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INFLUENCE OF CLAY ON WATER MOVEMENT IN COARSE-TEXTURED SOILS

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Abstract—Effects of clay content on saturated hydraulic conductivities (k) of two coarse textured soils, Vista (mixed thermic Typic Xerochrepts) and Hanford (mixed nonacid Typic Xerorthents), and a medium textured soil, Wyo (thermic Mollic Haploxeralfs) series, were investigated. The clay and combined sand + silt fraction extracted from each of the soils were mixed with the respective soils to yield mixtures ranging from 0% clay to clay levels exceeding those in the natural soils. Rates of water movement through prepared columns of the mixtures were compared to rates through unfractionated soils.

Hydraulic conductivities for unfractionated soil and prepared mixtures were high for the Vista (maximum k = 100) compared with the Hanford (maximum k = 30) and Wyo (maximum k = 20) samples. These conductivities suggest that the relatively even distribution of particles among fractions of sand, silt, and clay gave rise to a greater proportion of larger conducting pores in the Vista sample, whereas the preponderance of particles in the fine sand and very fine sand and coarse silt fractions of the Hanford soil and in the medium silt or fine silt and clay fractions of the Wyo soil limited the proportions of larger conducting pores. Marked differences in k were measured for mixed-fraction systems for all soils. The largest k values for the Hanford soil were from systems containing proportions of the different size fractions similar to that of the natural soil. The highest k values for the Vista soil were from systems containing a clay content slightly less than or greater than that of the natural soil. Additions of clay to Wyo soil increased k values.

Key Words—Clay fraction, Hydraulic conductivity, Particle size, Soil, Water movement.

INTRODUCTION

Many soils in the Central Valley of California are anomalous in that they permit moderately slow to extremely slow water movement, even though they are relatively coarse textured. The slow water movement, among other factors, results in reduced yield and vigor in plant growth, due to water stress from inadequate irrigation, excessive runoff of applied waters, inadequate leaching of salts, inadequate movement into the crop root zone of surface-applied fertilizers and soil amendments, water logging, and increased susceptibility to pests and disease.

The present investigation was designed to test the hypothesis that the slow rate of water movement in the soils in question is a consequence of one or a combination of factors associated with particle-size distribution, orientation and packing density of coarse-grained mineral particles, swelling and/or dispersion of relatively small quantities of non-aggregated interstitial clay, and the quality of irrigation water used. The objectives of this initial phase of this investigation were: (1) to characterize chemically and mineralogically three soils having a history of slow water movement; (2) to prepare texturally modified samples of problem soils using natural soil clay as the principal variable; and (3) to determine, with laboratory columns and with water of the same or similar composition as natural irrigation water, the saturated hydraulic conductivity (k) of the soil samples.

The effect of clay on the k value of soils is generally measured by adding standard clay minerals to the soils in question. As shown by Mingelgrin *et al.* (1978), using standard clays, different results may be expected depending on the history of the clay and, in particular, how it is ground. In the present study, natural clays, sands, and silts were extracted from the respective soils and used to modify the textures of the natural soils.

MATERIALS AND METHODS

Three soils, each with a history of slow water infiltration and/or percolation, were selected. Two were relatively coarse textured and formed from Sierra Nevada granitic parent materials on the east side of the San Joaquin Valley, California. The third soil had a medium texture and a relatively high silt content and formed from meta-sedimentary parent materials in the central portion of the Sacramento Valley, California. The properties and location of the soils are listed in Table 1.

For the purposes of this investigation, samples of surface horizons of each of the soils were collected. The Wyo soil was included with the coarse-textured granitic

Table 1. Starting materials.

Soil series	Classification	Parent material	Location
Vista	Coarse-loamy, mixed, thermic Typic Xerochrepts	Quartz diorite	Lindcove Field Station, Tulare County, California
Hanford	Coarse-loamy, mixed, nonacid, thermic Typic Xerorthents	Granitic alluvium	Kearney Agricultural Center, Fresno County, California
Wyo	Fine-loamy, mixed, thermic Mollic Haploxeralfs	Meta-sedimentary alluvium	Glenn County, California

Vista and Hanford soils because of its relatively high silt content.

Natural waters used for irrigation at each of the field locations were collected for use in laboratory column studies of k.

Characterization analysis

The soils and waters were characterized by standard laboratory methods. The soil properties included particle size data by the pipet method of Kilmer and Alexander (1949). The pH of the saturated soil paste and the electrical conductivity of the extracted solution were measured according to the procedures listed in Agricultural Handbook No. 60 U.S. Dept. of Agriculture (1954), and Na, K, Mg, and Ca were determined in saturation extract by atomic absorption spectroscopy. The cation-exchange capacity of the soils were measured by the Bower *et al.* (1952) method, and the organic carbon content was determined by Walkley's (1947) method. In the irrigation waters used for the conductivity measurements, the pH, the electrical conductivities, and the cations and anions were determined by the methods mentioned for the soils.

