



Effect of exchangeable sodium levels on physical properties of coal overburden samples having differing clay mineralogy
by Richard Henry Opper

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in Soils

Montana State University

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Abstract:

The effect of different levels of exchangeable Na^+ on the physical properties of overburden samples from eastern Montana and western North Dakota was studied. Samples having clay fractions dominated by either smectite, illite, or kaolinite were used in this research. The physical tests of hydraulic conductivity (K), coefficient of linear extensibility (COLE), shrinkage of briquets, and modulus of rupture (MOR) were used to indicate changes in physical properties.

The hydraulic conductivity of the smectite samples was essentially reduced to 0 at sodium adsorption ratio (SAR) values of 15, whereas all of the illite and kaolinite samples retained the ability to transmit water at SAR 15. Sample shrinkage reached a peak at SAR values of 10 for both the smectite and kaolinite sample groups with the kaolinite sample group showing the highest degree of swelling. No relationship between exchangeable Na^+ levels and MOR values was observed for the illite or kaolinite sample groups though the MOR values for the smectite samples appeared to increase with increasing SAR values.

Some refinements to the concept of a critical ESP value of 15 for determining sodic soil conditions are offered as are areas of related research.

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EFFECT OF EXCHANGEABLE SODIUM LEVELS ON PHYSICAL PROPERTIES OF
COAL OVERBURDEN SAMPLES HAVING DIFFERING CLAY MINERALOGY

by

RICHARD HENRY OPPER

A thesis submitted in partial fulfillment
of the requirements for the degree

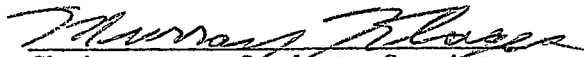
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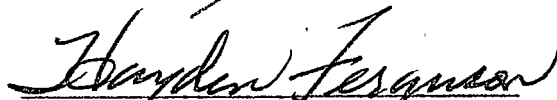
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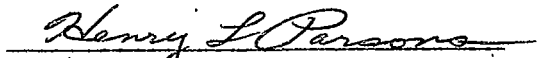
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ABSTRACT

The effect of different levels of exchangeable Na^+ on the physical properties of overburden samples from eastern Montana and western North Dakota was studied. Samples having clay fractions dominated by either smectite, illite, or kaolinite were used in this research. The physical tests of hydraulic conductivity (K), coefficient of linear extensibility (COLE), shrinkage of briquets, and modulus of rupture (MOR) were used to indicate changes in physical properties.

The hydraulic conductivity of the smectite samples was essentially reduced to 0 at sodium adsorption ratio (SAR) values of 15, whereas all of the illite and kaolinite samples retained the ability to transmit water at SAR 15. Sample shrinkage reached a peak at SAR values of 10 for both the smectite and kaolinite sample groups with the kaolinite sample group showing the highest degree of swelling. No relationship between exchangeable Na^+ levels and MOR values was observed for the illite or kaolinite sample groups though the MOR values for the smectite samples appeared to increase with increasing SAR values.

Some refinements to the concept of a critical ESP value of 15 for determining sodic soil conditions are offered as are areas of related research.

INTRODUCTION

Soil physical problems, such as swelling, slow permeability, and crusting are major impediments to successful reclamation in the northern Great Plains where efficient use of available water is essential. The effect of adverse soil physical properties must be minimized in order to establish and maintain a vegetative cover on previously mined land. Exchangeable sodium is responsible for many of the physical problems exhibited in natural soil systems and in spoil material. This study is concerned with the effect of exchangeable sodium on the physical properties of overburden samples from proposed mine sites in the northern Great Plains.

Overburden samples with clay fractions dominated by three different mineralogical groups were used in this research. The illite samples were taken from the Tanner Creek area on the Crow Indian Reservation, Section 24, T9S, R38E. The kaolinite samples and all the smectite samples except Kiewit A and No. 531 were drilled in the Colstrip Area, Western Energy mine area B, Section 21, T9S, R40E. Sample 531 was taken from the vicinity of Underwood, North Dakota and location information for the Kiewit sample was unavailable.

The United States Department of Agriculture Handbook 60 (U. S. Salinity Laboratory Staff 1954) defines sodic soils as having exchangeable sodium percentage values of 15 or greater. The degree to which exchangeable sodium affects soil physical properties depends to some extent upon the clay mineralogy of the soil samples. Perhaps

a single exchangeable sodium percentage is an insufficient means of identification of potential sodium hazards in overburden samples of the northern Great Plains which are characterized by diverse mineralogical composition. While not designed as a reclamation study, this report should clarify the nature of sodium problems in soils and may refine the definition of and identification of potential sodium hazards.

REVIEW OF LITERATURE

A qualitative definition of swelling in clay-water systems might be that swelling is the adsorption of water by clay colloids which results in an increase in the volume of the colloidal system (Baver et al. 1972). The water initially entering a clay-colloid system tends to be structured around the colloidal surfaces in an oriented arrangement (Baver et al. 1972). Subsequent water either fills existing pore spaces within the system or enlarges those pores through swelling. The degree of swelling of a material is controlled by many factors including the amount and size of pores, the type and amount of cations and aluminum oxides, the degree of structure of the soil material, and the stability of aggregates (Davidson and Page 1956, Fathi et al. 1971). Swelling has a direct effect on the physical properties of soils, including the hydraulic conductivity, modulus of rupture, and the linear extensibility (Quirk and Schofield 1955, Richards 1953, Franzmeier and Ross 1968). Both the AASHTO and the Unified engineering capability soil classification system are based in part on the potential shrinkage of soils (USDA 1971). An understanding of the dynamics of clay-water interaction clarifies the physical process of swelling.

Adsorption of Water by Clays

Hardy (1923) theorized that water in a clay-water system exists in two forms, one of which is crystalline and "ice-like." He suggested swelling in clays and soils is due solely to the adsorption

of vesicular (crystalline) water. Lauritzen and Stewart (1941) determined that the amount of shrinkage of a soil material depended upon the moisture range over which a given volume loss occurred. They concluded that shrinkage accompanying drying is dependent upon the manner in which the moisture is associated with the soil material and with the pore spaces within the soil mass. Low (1960) concluded that water exists in a structured form at the surface of soil clays, and that this structure imparts a high viscosity to adsorbed water. In later papers he elaborated on the adsorption of water by soil clays. Polar water molecules are attracted to the oxygen of clay surfaces by hydrogen bonds. Because of the directional nature of such bonds, water molecules in the second water layer can be expected to form somewhat weaker hydrogen bonds with the water molecules adjacent to the surface. A repeating sequence of water layers, each reproducing in part the structure of the tetrahedral oxygen sheet of the clay surface, is thus adsorbed on the surface of clay minerals. It is this structured water to which Low attributed the swelling of the system with the degree of swelling being determined by the thickness of the structured water layer (Low 1961).

Effect of Cation Amount and Specie on Swelling

In addition to direct adsorption of water by clays, repulsion of adjacent double layers also affects the swelling of clays (Baver et al.

1972). Cations attracted to the negative charges in clay particles are concentrated near the clay surface and decrease in concentration with distance from the particle. A diffuse double layer thus occurs consisting of the negatively charged clay surface and the diffuse concentration of balancing cations. Factors which influence the thickness of the double layer, such as exchangeable cation valence and effective size, and ion concentration in the bulk solution also affect the degree of intra-particle swelling. These factors are discussed more fully below.

Baver and Winterkorn (1935) observed the effect of cation species on the swelling of a soil material when they calculated the relative swelling of a beidellite-illite type clay saturated with Li^+ , Na^+ , and Ca^{++} to be 5.5, 4.4, and 1.0, respectively. Low (1961) explained these data as due to the hydration of adsorbed cations which breaks up the structure of the water films adsorbed on clay surfaces. Another explanation of the results observed by Baver and Winterkorn might be that addition of Li^+ and Na^+ expanded the double layer because of their large hydrated radii and low valence compared to Ca^{++} , thus increasing the repulsive force between the clay particles. In the same paper, Low observed that dissociated exchangeable cations lower the activity of water near the clay surface in much the same way as ions lower the activity of water in solution, giving rise to an osmotic attraction of water by clays. Fink and Thomas (1964) offered virtually the same

explanation for the phenomenon of "osmotic" swelling of clays. They observed that cations with high hydration energies will be located farther from a clay surface than will be cations with lower hydration energies due to the difference in thickness of the water hulls surrounding the hydrated cations. The coulombic force of attraction between clay surface and cation will decrease with distance. Water can thus move more freely between the clay surface and a highly hydrated cation, preserving the water structure from the clay surface to a greater distance from that surface and resulting in swelling. They concluded that clays saturated with a highly hydrated cation, such as Na^+ , will experience more osmotic swelling than will clays saturated with cations which may be partially dehydrated by strong electrostatic attraction to the surface, such as Ca^{++} . DuPlessis (1969) also observed that a decrease in ionic hydration is accompanied by a decrease in colloid swelling. It can be concluded on the basis of the above arguments that the exchangeable sodium percentage (ESP) will have a direct effect on the degree of swelling of a soil material because Na^+ both promotes osmotic swelling and expands the double layer.

The concentration of soluble cations is another factor which influences the swelling of soil materials. Baver (1930) reported that flocculation, an opposite of the swelling process, occurred when sufficient soluble salts were present in the soil solution. Norrish (1954) observed that interlayer expansion of swelling clays beyond $35\text{\AA}$

is continuous and linearly related to the reciprocal square root of the normality of the external solution ($N^{-\frac{1}{2}}$). Hemwall and Low (1956) determined that a net hydrostatic or osmotic repulsive pressure results when the ion concentration in the median plane between two parallel clay plates exceeds that in the external solution.

Effect of Clay Mineralogy on Swelling

Interlayer and macroscopic swelling are two types of swelling discussed in the literature. Interlayer swelling is a two-step process, the first of which is the stepwise hydration of interlayer surfaces and cations, and the second then being the continuous swelling previously discussed by Norrish (1954). Interlayer swelling is a reversible process as the clay platelets maintain a parallel orientation throughout the process. Macroscopic swelling, on the other hand, occurs not only between individual clay platelets but between clusters of clay platelets as well.

