possible It appeared that not so much the chemical, but the physical factors involved played the decisive rôle That means that if a chemical cannot penetrate easily into the concrete, much time will be required for trouble to occur. If the concrete is porous, then the chemical can penetrate into the concrete more quickly and destroy it It may be better to use machanical obstacles in such a case

DR A F GILL, *Canadian National Research Council* I should like to ask if Dr Winterkorn would care to express an opinion or give data that would indicate the amount of base exchange that might be expected under road conditions in a clay surface to which different salts have been added

DR WINTERKORN: It will depend upon the concentration of the salt If you have sodium clay and calcium chloride you will not get all of the sodium from the base, that is, a certain amount of sodium will stay on the surface of the soil particles To get a complete exchange, it would be necessary to wash the soil several times with new solution Now, in general, we can say that the potassium ion will tend to expel the sodium ion, and the monovalent ions will tend to expel the calcium ion If iron chloride solution is present even though the sodium cannot get out of the system, 100 per cent exchange can be very nearly attained The base exchange capacity can be determined by several standard methods

MR C M JOHNSTON, *U S Bureau of Public Roads*: I should like to ask Dr Winterkorn if once a soil particle has been

treated with, say, calcium salt and the thickness of the water film thus made thinner, would washing out the calcium salt cause the water film to become thicker again or not?

DR. WINTERKORN. This is very difficult to answer because there are so many things that can happen in such a system and I do not think that within the extent of my knowledge I could say exactly what happens. If the concentration of salt in the solution is lowered the water film should tend to increase in thickness because of the decreased competition of the ions in solution for the water adsorbed on the soil surface. On the other hand, you have seen the effects of difference of concentration of salts on plasticity. The whole process appears to be so complicated that I beg to be excused at this time.

MR. HOGENTGLER: I should like to ask Dr. Looker a question similar to the one I asked Dr. Winterkorn. Do you know of any chemical combination which salt might make in the soil which would tend to produce a more permanent cement than just the solution of salt film?

DR. C. D. LOOKER, *International Salt Company*. I want to add to what Dr. Winterkorn has just said about base exchange. He has indicated that calcium will drive out potassium and sodium and take their places in clay. Base exchange reactions do not complete themselves in the presence of appreciable quantities of the free salts. Clay that has been treated with sodium chloride will not give up all its sodium to calcium until the free sodium chloride has largely been leached from the soil.

Base exchange reactions are reversible. They depend upon freedom of movement of solutions through the soil mass and the presence of an excess of one of the respective ions available for reaction. If a solu-

tion containing calcium ions is passed through a clay saturated with sodium ions, calcium ions will replace sodium ions, which will be washed out of the clay. The reverse reaction will take place if a solution containing sodium ions is passed through a clay saturated with calcium ions. Similar exchanges take place in zeolite sands used for softening water. After the sands have reached their capacity for absorbing calcium and magnesium ions they are regenerated with sodium chloride solution.

In practice, base exchange reactions would complete themselves very slowly, if at all, in the well compacted stabilized wearing course or base course that had been treated with either sodium chloride or calcium chloride.

It is generally agreed that there is no significant chemical combination between sodium chloride and clay that materially aids in cementing the particles together. Sodium chloride may aid in making more soluble certain soil constituents, such as calcium carbonate and calcium sulfate, the recrystallization of which may aid stability, but the increase seems too slight to be of much benefit.

Sodium chloride does change the nature of clay, because of adsorption, to make it more plastic and impermeable to the passage of water.

Dr. Winterkorn spoke last year of the tendency of the pores of a dry clod of sodium clay to close themselves when put into water and to permit only a very slow diffusion of water into the interior of the clod.