Mineralogical analyses

Mineral species in soil clay fractions (<2 μm) were identified with a Diano XRD-8000 x-ray powder diffractometer by procedures described by Whittig and Allardice (1986). The amounts of particular mineral species were estimated by species-specific chemical methods outlined by Jackson (1969). Total Na, K, and Ca analyses, necessary for quantitative allocations of feldspars and mica in the soil fractions, were performed on samples following HF dissolution (Silberman and Fisher, 1979). The kaolinite percentage was estimated by differential thermal analysis (DTA) (Barshad, 1952).

Preparation of soil columns

The suppositions that particle-size distribution and particle-packing density are influential factors in regulating the rate of water movement in the selected soils prompted the design of soil mineral systems containing different quantities of natural soil size-fractions for the k studies. Thus, large quantities of clay (< 2 μm) and of sand + silt (2 mm – 2 μm) were obtained from samples of each of the soils under consideration. To minimize chemical changes during dispersion and fractionation, no chemical treatments were employed during the processes. The soils, in suspensions, were dispersed by ultrasonic vibration (Busacca *et al.*, 1984), and the clay fraction was separated from the sand + silt fractions by sedimentation and decantation (Jackson, 1969). The separated fractions were freeze dried. A series of soil mixtures containing different proportions of size fractions were prepared by adding separated clay or sand + silt to samples of unsegregated soils. Each mixture was tumbled for 30 min in a rotating cylinder to ensure uniform mixing of materials.

Soil columns for the k measurements were prepared using 5-cm diameter, 10-cm long Plexiglas cylinders. The bottom of each cylinder was fitted with a rubber stopper and glass access tube. A 1-cm layer of quartz sand was placed in the bottom of each cylinder, and a 100-g sample of soil mixture was positioned on top of the sand layer. All soil mixtures were adjusted to 4-cm height to effect uniformity in density of materials. Columns were completed by placing a 1-cm layer of quartz sand over the soil mixtures and closing the tops with a vented rubber stopper.

Prior to measurements of k, the soil mixtures were saturated and the spaces above the mixtures were filled by allowing water to enter through the bottoms of the columns at a very slow, controlled rate. Difficulties were encountered in some experiments in saturating the soil columns without disturbing the soil mixtures. If such difficulties were evident, the columns were discarded.

Special care was taken to pack all the columns to the same bulk density. The bulk density of the columns containing the mixtures was only 1.27 kg/m^3. Consequently, the columns containing the natural soils had to be packed less densely than normal to conform to this value.

Hydraulic conductivity measurements

Filtered natural irrigation waters, collected at each field location, were used for k measurements. Hydraulic conductivities were also determined for each natural soil using distilled water and saturated gypsum solutions.

Table 2. Analysis of variance results on the final values for k values for the respective soils.[1]

Wyo clay (%)	k (after 2 liters)	Wyo clay (%)	k (after 10 pore volumes)
33	1.1ab	23	7.5a
28	15.5a	22	4.2a
23	4.9ab	21	0.9a
0	1.1b	11.5	0.7a
		0	4.9a
Wyo treatment	k (after 2 liters)		
Gypsum	46.5a		
Distilled	0.6b		
Irrig. 0%	1.3b		
Irrig. 23%	4.9b		
Hanford clay (%)	k (after 2 liters)	Hanford treatment	k (after 2 liters)
14	7.6d	Gypsum	28.2a
12	13.1bcd	Distilled	12.9ab
10	15.5abcd	Irrig. 0%	5.8b
8	16.7abcd	Irrig. 8%	18.0ab
7.8	20.3a		
7.7	16.8ab		
7.5	10.8bcd		
1	7.2d		
0	5.9d		
Vista clay (%)	k (after 2 liters)	Vista treatment	k (after 2 liters)
17	80.4bc	Gypsum	28.2a
13	54.8bc	Distilled	12.9ab
12.5	165.8a	Irrig. 0%	5.8b
6.5	60.6bc	Irrig. 8%	18.0ab
0	15.9c		

[1] Mean values followed by different letters are statistically significant at the 10% level of probability.

Data followed by the same letter are not significantly different at the 5% confidence level.