Demixed and mixed ion models have been proposed to explain the two types of swelling behavior in mono and divalent cation clays. The demixed model is applicable only to clays having internal exchange sites. Shainberg and Kemper (1966) offered the following explanation of the demixed ion model: Although Ca^{++} and Na^{+} have similar mobilities in solution, Ca^{++} , because of its divalent charge, has a much lower mobility than Na^{+} near the clay mineral surfaces. In a bi-ionic

system, the less mobile cation Ca^{++} will occupy internal exchange sites, while Na^+ will dominate the remaining (external) sites by default. The demixed ion model predicts clays to consist of a mixture of homo-ionic Ca^{++} saturated interlayers and Na^+ saturated interlayers and external surfaces, with only the Na^+ regions exhibiting interlayer swelling (McNeal 1970). Calcium saturated interlayers tend to adsorb only three layers of water (Blackmore and Miller 1961), while Na^+ saturated interlayers tend to adsorb additional water osmotically (Norrish and Quirk 1954). The result of ion sorting is the formation of "tactoids" or stacks of clay platelets no thicker than $1\text{ }\mu\text{m}$ (Mills and Zwarich 1973). Shainberg and Kaiserman (1969) verified the existence of tactoids through light transmission studies of Ca^{++} and Na^+ montmorillonite suspensions. Mills and Zwarich (1973) determined that bentonite tactoids under a particular set of experimental conditions consisted of 12 clay platelets, each $19\text{ }\text{\AA}$ thick for a total thickness of $.230\text{ }\mu\text{m}$. The sorting of ions of different valences has been demonstrated only for the internal surfaces of clays.

The mixed ion model predicts that individual clay surfaces consist of a mixture of exchangeable ion species. According to the mixed ion model, continuous swelling occurs both between the internal and external surfaces of clay particles with the amount of swelling depending, among other things, upon the relative amounts of Na^+ and Ca^{++} present. Even if some demixing does occur, this model is applicable to illite and

kaolinite clays because kaolinite has virtually no internal exchange sites and most internal exchange sites of illite are bound up by K^+ (Baver et al. 1972).

The ESP of a montmorillonite tactoid saturated internally with Ca^{++} and externally with Na^+ is low because of the low proportion of external surfaces of this mineral. According to the literature, external surfaces may be completely saturated with Na^+ at ESP values as low as 15 and appreciable interparticle swelling can occur (Shainberg et al. 1971). This is a possible explanation for the common dividing line between sodic and non-sodic soils (U. S. Salinity Laboratory Staff 1954). The demixed ion model thus explains the hypersensitivity of montmorillonite to Na^+ .

Hydraulic Conductivity

Hydraulic conductivity (K) is a measure of the ability of the soil to transmit water (Black 1965) and has been found to be a function of the pore size as well as distribution within a sample (Marshall 1958). The dispersing effect of Na^+ generally reduces the hydraulic conductivity of a sample (Brooks et al. 1956, Reeve 1957, Waldron and Constantin 1968). McNeal and Coleman (1966) postulated that the decrease in conductivity following an increase in sample ESP can result both from particle dispersion and from the closing of pores by interlayer swelling. Dixit and Lal (1972) reported that an increase

in exchangeable Na^+ from 0-30% decreased the K values of soils of six different textural classes from a mean of 2.79 to a mean of .16 cm/hr.

Modulus of Rupture

Soil modulus of rupture (MOR) values have been reported to be sensitive to additions of both Ca^{++} and Na^+ (Dollhopf 1975, Moe et al. 1971, Richards 1953). Two different sources have reported MOR values to increase linearly with increasing exchangeable Na^+ (Brooks et al. 1956, Reeve et al. 1954).

Coefficient of Linear Extensibility

A high degree of correlation exists between the shrink-swell potential of soils or soil components and the ESP of the soil (Waldron and Constantin 1968 and 1970, McNeal et al. 1966, Davidson and Page 1956, Reeve et al. 1954). Coefficient of linear extensibility (COLE) values are often used to monitor the physical changes that occur at various soil ESP values.

Anderson et al. (1973) found COLE values of soil materials to be highly correlated ($R^2 = .938$) with the combination of % fine clay and the sample ESP. The R^2 value for fine clay alone was found to be .863, whereas that for ESP alone was only .323. McCormack and Wilding (1975) found COLE values to be highly correlated with total clay content ($R^2 = .93$). Franzmeier and Ross (1968) determined COLE values of 0 to .03 between the 1/3 bar moisture content and oven drying to be non-

critical, .03 to .06 marginal, .06 to .10 critical, and values greater than .10 to be very critical in terms of soil material swelling potentials. They found kaolinite and illite samples to have COLE values less than .03, whereas montmorillonite samples generally had values greater than .03. They also determined that soils with clay fractions dominated by montmorillonite (>50%) generally respond as if their clay fraction was composed solely of montmorillonite.

MATERIALS AND METHODS

Experimental Design

Overburden samples ranging in depth from .6 to 72 meters (2 to 235 ft) from proposed coal mine sites in eastern Montana and western North Dakota were used in this research. Samples having clay fractions dominated by smectite, illite, or kaolinite were identified by the Montana Agricultural Experiment Station in previous studies by the use of X-ray diffraction techniques. Four or five overburden samples representative of each clay type were used in the experiments. Clay percentages were identified by pipette analysis. The widest range in particle size distribution available was chosen within each mineralogical sample group. Table 1 lists some physical and mineralogical properties of the samples used in this research. Table 2 shows the experimental design including the samples and the number of replications of each sample used in the individual experiments.

Inducing Exchangeable Sodium Percentages

A range of exchangeable sodium percentage (ESP) values was imposed on each sample used in this research to monitor changes in physical properties resulting from changes in ESP values. The United States Salinity Laboratory has determined that at low values (<30) a near-linear relationship exists between the equilibrium ESP of a sample and the sodium adsorption ratio (SAR) of the sample solution (1954). By forcing a solution of known SAR through a sample, the ESP of the

Table 1. Physical and mineralogical sample properties.

Sample #	Depth	Sand	Silt	Clay	Textural class	Smectite	Illite	Kaolin- ite	Quartz	Vermic- ulite	Chlorite
	m	-----%-----									
Kiewitt A		71	18	11	SL	4	T	T	T	-	T
531	13.7-15.2	66	18	16	SL	4	T	T	T	T	1
45246	.6- 1.5	33	43	24	L	3	1	T	T	-	T
45250	6.0- 7.6	11	63	26	SiL	3	1	T	T	-	1
45254	12.2-13.4	36	48	16	L	3	1	1	-	-	1
8	10.4-13.7	6	56	38	SiCL	T	4	1	T	T	T
9	13.7-19.2	34	36	30	CL	T	3	2	T	-	1
11	29.6-31.1	32	41	27	L-CL	-	4	1	T	-	T
12	32.0-35.4	22	51	27	SiL-CL	T	4	1	T	-	T
18	63.7-71.6	33	48	19	L	-	3	2	-	1	1
44534	37.8-39.3	64	26	10	SL	-	2	3	-	-	T
44535	39.6-41.1	18	65	17	SiL	-	2	3	-	-	-
44540	48.8-50.6	14	70	16	SiL	-	2	3	-	-	1
45263	41.1-42.7	81	16	3	LS	-	1	4	-	-	-
45266	45.1-46.6	17	65	18	SiL	-	2	3	T	-	1

* T = 0- 5% 1 = 6- 25% 2 = 26-50% 3 = 51-75% 4 = 76-100%

Table 2. Experimental design.

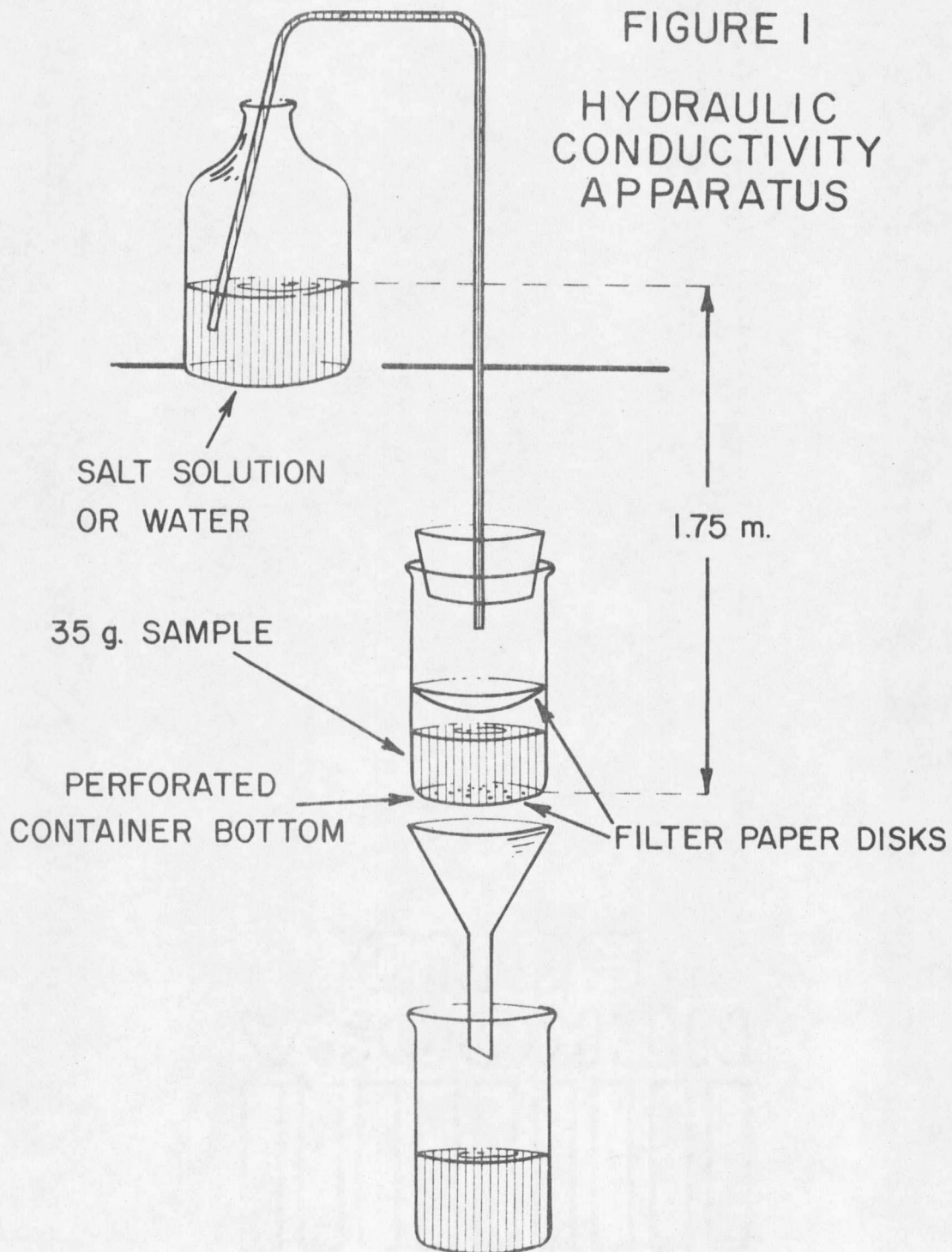
		<u>Hydraulic Conductivity</u>					<u>Shrinkage of Briquets</u>					<u>Modulus of Rupture</u>					<u>Coefficient of Linear Extensibility</u>				
		SAR	0	5	10	15	20	SAR	0	5	10	15	SAR	0	5	10	15	SAR	0	5	10
Kiewitt A 531 45246 45250 45254	3 reps	4	3	4	-		2	2	2	2		2	-	2	2		2	2	2	2	
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	4 reps	4	3	4	-		2	2	2	2		2	2	1	1		2	2	2	1	
	3 reps	4	3	4	-		2	2	2	2		2	2	-	-		2	2	-	2	
	3 reps	4	4	4	-		2	2	2	2		2	2	-	-		2	-	1	2	
8 9 11 12 18	4 reps	-	4	4	-		-	-	2	2		-	-	2	2		2	-	2	2	
	3 reps	-	3	4	-		-	-	2	2		-	-	2	2		2	-	2	2	
	2 reps	-	3	3	-		-	-	2	2		-	-	2	2		2	-	2	2	
	3 reps	-	3	3	-		-	-	2	2		-	-	2	2		2	-	2	2	
	4 reps	-	3	4	-		-	-	2	2		-	-	2	2		2	-	2	2	
44534 44535 44540 45263 45266	3 reps	-	4	4	-		2	-	1	2		2	-	2	2		2	-	2	-	
	3 reps	-	4	4	1		1	-	1	1		2	-	1	1		1	-	-	2	
	4 reps	-	3	4	2		1	-	1	1		2	-	2	2		1	-	2	-	
	3 reps	-	3	3	-		2	-	1	1		2	-	2	1		-	-	-	-	
	4 reps	-	4	4	4		-	-	-	-		-	-	-	-		2	-	2	2	