The reasons for this are very well explained in the following quotation from Technical Bulletin No. 12, University of Arizona:

"It is a matter of common knowledge that water percolates freely through soils as long as they contain relatively large amounts of salts. When the solutes have been largely reduced, however, unless the irrigation water

contains soluble calcium, the rate of percolation falls off rapidly and often reaches a point at which downward water movement ceases. In the words of the farmer, the soil "freezes up." When finally dried, such soils are hard, puddled, and unfit for cultivation, and when re-wetted, they "run together" and refuse to "take water." In fact they are in far worse physical condition than before reclamation operations were begun.

"As the concentration of sodium salts in the soil solution is reduced by leaching, the hydrolysis of the sodium zeolites present in varying proportions in all alkaline soils yields hydroxyl ions in ever increasing amounts. The soil thus becomes more alkaline, and there has been much discussion as to whether the cation or anion is chiefly concerned in the accompanying increased dispersion. While the direct relationship of concentration of sodium zeolite, or of sodium or of hydroxyl ions, to dispersion is open to question, it must be admitted that dispersion follows the hydrolysis and subsequent ionization of the sodium zeolite."

PROF. E. E. BAUER, *University of Illinois*. Mr. Hogentogler gave us an explanation of moisture films. I wonder if he could say something on base exchange, putting it as simply as he possibly can.

MR. HOGENTOGLER. My first attempt at base exchange was not so good. That was in the pH values. It is very simple to take a pH value and see how much hydrogen you have to replace. But when you attempt to apply that quantitatively you need a hundred times as much neutralizer to take care of it. Generally, and I want a little support on this,—I think both Dr. Winterkorn and Dr. Looker can add something,—there is an indication that in the more acid soils a little admixture of lime material is beneficial. There is an indication that the chemical might be retained longer if such admixtures are used than if they are not used, but I cannot give you the reason why.

MR. W. H. SIMONSON, *U. S. Bureau of Public Roads*. I am wondering if, in thinking of soil stabilization under the roadbed itself, there are not associated factors

affecting the solution of the problem. Are there not other factors adjacent and outside the so-called subgrade proper which might be included in the study of laboratory theory for a possible field application so that we may obtain a better understanding of the general relationship of all the field factors found in actual practice? Are there any associated factors that may have some bearing on the laboratory experiments of a fundamental scientific nature?

We have listened to Mr. Hogentogler's very fine elucidation of film relations in connection with soil particles in which he explained how the problem really goes down to a proper understanding of the changing conditions. If that is true, then we find that nature really does the mixing in connection with what actually takes place, and we must further investigate and test out the true relationships of the conditions of capillarity that may change, the changing moisture conditions, the changing temperature conditions, and any other natural changes in the field under which we really have to operate. My thought is that stabilization after all is fundamentally the problem of trying to find some way of establishing an economical natural balance. Every artificial application we may make that does not take into consideration all of the forces of nature means we have to spend money to keep continually maintaining the conditions we have set up to the degree that the balance of nature may have been disturbed.

At the present time, with budgets as they are, these broad considerations become of increasing relative importance. Undoubtedly the general application of the investigative studies to effect economies in the initial construction as well as in subsequent maintenance is the ultimate objective of the research work and I should like to ask Mr. Hogentogler if there are not other factors in the field which might be involved and need coor-

dination with these studies so that we may be able to get some comprehensive comparison of data in the final results

Specifically, I have in mind the streamlined highway section on which I think a good deal of work has been done in a few states, but the observations may not have been correlated in the soil studies of this committee For my own information, I would like to have some comments by Mr Hogentogler and others concerning it

For instance, in changing from the deep V-ditch section close to the edge of the pavement to the more recent type of flattened shoulder slope section with shallow gutter drainage farther removed from the center-line of the highway, has there been any effect on subgrade stabilization in the sense of maintaining a more stable water table? Does such a change in cross section aid in avoiding the possible breakups in highway surfacings due to the heaving of this subgrade during thawing and freezing? Undoubtedly a great deal of research information could be brought out in this direction Such observations may indicate that the kind or type of highway cross section under certain conditions fundamentally affects the problem of soil stabilization under the traveled way