Water delivery tubes were connected to inlets at the top of water-filled columns at the beginning of the measurement of k. Care was exercised to avoid air bubbles in the delivery lines and disturbance of soil by water entry. Water deliveries from 2-liter Mariotte bottles were controlled, and constant 10-cm heads were maintained throughout the measurements. Water passing through the columns was collected in test tubes by means of a time-controlled fraction collector. Some measurements were terminated if 10 pore volume had passed through the soil columns, due to very slow rates of water movement; for most experiments, however, the measurements were continued until two liters of water had passed through the columns.

Two to five replicates of hydraulic conductivity were made for each natural soil and prepared mixture. Hydraulic conductivity values were calculated for each incremental period of effluent collection.

Statistical treatment of hydraulic conductivity data

Hydraulic conductivity values for replicates of each natural soil or soil mixture, respectively, were pooled. A second-order polynomial regression was determined for each sample and plotted to represent each soil or mixture. For all experiments, with the exception of systems measured with saturated gypsum solutions, k values were at or very near the steady state at the end of the measurements. An analysis of the variance on the final k-values for respective soils was performed, the results of which are given in Table 2.

RESULTS

Soil physical and chemical characteristics

Differences in textural characteristics of the three soils are shown by the data in Table 3. The coarse texture of the Vista soil is confirmed by the very high sand content (70.4%). Even though dominated by sand, the particles were more evenly distributed among the particle-size ranges in the Vista soil than in the Hanford and Wyo soils. Both the Hanford and Wyo soils had relatively high proportions of particles in intermediate size ranges. In both the Hanford and Wyo soils, 74% of mineral particles occurred in the silt, very fine sand, and fine-sand fractions. The 25.3% clay in the Wyo soil contrasts with the relatively small clay content of the Hanford and Vista soils.

Soil and water chemical characteristics

The Hanford and Vista soils are chemically similar (Table 4); they have low contents of organic carbon and soluble ions, and Ca is the dominant exchangeable

Table 3. Particle-size distribution in soil samples.

	Sand (%)						Silt (%)			
	v.c.	c	med	fine	v. fine		c	med & fine		Clay (%)
Size (mm)	2–1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	Total	0.05–0.02	0.02–0.002	Total	$<2\ \mu m$
Hanford	0.6	7.4	8.2	17.9	11.4	45.5	29.9	16.9	44.8	9.7
Vista	18.6	18.3	10.3	17.1	6.1	70.4	8.6	9.1	17.7	11.7
Wyo[1]	0.0	0.1	1.1	11.0	10.0	22.2	17.1	35.4	52.5	25.3

[1] Data provided by M. J. Singer, Land, Air, and Water Resources Department, University of California, Davis, California. v.c. = very coarse; c = coarse; med = medium; fine = fine; v.fine = very fine.

Table 4. Chemical properties of soil samples.

Soil	pH	Organic carbon (%)	EC	Soluble Ca	Soluble Mg	Soluble K	Soluble Na	Exchangeable Ca	Exchangeable Mg	Exchangeable K	Exchangeable Na	CEC
			(mmho/cm)	(meq/100 g)				(meq/100 g)				
Hanford	7.8	0.49	0.9	0.1	<0.1	0.2	0.1	6.8	1.9	0.3	<0.1	8.0
Vista	6.5	0.63	0.7	0.1	<0.1	<0.1	<0.1	7.3	1.7	0.4	<0.1	11.0
Wyo[1]	7.0	2.12	0.7	0.2	0.1	<0.1	<0.1	11.9	3.5	0.8	0.2	20.0

[1] Data provided by M. J. Singer, Land, Air, and Water Resources Department, University of California, Davis, California.

cation in each. The Wyo soil, similarly, has a low content of soluble ions, and the exchange complex is dominated by Ca. The organic carbon content and the cation-exchange capacity of the Wyo soil are relatively high, however, compared with the Hanford and Vista soils. The cation-exchange capacities of the three soils are consistent with the clay contents. The three waters used for hydraulic conductivity measurements all contained low levels of soluble ions (Table 5).

Mineralogy of clay fractions

As revealed by X-ray powder diffraction (XRD) analyses, expandable phyllosilicates were major components of the clay fractions of two of the soils. Qualitative estimates of the XRD patterns indicate that expandable smectite was dominant and that vermiculite and mica were present in smaller quantities in each soil. The clay fraction of the Wyo soil also contained an appreciable quantity of chlorite.

The partial quantitative analyses of the clay mineralogy (Table 6) show that the mica content was about the same in the three soils and that the kaolinite content was greatest in the Vista soil. Clay fractions of all the soils also contained quartz, feldspars, and noncrystalline components. They were identified by X-ray powder diffraction and chemical methods (Jackson, 1956). Thus, Hanford and Wyo soils contained smectite-vermiculite clays, whereas the Vista soil contained a kaolinite-mica clay.