sample can be raised or lowered to a predictable value. A minimum of 1 liter of solution having electrical conductivity of 4.0 mmhos/cm and known SAR was forced through each replication of each sample under hydraulic head of about 1.75 meters. Samples were washed with distilled water for five days or until a minimum of 1 liter of water had passed through to remove soluble salts. They were then tested for hydraulic conductivity, briquet shrinkage, and modulus of rupture. Initial results of linear extensibility tests were considered random enough to merit sodium resaturation. Samples were dry-ground and sieved to limit particle size to ≤ 1 mm in diameter. Crushed samples weighing 50 to 75 grams were washed four times with solutions of various SAR values and an electrical conductivity of 4.0 mmhos/cm. They were leached with 200 to 500 ml of distilled water to remove soluble salts and were then used in the linear extensibility tests.

Hydraulic Conductivity

Hydraulic conductivity was used in this research as a means of quantifying the physical changes that occurred in samples over a range of ESP values.

The conductivity apparatus can be seen in Figure 1. The sample container was perforated on the bottom to allow passage of water through the sample which was crushed and sieved to < 1 mm in size. The container was covered on top and bottom with Whatman #40 filter paper.



The hydraulic head was raised to a uniform height by filling the upper bottles with distilled water. The amount of water flowing through the sample per unit time was then measured. The equation used to calculate the hydraulic conductivity (K) of the samples was

$$K = (Q/At)(L/\Delta H) \quad (\text{Black 1965})$$

where Q is the volume of water passing through the sample in a known time t. A is the cross-sectional area of the sample, L is the length of the sample, and ΔH is the hydraulic head.

COLE Tests

Coefficient of linear extensibility (COLE) is a measure of the shrink-swell potential of a soil. Calculation of COLE involves a measurement of the 1-dimensional length change between two moisture contents of a Saran-coated natural ped or clod.

In most cases, the standard COLE procedure was not suitable for this research because there were no soil peds or clods of material available. Samples were already crushed and sieved upon receipt. Schafer and Singer (1976) developed an alternative method of measuring COLE. The Schafer and Singer method involves a measurement of the 1-dimensional length change upon drying of rods formed from pastes of soil material near saturation. The $COLE_{rod}$ procedure was found to be highly correlated to the standard COLE procedure ($R^2 = .83$) and was more suitable for this research. Rods formed from pastes just below

a saturated condition 1 cm in diameter and 9-12 cm long were extruded onto a ceramic plate as shown in Figure 2. The rods were then allowed to air-dry. The change in length between the wet and dry rods was measured and the linear extensibility between 0 to 1/10 bar and air-dry moisture tensions was calculated by the equation

$$COLE_{rod} = (l_m - l_d)/l_d \quad (\text{Schafer and Singer 1976})$$

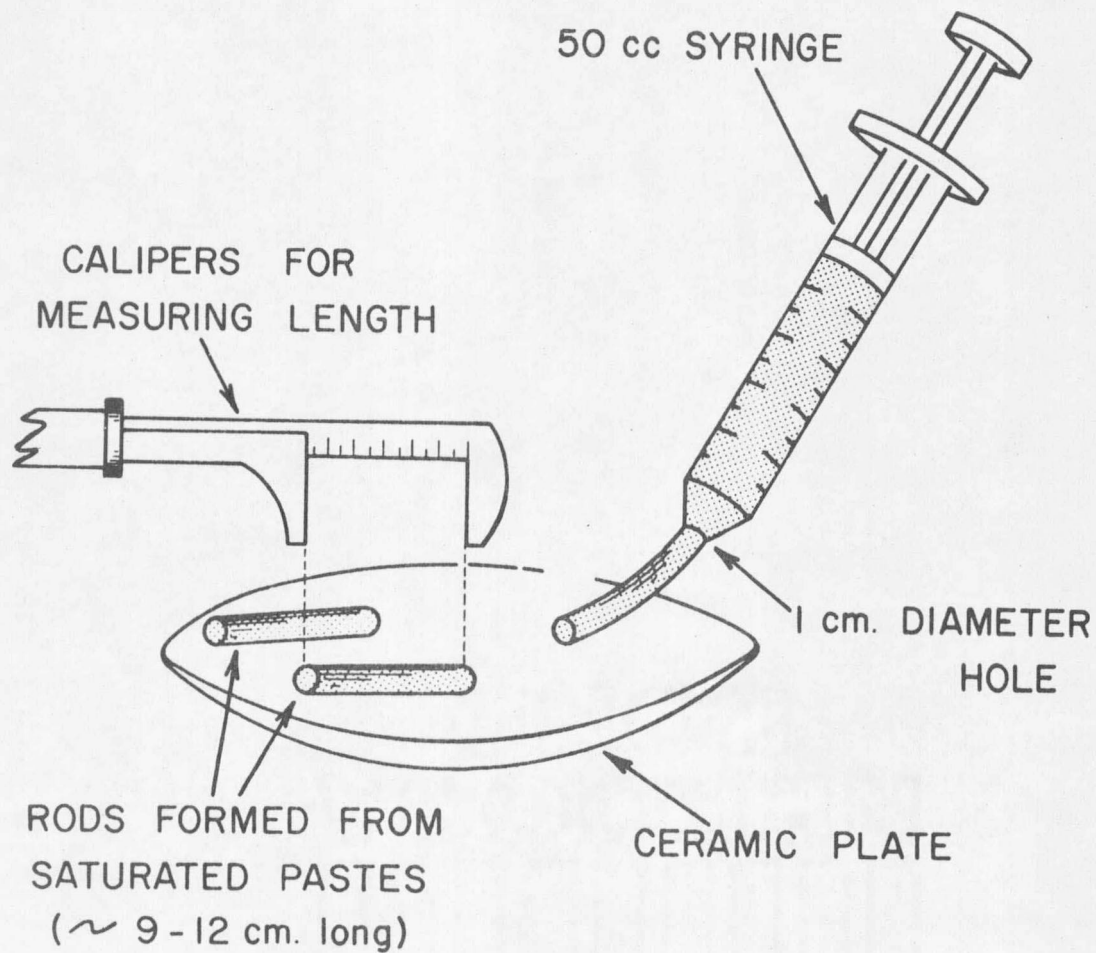
where l_m and l_d represent the moist and dry rod lengths, respectively.

Modulus of Rupture

Modulus of rupture is a measure of the minimum force necessary to break a specially-molded briquet of soil material. This test gives an indication of the crusting strength of specific soil materials (Richards 1953).

The technique of modulus of rupture used in this research was similar to that described by the United States Salinity Laboratory Staff (1954) except that the briquet molds were filled with a saturated paste. First attempts at making briquets according to the United States Salinity Lab procedure gave unsatisfactory results. Cracks formed in the briquets rendering them useless for testing crusting strength. Usable briquets resulted when molds filled with saturated pastes were allowed to dry for two months in a 95% relative humidity chamber composed of an airtight tub, the bottom of which contained

FIGURE 2
COLE TEST



a 13% H_2SO_4 solution to give a 95% relative humidity (U. S. Salinity Laboratory Staff 1954).

Modulus of rupture was determined by the equation

$$M = (3FL)/(2bd^2) \quad (\text{U. S. Salinity Lab. Staff 1954})$$

where F is the breaking force in dynes (gram-weight of breaking force x 980), L is the distance between the lower two supporting bars of the testing apparatus, b is the width of the briquet, and d is the depth or thickness of the dried briquet. All linear measurements are in centimeters.

In addition to modulus of rupture, the % shrinkage of the briquets upon drying was also measured.

RESULTS AND DISCUSSION

Kaolinite Samples

Hydraulic Conductivity

Hydraulic conductivity might be expected to decrease as the exchangeable sodium percentage is raised because of the closing of pores by particle swelling (McNeal et al. 1966). This was indeed the case for the kaolinite samples used in this research as illustrated by the data in Table 3. Every sample except No. 44535 exhibited a decrease in conductivity as sodium adsorption was increased. Table 3 also shows that the decrease in conductivity as SAR was increased from 0 to 15 is usually statistically significant. The only exception to this is sample No. 45263 which only has 3% clay (Table 1). In light of the coarse texture of sample 45263, it is not surprising to find a non-significant treatment effect although a near-linear decrease in hydraulic conductivity did occur for the sample.