Also, there may be involved additional factors which indicate a definite relationship to this whole general highway problem It is believed that investigation along these lines would be desirable to find out the possible relationship of various types of cross section to the subgrade stabilization problem We need to know what influence, if any, different ratios of slope grading and depths of drainage may have on the subgrade under the pavement We ought to find out if the protection of various sand, loam and clay soils and slopes with suitable vegetative cover has any stabilizing influence on the conditions immediately under the pavement

Mr Hogentogler has probably been

thinking indirectly about these associated factors outside of the surfacing itself, and it is believed it would be of interest to this group if he could outline the possible practical application of these considerations to the detailed problem under discussion this morning

MR HOGENTOGLER: My own opinion is that it is an absolute waste of money to put deep side ditches generally along the entire length of the road to drain subgrades It is better to use ditches only to take care of surface water and use definitely designed under-drainage to lead out water from sags in the grade and where there is need for under-drainage due to seepage and the like It appears that in the long run we will obtain stability at least cost in this manner

Now as to the use of tests, we can divide that into two parts In using the plasticity tests, moisture equivalents and the like, we do not mean to convey the impression that the results as such disclose what that soil will do in the field The tests are of value only when we have examined and found out enough about performances of particular soils in the field and correlated this performance with the test results obtained in the laboratory The constants have no value whatever without a corresponding knowledge of how the soils perform under service conditions

Now take the shrinkage test,—it has always been very popular We take a sample into the laboratory and prepare it in a certain way and put it in the oven and dry it, and we say that it shrinks so much Now here is the hitch If we take two samples into the laboratory and perform the shrinkage test, we may find that one shrinks 50 per cent and the other 65 per cent But if before placing the samples in the oven we determine the shrinkage that occurs on air drying at room temperature, we may find the first to shrink 10 per cent and the other 45 per

cent so there is no significance at all in that test for definitely saying how much that soil is going to shrink in the field. But after we find out what the soil did in the laboratory test, we get a certain index of performance. That is true for soils that are subject to climatic changes. In the case of foundation soils not subject to climatic changes, we can do something in the laboratory about determining the mechanical properties and actually applying the information to definite cases.

DR GILL: I have been very much interested in Dr Winterkorn's statement regarding the swelling of sodium type clays. The thought that this swelling rather than being a disadvantage might be effective in sealing off a road surface in wet weather, has some very interesting possibilities. The report of the Subcommittee on Treatment with Sodium Chloride mentioned the sealing effect, but ascribed it to the redispersion of coagulated clay as the surface salt was leached out. I wonder if Dr Winterkorn would say anything in greater detail regarding the mechanism or practical importance of this swelling?

DR WINTERKORN: In the water adsorption and swelling of sodium-clay, two phenomena play a rôle. The first is the hydration of the sodium ions (and perhaps satisfaction of some "rest" valencies of the mineral surface by adsorption of the water dipoles); and the second is the osmotic or kinetic effect which causes the ions to migrate as far from the mineral

surface as the electrostatic attraction permits. Hydration is connected with a more or less definite amount of energy which appears in the heat of wetting. The energy involved in the osmotic part of swelling depends upon the concentration, or better on the activities of the ions around the soil particles and of those in the available swelling liquid. The general formula for the work which osmotic forces are able to perform is as follows:

$$W = RT \ln \frac{c_1}{c_2}$$

where W = work

R = gas constant

T = absolute temperature

c_1 and c_2 = concentration activities

A sodium soil-water system can be expected to continue to swell after saturation of the hydration capacity until the osmotic attractive forces are balanced by those resisting the inflow of water, which are the electrical attraction of the ions by the surface of the soil particles, the viscous properties of the swelling liquid and the outside pressure.

MR. HOGENTGLER: Does that mean that swelling would not take place in a soil with large swelling properties and low energy, if the soil were under pressure?

DR WINTERKORN: Quite true. If the outside pressure plus the mechanical resistance to the entrance of water equals the osmotic pressure around the soil particles, the soil will stop swelling.