Sample 45263 has a relatively high hydraulic conductivity probably due to its coarse texture. The analysis of variance presented below indicates a high variation in conductivity within treatments (SAR values) which can be attributed to the disproportionately high conductivities of sample 45263. Conductivity decreases between SAR 0 and SAR 20 are significant ($P = .05$) when sample 45263 is ignored. In order to avoid such large variations within treatments without discarding samples,

Table 3. Average hydraulic conductivity values for individual kaolinite samples. 1/

Sample No.	SAR 0	SAR 10	SAR 15	SAR 20
	-----cm/hr-----			
44534	.177 a	.012 b	.0045 b	--
44535	.007 b	.015 a	.008 b	.004 b
44540	.020 a	.017 ab	.007 b	.0035 b
45263	1.700	1.425	1.250	--
45265	.047 a	.030 b	.029 b	.015 c
Mean, all kaolinite samples	.348	.315	.208	.008

1/ Values in the same row followed by different letters are significantly different at $P = 0.05$ according to the Newman-Keuls Test (Snedecor and Cochran 1967).

Analysis of Variance for the Mean of All Kaolinite Sample Data:

<u>Source of variation</u>	<u>df</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F-value</u>
Between treat.	3	.68	.2282	.773
Within treat.	58	17.12	.2952	
Total	61	17.81		

results are expressed below and in following sections as percentages of those samples without sodium.

No significant treatment effect was seen in Table 4, although conductivity does decrease by nearly 70% as the SAR value is increased from 0 to 20. Apparently the irregularity of sample 44535 is sufficient to mask significance as the conductivity decrease becomes significant ($P = .05$) when those sample values are discarded.

Coefficient of Linear Extensibility

Although no significant treatment effect on COLE values of individual samples was observed, linear extensibility of all kaolinite samples increased upon addition of exchangeable Na^+ . Table 5 shows the effect of SAR values on the linear extensibility of the individual samples.

A significant ($P = .05$) treatment effect is shown when COLE values are expressed as a percent of those samples without sodium (Table 6).

Briquet Shrinkage

Most of the briquets curled upon drying rendering dry volume measurements difficult, if not meaningless. In spite of experimental flaws, results for kaolinite briquet shrinkage were similar to results of linear extensibility tests (Tables 7 and 8). Again, shrinkage increased with increasing SAR values but not significantly. Signifi-

Table 4. Hydraulic conductivity values for kaolinite samples expressed as a % of those samples without sodium.

SAR 0	SAR 10	SAR 15	SAR 20
<u>-----Percent-----</u>			
100	90.7	57.4	32.5

Table 5. Average COLE values for individual kaolinite samples $(l_m - l_d) / l_d$.

Sample No.	SAR 0	SAR 10	SAR 15
44534	.014	.063	--
44535	.050	--	.076
44540	.037	.065	--
45266	.033	.036	.056
Mean, all kaolinite samples	.036 a	.055 b	.066 c

Table 6. COLE values for kaolinite samples expressed as a % of those samples without sodium.

SAR 0	SAR 10	SAR 15
<u>-----Percent-----</u>		
100 a	162.7 ab	160.8 b

Table 7. Average % briquet shrinkage for individual kaolinite samples.

Sample No.	SAR 0	SAR 10	SAR 15
	<u>-----Percent-----</u>		
44534	12.35	7.60	12.94
44535	17.50	19.40	20.80
44540	18.90	19.40	19.40
45263	2.75	10.20	10.20
Mean, all kaolinite samples	11.10	14.15	16.56

Table 8. Kaolinite briquet shrinkage expressed as a % of those samples without Na⁺.

SAR 0	SAR 10	SAR 15
	<u>-----Percent-----</u>	
100	163.2	182.7

cance may have been masked by the high variation within the treatment as shown by the analysis of variance presented below:

<u>Source of variation</u>	<u>df</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F-value</u>
Between treat.	2	14960	7841	.591
Within treat.	9	113900	12660	
Total	11	128900		

Modulus of Rupture

Although briquets were dried for several months at high humidities, cracks still appeared in some briquets, lowering their crusting strength. Modulus of rupture, thus, showed no increasing or decreasing trend upon addition of exchangeable Na^+ (Tables 9 and 10).

The linear increase in MOR with increasing exchangeable Na^+ reported by Brooks et al. (1956) and Reeve et al. (1954) was not apparent within the kaolinite sample group. One reason for the lack of uniform variation in MOR values might be the curving and cracking of the briquets upon drying. Another reason might be that stirring the saturated paste destroyed the microaggregates in the sample and promoted parallel orientation of sample colloids, thus increasing MOR values, especially at low adsorbed Na^+ levels. Brooks and Reeve did not use saturated pastes in their respective studies of modulus of rupture.

Table 9. Average modulus of rupture values for individual kaolinite samples.

Sample No.	SAR 0	SAR 10	SAR 15
	----- Dynes $\frac{-3}{cm^2}$ -----		
44534	9,425	8,465	9,510
44535	14,320	13,240	13,410
44540	11,560	11,340	11,980
45263	4,725	4,295	4,190
Mean, all kaolinite samples	10,010	8,779	10,090

Table 10. Modulus of rupture values for kaolinite samples expressed as a percent of those samples without sodium.

SAR 0	SAR 10	SAR 15
	----- <u>Percent</u> -----	
100	87.7	100.7

Smeectite SamplesHydraulic Conductivity

The hydraulic conductivity of the smectite samples was very sensitive to changes in adsorbed sodium. The conductivity of every sample decreased upon an increase in SAR. The conductivity decrease for every sample was highly significant ($P = .01$) as the SAR was increased from 0 to 10. Hydraulic conductivity virtually ceased for several samples at SAR values as low as 10 as seen in Table 11.

The conductivity decrease is illustrated even more dramatically when expressed on a percentage basis as seen in Table 12. The analysis of variance presented below shows that variation between treatments is almost entirely responsible for conductivity decreases.

<u>Source of variation</u>	<u>df</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F-value</u>
Between treat.	3	25800	8598	589**
Within treat.	10	146	14.6	
Total	13	25940		

**Significant at the 99% level ($P = .01$).

Coefficient of Linear Extensibility

The linear extensibility of the smectite samples generally increased with an increase in exchangeable Na^+ , though the increase was not significant.

Table 11. Average hydraulic conductivity (cm/hr) for individual smectite samples.

Sample No.	SAR 0	SAR 5	SAR 10	SAR 15
-----cm/hr-----				
A	.487 a	.350 a	.132 b	.016 b
531	.540 a	.370 b	.025 c	.004 c
45246	.014 a	.003 b	.000 b	.000 b
45250	.013 a	.003 b	.000 c	.000 c
45254	.034 a	.003 b	.000 b	.000 b
Mean, all smectite samples	.224	.134	.029	.004

Table 12. Hydraulic conductivity for smectite samples expressed as a % of those samples without sodium.

SAR 0	SAR 5	SAR 10	SAR 15
-----Percent-----			
100 a	18.6 b	4.3 c	.6 c

No significant increase in linear extensibility is shown in Table 13 or 14 where COLE is expressed as a percent basis.

Shrinkage of soils upon drying is at a maximum when the initial water content is just below the saturation point (Franzmeier and Ross 1968). The saturation point of a sodium dominated smectite is arbitrary due to the lack of structure and defined pore space. The inevitable variation in initial water content of sodium dominated smectite may account for the lack of significant shrinkage upon drying.

Briquet Shrinkage

Briquet shrinkage upon drying increased with increasing exchangeable sodium (Tables 15 and 16). The three finest textured smectite samples (45246, 45250, 45254) showed significant ($P = .01$) shrinkage as the SAR was increased.

Briquet shrinkage was used in this research as a check on COLE data. There was not good agreement between the COLE data and the briquet shrinkage data for the smectite samples. The major difference between the two tests was the drying time for the samples. It appears that the influence of SAR on shrinkage is more pronounced under the slow drying conditions used in the briquet shrinkage tests. Gerard (1965) found that slow drying increases the crusting strength because of the greater close packing of fine particles which also promotes shrinkage.

Table 13. Average COLE values for individual smectite samples.

Sample No.	SAR 0	SAR 5	SAR 10	SAR 15
A	.094	.100	.102	.104
531	.022	.034	.028	.040
45246	.137 a	.150 a	.166 a	.100 b
45250	.113	.122	--	.116
45250	.076	--	.108	.110
Mean, all smectite samples	.088	.102	.100	.094

Table 14. COLE values for smectite samples, expressed as a % of those samples without Na⁺.

SAR 0	SAR 5	SAR 10	SAR 15
<u>Percent</u>			
100	121.9	127.0	126.1

Table 15. Average % briquet shrinkage of individual smectite samples.

Sample No.	SAR 0	SAR 5	SAR 10	SAR 15
-----Percent-----				
A	23.90	24.20	27.40	26.70
531	12.20 a	18.20 b	12.55 a	14.00 a
45246	38.00 a	46.05 b	50.60 c	53.40 d
45250	32.30 a	33.70 b	44.30 c	45.70 d
45254	26.35 a	30.90 b	38.00 c	39.40 d
Mean, all smectite samples	26.55	30.61	34.57	35.89

Table 16. Smectite briquet shrinkage expressed as a % of those samples without sodium.

SAR 0	SAR 5	SAR 10	SAR 15
-----Percent-----			
100 a	118.9 ab	126.7 b	131.7 b

Modulus of Rupture

Some increase in modulus of rupture resulted from an increase in SAR, but the linear increase reported by Brooks et al. (1956) and Reeve et al. (1954) was not reproduced in this research. Curling and cracking of briquets upon drying occurred with the smectite samples which may have introduced error. A general increase in MOR for some smectite samples did occur with increasing exchangeable sodium as seen in Tables 17 and 18.

Illite Samples

Hydraulic Conductivity

The hydraulic conductivity of all illite samples decreased significantly ($P = .05$) as the SAR of the samples was raised from 0 to 15 (Tables 19 and 20). The significant conductivity decrease is apparent when data are presented as conductivity values for individual samples, a composite of all illite samples, and as % decrease as compared to those samples without sodium. Hydraulic conductivity appeared to be the test most sensitive to changes of SAR values of the illite samples.

Coefficient of Linear Extensibility

COLE values generally increased with the addition of exchangeable Na^+ , although the increase was not often non-significant. Four samples displayed increases in linear extensibility upon each addition

Table 17. Average modulus of rupture for individual smectite samples.

Sample No.	SAR 0	SAR 5	SAR 10	SAR 15
----- Dynes ⁻³ /cm ² -----				
A	17,260	--	17,010	20,090
531	6,511	--	7,490 a	9,190 b
45246	24,390 a	34,560 b	38,000 c	41,420 d
45250	18,640	19,210	--	--
45254	23,160 a	33,240 b	--	--
Mean, all smectite samples	18,000	29,000	12,400	20,320

Table 18. Modulus of rupture for smectite samples expressed as % of those samples without sodium.

SAR 0	SAR 5	SAR 10	SAR 15
-----Percent-----			
100 a	129.4 ab	123.1 b	146.3 b

Table 19. Average hydraulic conductivity of individual illite samples.

Sample No.	SAR 0	SAR 10	SAR 15
	<u>cm/hr</u>		
8	.057 a	.036 a	.005 b
9	.068 a	.019 b	.004 c
11	.09	.017	.004
12	.017 a	.017 a	.004 b
18	.068 a	.049 a	.008 b
Mean, all illite samples	.048 a	.028 b	.005 c

Table 20. Hydraulic conductivity of illite samples expressed as % of those samples without sodium.

SAR 0	SAR 10	SAR 15
	<u>Percent</u>	
100 a	86.6 a	18.0 b

of exchangeable Na^+ (Table 21). One sample (no. 9) showed an inexplicable decrease in extensibility upon an increase in exchangeable Na^+ .

Coefficient of linear extensibility values for the illite mineralogical sample group increase slightly upon an increase in exchangeable Na^+ although the increase is not significant.

The analysis of variance for the data in Table 22 is as follows:

<u>Source of variation</u>	<u>df</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F-value</u>
Between treat.	2	828.4	414.2	1.8
Within treat.	<u>12</u>	<u>2713.0</u>	226.1	
Total	14	3541.4		

Even when expressed as a percent of those samples without sodium, variation within treatments is so large that the increase in COLE values does not appear to be significant (Table 22). Worthy of mention is the similarity between the COLE values for illite samples and those for the smectite samples. Smectite samples would be expected to display a greater shrink-swell potential than the illite samples upon an increase in exchangeable sodium. Table 1 shows that the illite samples have an average of about 10% more clay than the smectite samples. This could account for the similarity between mineralogical groups and would agree with the significant effect of clay content on COLE values found by McCormack and Wilding (1975).

Table 21. Average COLE values for individual illite samples.

Sample No.	SAR 0	SAR 10	SAR 15
8	.096 a	.112 ab	.128 b
9	.112 a	.100 a	.088 b
11	.061 a	.066 a	.085 b
12	.087 a	.091 b	.106 c
18	.076	.087	.089
Mean, all illite samples	.087	.092	.099

Table 22. COLE values for illite sample group expressed as a % of those samples without Na⁺.

SAR 0	SAR 10	SAR 15
<u>Percent</u>		
100	106.8	118.0

Shrinkage of Briquets

Illite briquets saturated at SAR 0 were not used in this research due to lack of material. The shortage of material was obvious only when it was too late to correct the problem. The drying procedure lasts several months and there was not enough time to send for additional material. The value of the data in this section is limited because of the lack of data at SAR 0 and the narrow range between the two SAR values tested.

There appears to be essentially no difference in briquet shrinkage of illite samples between SAR 10 and SAR 15 (Table 23).

Modulus of Rupture

Data are also lacking for modulus of rupture of illite samples at SAR 0. Modulus of rupture did show a general increase with an increase in SAR for most illite samples, although the increase was usually not significant (Table 24).

Comparison of Mineralogical Groups

Hydraulic Conductivity

Figure 3 illustrates the decrease in hydraulic conductivity for all the mineralogical groups with increasing SAR values. The effect of SAR on hydraulic conductivity is more pronounced in the smectite group than in the illite or kaolinite groups. For each increment of five SAR units, the conductivity of the smectite samples as presented

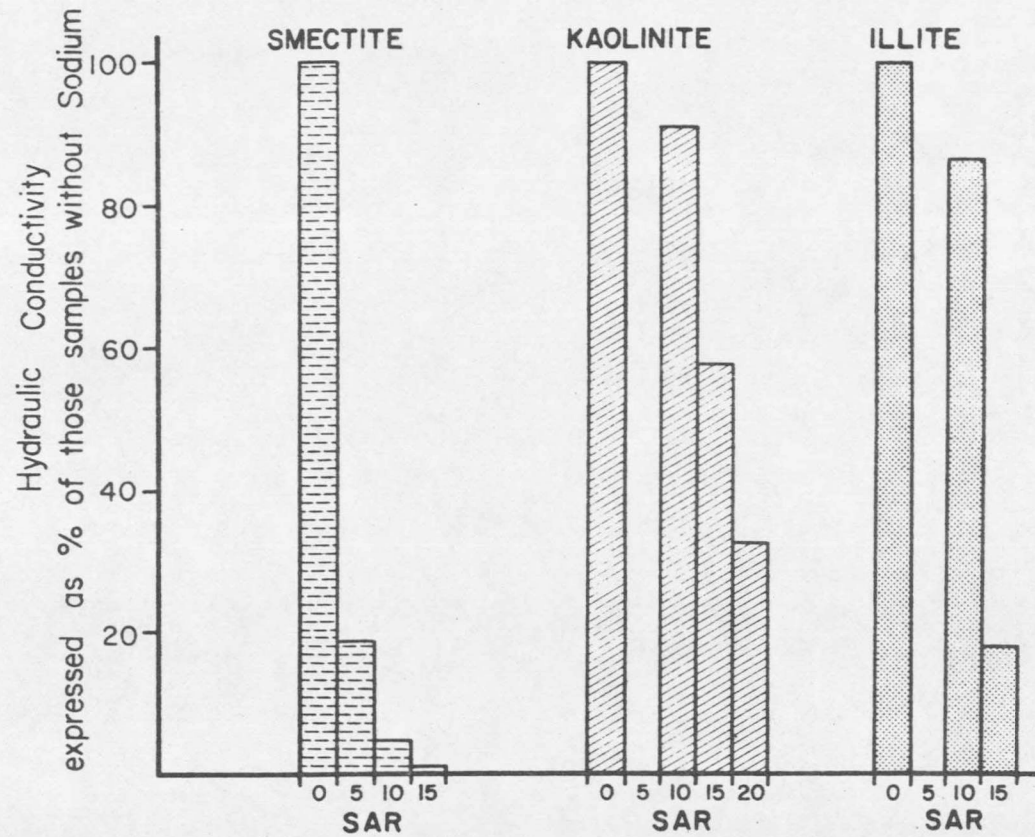
Table 23. Average % shrinkage of briquets for individual illite samples.

Sample No.	SAR 10	SAR 15
-----Percent-----		
8	31.00	32.65
9	30.50	33.05
11	26.25	23.00
12	28.50	26.90
18	27.15	26.00
Mean, all illite samples	28.68	28.32

Table 24. Average MOR values for individual illite samples.

Sample No.	SAR 10	SAR 15
----- Dynes ⁻³ /cm ² -----		
8	17,510 a	24,950 b
9	22,090	26,890
11	6,260	5,520
12	15,770 a	21,470 b
18	15,510	14,650
Mean, all illite samples	15,430	18,690

Figure 3. Effect of SAR on Hydraulic Conductivity



in Figure 3 decreased from about 75% to 85% of the value at the higher SAR. Conductivity of kaolinite decreased a maximum of about 45% for a similar change in SAR. Illite samples showed a conductivity decrease of nearly 80% between SAR 10 and 15, but like the kaolinite samples, the decrease in conductivity between SAR 0 and SAR 10 was slight.

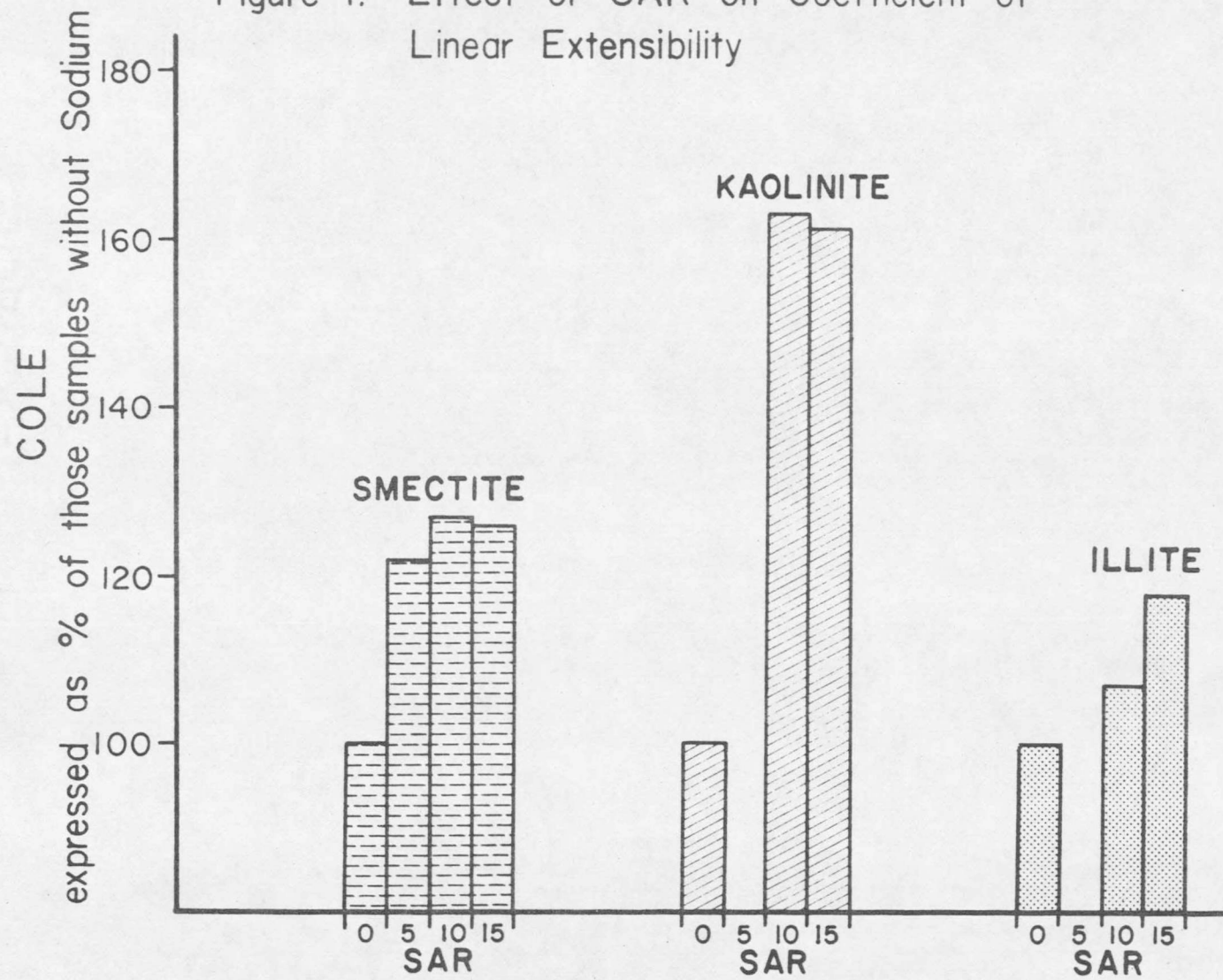
Coefficient of Linear Extensibility

The COLE values of all the sample groups generally increase with an increase in SAR as seen in Figure 4. The largest COLE increase in the smectite samples occurred between SAR 0 and SAR 5 with very little change in linear extensibility seen between samples equilibrated at SAR 5, SAR 10, or SAR 15. Essentially all the change in COLE for the kaolinite samples occurred between SAR 0 and SAR 10. The illite samples, which appeared to be less sensitive to SAR changes than the kaolinite samples in this particular test, showed maximum COLE changes between SAR 10 and SAR 15.

Briquet Shrinkage

The effect of SAR on briquet shrinkage can be seen in Figures 5a and 5b. Illite samples were not expressed as a % of those samples without sodium because they were not measured at SAR 0 for this test or for modulus of rupture. Figure 5b was constructed from raw data and includes the illite samples. Results of this tests were similar to those of the COLE test for the smectite and kaolinite samples.

Figure 4. Effect of SAR on Coefficient of Linear Extensibility



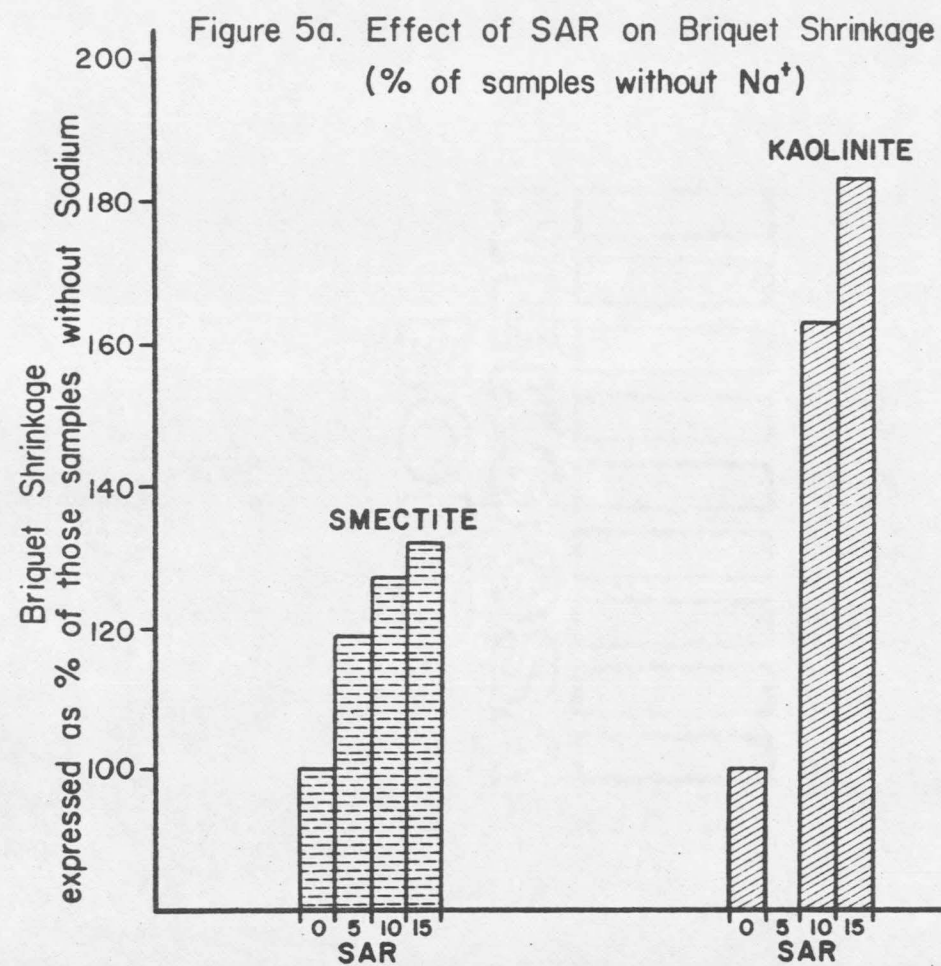


Figure 5b. Effect of SAR on Briquet Shrinkage (%)

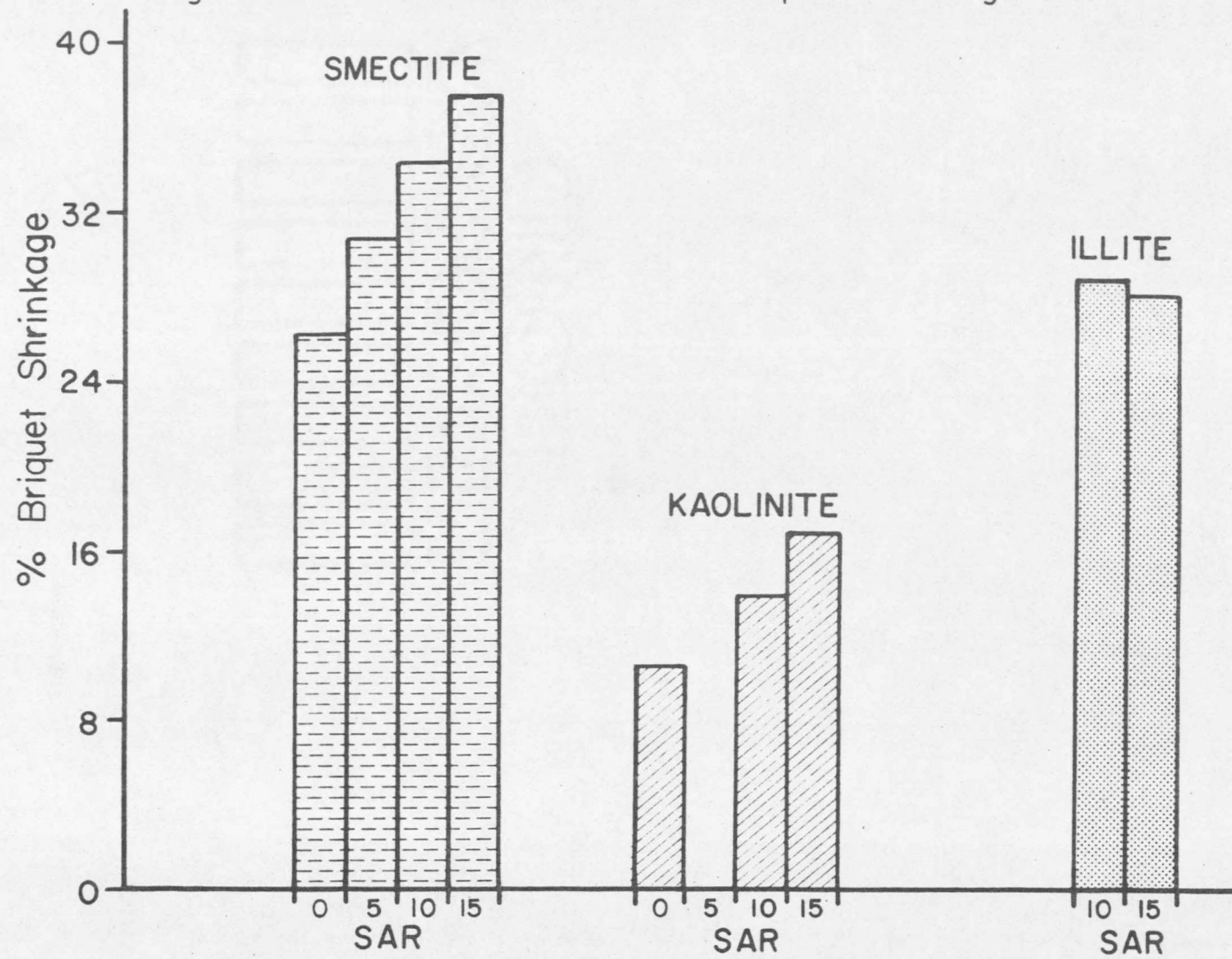
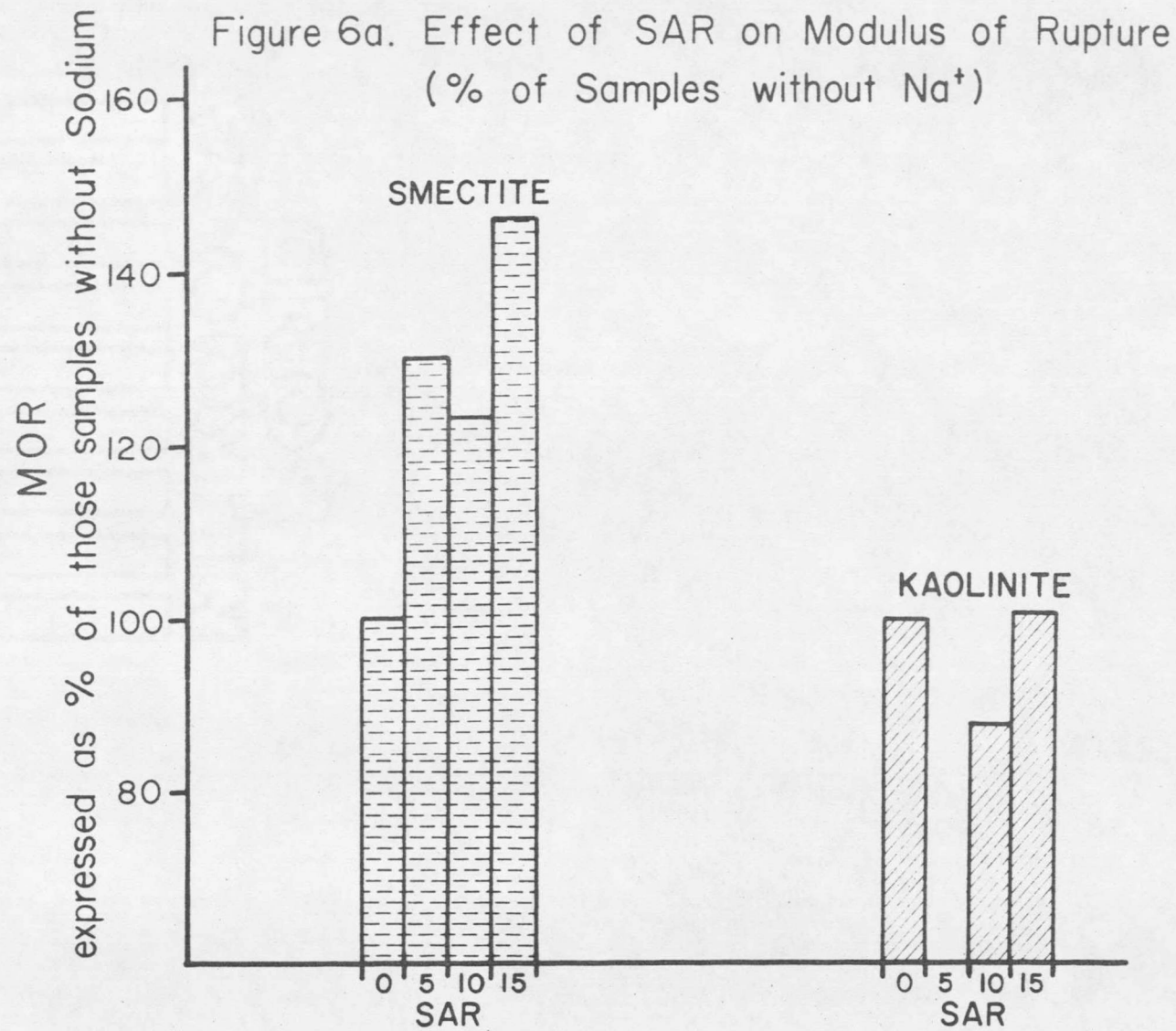
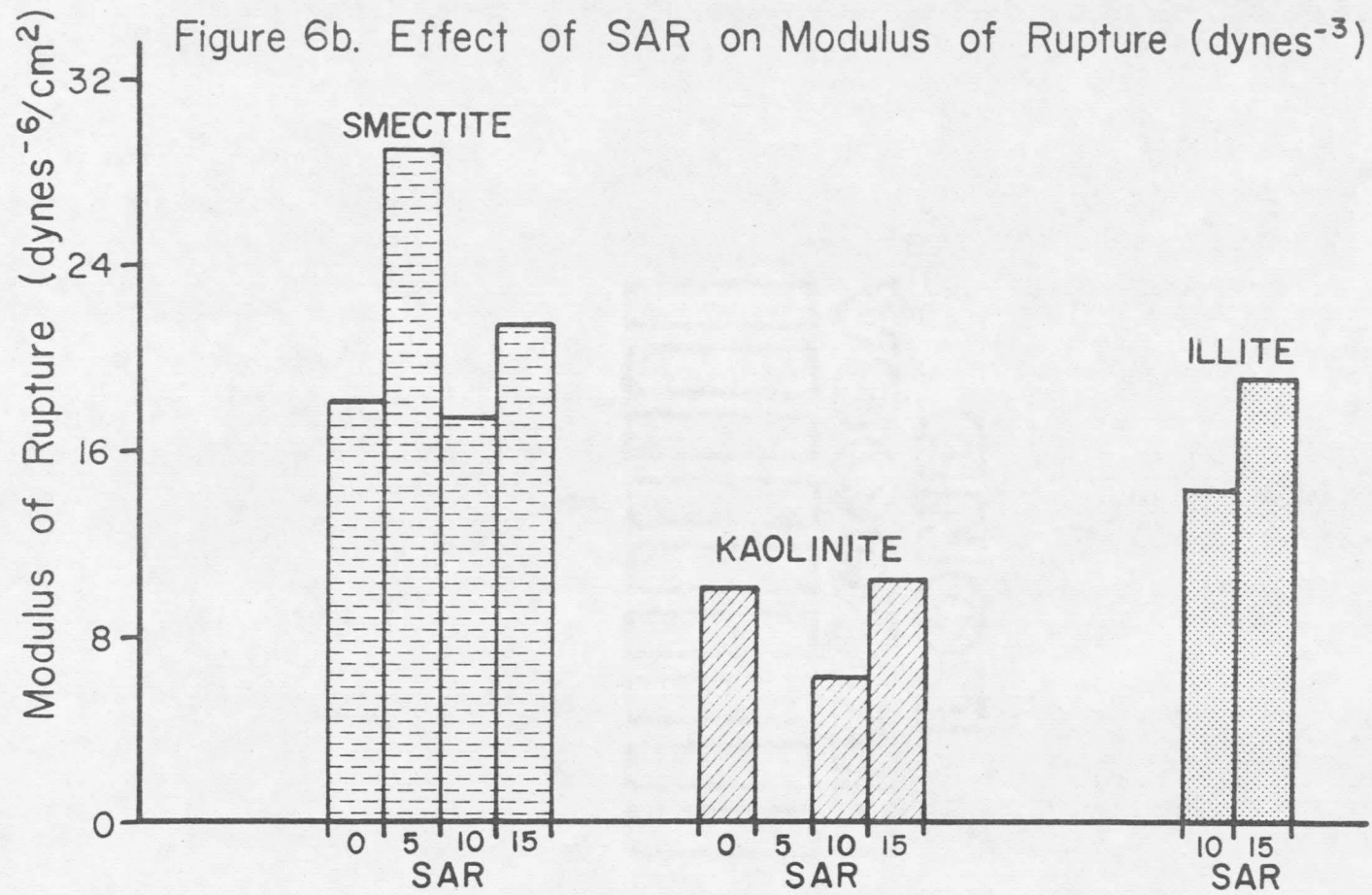


Figure 5a shows the maximum shrinkage for the smectite samples to occur between SAR 0 and SAR 5, although the shrinkage was nearly linear. As in the COLE test, the maximum shrinkage of the kaolinite samples occurred between SAR 0 and SAR 10. Figure 5b shows that the shrinkage for the smectite samples and possibly the kaolinite samples is essentially linear. Lack of data for the kaolinite samples at SAR 5 allows only a suggestion of the linear relationship between SAR and shrinkage. There appears to be essentially no change in shrinkage of the illite samples between SAR 10 and SAR 15.

Modulus of Rupture

Figures 6a and 6b show the effect of SAR on modulus of rupture. The smectite samples show a general increase in MOR as the exchangeable sodium is raised. The most pronounced increase in MOR is shown to occur between SAR 0 and SAR 5. Kaolinite samples show no general relationship between SAR and MOR. It is difficult to obtain accurate reproducible results from this test because of the cracks that often form upon drying. Lack of a visible trend may be due primarily to experimental error. Data are insufficient for the illite samples to conclude a relation between SAR and MOR although Figure 6b shows an increase in MOR as the SAR is raised from 10 to 15.





SUMMARY AND CONCLUSIONS

Table 25 indicates the occurrence of significant treatment effect on results of the physical tests performed on the three mineralogical sample groups.

The smectite samples displayed a hypersensitivity to Na^+ in the hydraulic conductivity tests. Hydraulic conductivity decreases are significant in almost all cases when the range of SAR values compared is 5 or greater. The conductivity decrease between SAR 10 and 15 is not significant for the smectite samples, but this is because most smectite samples had virtually ceased to transmit water by the time the SAR value was equilibrated at 10. The decrease resulting from raising the SAR another 5 units thus had to be slight because the adverse effects of Na^+ had already manifested themselves at SAR 10. The external surfaces of the smectite clays were apparently influenced by sodium at very low SAR values. This indicates the ion sorting effect described by Shainberg and Kemper (1966) was occurring on the clay surfaces, resulting in tactoid formation and increased clay mobility due to interaction of expanded double layers (Baver et al. 1972). Particle dispersion and the closing of pores by interlayer swelling, the latter a predominately smectite phenomenon, also likely explains the conductivity decreases (McNeal and Coleman 1966). By contrast, the hydraulic conductivity of the kaolinite samples was still relatively high (.2 cm/hr) at SAR 15. All of the kaolinite samples tested continued to transmit water at SAR values of 20. There was no significant

Table 25 . Significant treatment effect

SAR values compared	Hydraulic Conduc.			COLE			Briquet Shrinkage			MOR		
	Kaoli- nite	Smec- tite	Il- lite	Kaoli- nite	Smec- tite	Il- lite	Kaoli- nite	Smec- tite	Il- lite	Kaoli- nite	Smec- tite	Il- lite
	-----cm/hr-----						-----%-----			-----dynes/cm ² -----		
0- 5	--	NS	--	--	NS	--	--	NS	--	--	NS	--
0-10	NS	*	*	*	NS	NS	NS	NS	--	NS	NS	--
0-15	NS	*	*	*	NS	NS	NS	NS	--	NS	NS	--
0-20	NS	--	--	NS	--	--	NS	--	--	NS	--	--
5-15	--	*	--	--	NS	--	--	NS	--	--	NS	--
10-15	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS
10-20	NS	--	--	--	--	--	--	--	--	--	--	--
15-20	NS	--	--	--	--	--	--	--	--	--	--	--
	-----% of those samples w/o sodium-----											
0- 5	--	*	--	--	NS	--	--	NS	--	--	NS	--
0-10	NS	*	NS	NS	NS	NS	NS	*	--	NS	NS	--
0-15	NS	*	*	*	NS	NS	NS	*	--	NS	*	--
0-20	NS	--	--	--	--	--	--	--	--	--	--	--
5-10	--	*	--	--	NS	--	--	NS	--	--	NS	--
10-15	NS	NS	*	NS	NS	NS	NS	NS	--	NS	NS	--
10-20	NS	--	--	--	--	--	--	--	--	--	--	--
15-20	NS	--	--	--	--	--	--	--	--	--	--	--

* = significant difference found between SAR values compared.

NS = no significant difference found between SAR values compared.

-- = test was not performed at one of the SAR values compared.

treatment effect for this test on the kaolinite sample group, although this was in part due to the variation within treatments. SAR had an obvious detrimental effect on the conductivity of the kaolinite samples, yet the adverse effects of Na^+ were not well manifested until the SAR value reached 20. Lack of interlayer surface area and the resulting inability of kaolinite to sort Ca^{++} and Na^+ cations is a plausible explanation of the difference in Na^+ sensitivity between these two sample groups. Illite samples reacted similarly though less dramatically than the smectite samples upon addition of exchangeable Na^+ . In most cases, an increase of 10 SAR units resulted in a significant decrease in the hydraulic conductivity of the illite samples. Perhaps some interstratification of smectite and illite minerals occurred. This would produce more interlayer space than would be found in a pure illite giving rise to some demixing of Na^+ and Ca^{++} . The purity of clay minerals is difficult to verify, though a trace of smectite was found in most of the illite samples and none was found in the kaolinite (Table 1).

Kaolinite seemed to be the mineral most sensitive to changes of SAR in the COLE test. In contrast to the hydraulic conductivity test, kaolinite was the only mineral which displayed a significant SAR treatment effect in the COLE test. This is somewhat inconsistent with the results reported in the literature. The kaolinite had a low SAR 0 COLE value which exaggerated the COLE increase when expressed as a

percentage of the value at SAR 0. For example, an increase in COLE value for the kaolinite samples of .019 units resulted in a 63% increase from the SAR 0 value, whereas an increase of .014 COLE units for the smectite samples resulted in only a 21.9% increase. The unexpected results of this test cannot, however, be explained solely on the basis of interpretation. Sample error may have been introduced by adding too much water to the smectite samples in an attempt to bring them to saturation. The saturation point is more easily achieved with kaolinite samples than with smectite samples. This test was performed on a porous ceramic plate which attracts water in much the same way as does soil clays. Water may have resulted in a cohesive attraction between the COLE rods and the ceramic plate. This attraction would have been most pronounced with the smectite samples due to their small particle size. Indeed, most smectite COLE rods split into segments during drying, lending credence to this explanation. Perhaps this test would yield more accurate results if run on a glass rather than ceramic plate.

The briquet shrinkage test was used as a check on the COLE test. The results of the two tests in this research are comparable with the effect of treatment variation on shrinkage being slightly more linear and more pronounced in the briquet shrinkage test. This can be attributed in part to the slow drying process involved in the manufacturing of the briquets (Gerard 1965).

The linear increase in modulus of rupture with increasing exchangeable Na^+ reported in the literature (Brooks et al. 1956, Reeve et al. 1954) was not observed in this research. Indeed, MOR showed no apparent relationship to increasing exchangeable Na^+ for the kaolinite samples. The smectite samples did show a general increase in MOR values with increasing exchangeable Na^+ . Due to the cracks which appeared in most briquets used in this test, results of the modulus of rupture test are generally inconclusive.

Results of the hydraulic conductivity test indicate most clearly the fact that the various clay mineral groups display different sensitivities to Na^+ . Conductivity of smectite samples was dramatically reduced at SAR values of 10 or less whereas the kaolinite samples continued to transmit water at SAR values of 20. Results of this test suggest that the "critical" exchangeable sodium percentage value of 15 defined by the United States Salinity Laboratory Staff (1954) may be too high for samples whose clay fractions are dominated by smectite and too low for kaolinite samples. Perhaps a single sodium percentage without regards to dominant clay minerals is an inadequate means of characterization of potential sodium hazards. Results of other tests did not verify this finding, yet procedural flaws and experimental error may have rendered the other results less meaningful. COLE tests should be run on a glass plate to negate cohesion between the COLE rods and the ceramic plate. Briquets should be manufactured from crushed

samples as outlined by the United States Salinity Laboratory Staff (1954) instead of saturated pastes. They should, however, be allowed to slow dry in a constant humidity chamber as specified in this report. To prevent briquet curling, perhaps the briquets should be sandwiched while drying between moist filter paper and flat screen.

To understand the interaction of clay mineralogy and exchangeable Na^+ levels on soil physical properties, several other areas of research are suggested. It would be beneficial to establish the existence and the nature of the correlation between the procedure for imposing SAR values on samples used in this research and the resulting sample ESP values. This would be especially helpful in refining the concept of the "critical" ESP value. Also, the same tests might be performed on commercially pure clay samples of known composition as the treatment effects would be more pronounced.

APPENDIX.

Table 26. Hydraulic conductivity (cm/hr) for kaolinite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15	SAR 20
44534	1	.154	.013	.006	--
	2	.202	.010	.006	--
	3	.174	.013	.003	--
	4	--	.012	.003	--
44535	1	.010	.015	.007	.004
	2	.006	.018	.017	--
	3	.006	.014	.006	--
	4	--	.014	.006	--
44540	1	.029	.020	.015	.004
	2	.013	.010	.006	.003
	3	.024	.020	.005	--
	4	.015	--	.003	--
45263	1			1.200	--
	2			1.350	--
	3			1.200	--
45266	1	.055	.028	.034	.015
	2	.038	.035	.018	.013
	3	.052	.030	.033	.009
	4	.042	.029	.033	.009

Table 27. COLE values for kaolinite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15
44534	1			
	2			
44535	1	.050	--	.081
	2	--	--	.070
44540	1	.037	.069	--
	2	--	.061	--
45266	1	.045	.022	.055
	2	.021	.050	.057

Table 28. % briquet shrinkage for kaolinite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15
44534	1		7.60	
	2		--	
44535	1	17.5	19.4	20.8
44540	1	18.9	19.4	19.4
45266	1	1.2	10.2	10.2
	2	4.3	--	--

Table 29. Modulus of rupture (dynes) for kaolinite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15
44534	1	9370	8820	10190
	2	9480	8110	8830
44535	1	14780	13240	13410
	2	13850	--	--
44540	1	11430	11660	11660
	2	11690	11030	12290
45263	1	4990	4430	4160
	2	4460	4160	--

Table 30. Hydraulic conductivity (cm/hr) for smectite samples.

Sample #	Rep.	SAR 0	SAR 5	SAR 10	SAR 15
A	1	.540	.369	.075	.018
	2	.540	.390	.162	.018
	3	.381	.288	.219	.015
	4	--	.351	--	.015
531	1	.540	.357	.021	.006
	2	.540	.402	.036	.003
	3	.540	.351	.018	.003
	4	.540	--	--	.003
45246	1	.012	.003	0	0
	2	.006	.003	0	0
	3	.021	.003	0	0
	4	.015	.003	--	0
45250	1	.015	.003	0	0
	2	.012	.003	0	0
	3	.012	.003	0	0
	4	--	.003	--	0
45254	1	.033	.003	0	0
	2	.027	.003	0	0
	3	.042	.003	0	0
	4	--	.003	0	0

Table 31. COLE values for smectite samples.

Sample #	Rep.	SAR 0	SAR 5	SAR 10	SAR 15
A	1	.091	.103	.105	.102
	2	.096	.097	.098	.106
531	1	.014	.032	.022	.030
	2	.029	.036	.033	.051
45246	1	.145	.154	.162	.100
	2	.129	.147	.169	--
45250	1	.117	.131	--	.118
	2	.109	.114	--	.114
45254	1	.087	--	.108	.107
	2	.064	--	--	.114

Table 32. % briquest shrinkage for smectite samples.

Sample #	Rep.	SAR 0	SAR 5	SAR 10	SAR 15
A	1	27.4	22.4	27.4	26.2
	2	20.4	26.0	27.4	26.2
531	1	--	--	12.5	14.0
	2	--	--	12.6	14.0
45246	1	33.0	45.7	50.6	53.4
	2	38.0	46.4	50.6	53.4
45250	1	32.3	33.7	44.3	45.7
	2	32.3	33.7	44.3	45.7
45254	1	26.0	30.9	38.0	39.4
	2	26.7	30.9	38.0	39.4

Table 33. Modulus of rupture (dynes) for smectite samples.

Sample #	Rep.	SAR 0	SAR 5	SAR 10	SAR 15
A	1	17580	--	17140	15770
	2	16950	--	16880	26020
531	1	6310	--	7920	9160
	2	6713	--	7060	9220
45246	1	24290	35240	38000	41420
	2	24500	33870	--	--
45250	1	12890	16320	--	--
	2	24400	22100	--	--
45254	1	22840	33780	--	--
	2	23490	32700	--	--

Table 34. Hydraulic conductivity (cm/hr) for illite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15
8	1	.036	.033	.006
	2	.060	.045	.006
	3	.066	.042	.006
	4	.066	.024	.003
9	1	.072	.018	.006
	2	.072	.018	.003
	3	.060	.021	.003
	4	--	--	.003
11	1	.012	.024	.003
	2	.006	.018	.003
	3	--	.009	.006
12	1	.021	.021	.003
	2	.015	.015	.003
	3	.015	.015	.006
18	1	.057	.024	.006
	2	.045	.087	.012
	3	.078	.036	.009
	4	.093	--	.006

Table 35. COLE values for illite samples.

Sample #	Rep.	SAR 0	SAR 10	SAR 15
8	1			
	2			
9	1	.110	.103	.086
	2	.115	.098	.090
11	1	.063	.066	.089
	2	.059	.066	.081
12	1	.088	.091	.106
	2	.086	.092	.106
18	1	.074	.096	.083
	2	.078	.079	.095

Table 36. % briquet shrinkage for illite samples.

Sample #	Rep.	SAR 10	SAR 15
8	1		
	2		
9	1	30.5	33.7
	2	30.5	32.4
11	1	27.2	23.0
	2	25.3	23.0
12	1	28.5	26.9
	2	28.5	26.9
18	1	26.3	25.1
	2	28.0	26.9

Table 37. Modulus of rupture (dynes) for illite samples.

Sample #	Rep.	SAR 10	SAR 15
8	1	18990	24520
	2	16040	25380
9	1	20980	27480
	2	23200	26300
11	1	6570	5590
	2	5950	5450
12	1	14540	20910
	2	17000	22020
18	1	14220	14320
	2	16800	14980

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