Hydraulic conductivity measurements

Saturated hydraulic conductivities were determined for several prepared soil columns over a period of many months. In this report, only data obtained over the full period of study are listed.

The rates of movement of saturated gypsum solution, natural irrigation water, and distilled water through the three unfractionated soils are shown in Figure 1. In general, movements of solutions through the Vista soil, containing a clay fraction having the least smectite-vermiculite, were relatively rapid (k = 100). Movements through the Hanford and Wyo soils, both rich in expandable clays, were slow ($k < 30$) and very slow ($k < 20$), respectively. For each soil, k was greatest for the saturated gypsum solution and lowest for the distilled water. The k values obtained with the gypsum solution progressively increased over the period of measurement for the three soils. The k values using distilled water remained nearly constant for the Vista soil, increased slightly for the Hanford soil, and decreased to essentially zero for the Wyo soil. The k values obtained using natural irrigation water, although generally greater than for the distilled water, showed patterns of change similar to that for the distilled water for the Hanford and Wyo soils. For the Vista soil, the initially very large k values using irrigation water decreased markedly during the period of measurement and attained the same value as for the distilled water at the end of the period.

Also shown in Figure 1 are k values obtained for sand + silt (0%) extracted from each soil, using natural irrigation waters. The k values for sand + silt from the Vista and Hanford soils were considerably lower for the unfractionated soils, whereas the k values for the sand + silt were very nearly the same for the Wyo soil. Relatively little change in k was recorded for the sand + silt in any experiment over the period of measurement.

Hydraulic conductivity data for prepared mixtures of clay and sand + silt for the three soils are plotted

Table 5. Composition of irrigation waters.

Water site	pH	EC	Soluble ions Ca	Mg	K	Na	Cl	CO_3	HCO_3	SO_4	NO_3
		(mmho/cm)	meq/100 g								
Hanford	7.5	0.29	1.3	1.0	0.1	0.7	0.3	—	2.4	0.2	1.8
Vista	7.6	0.28	1.0	0.5	<0.1	1.1	0.9	—	1.7	0.2	1.1
Wyo	7.4	0.39	1.5	1.4	<0.1	1.0	0.6	—	3.2	0.1	1.3

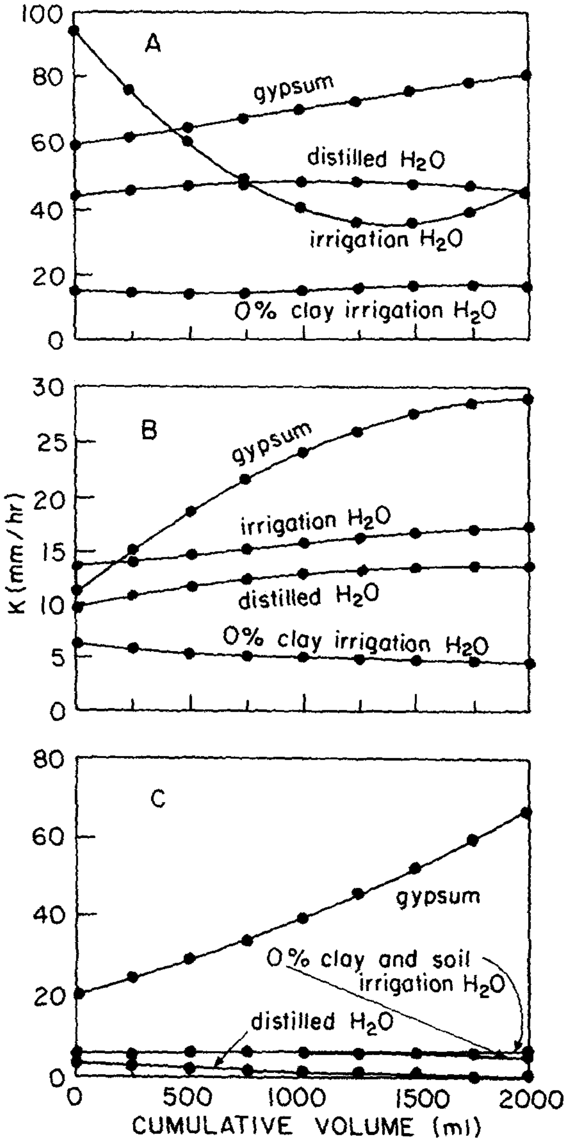

Figure 1. Second-order polynomial regression plots of saturated hydraulic conductivities (k) of unfractionated soils and of separated sand + silt fractions vs. time with a saturated gypsum solution, distilled water, or natural irrigation water. (A) Vista soil (Typic Xerochrepts); (B) Hanford soil (Typic Xerorthents); (C) Wyo soil (Mollic haploxeralfs).

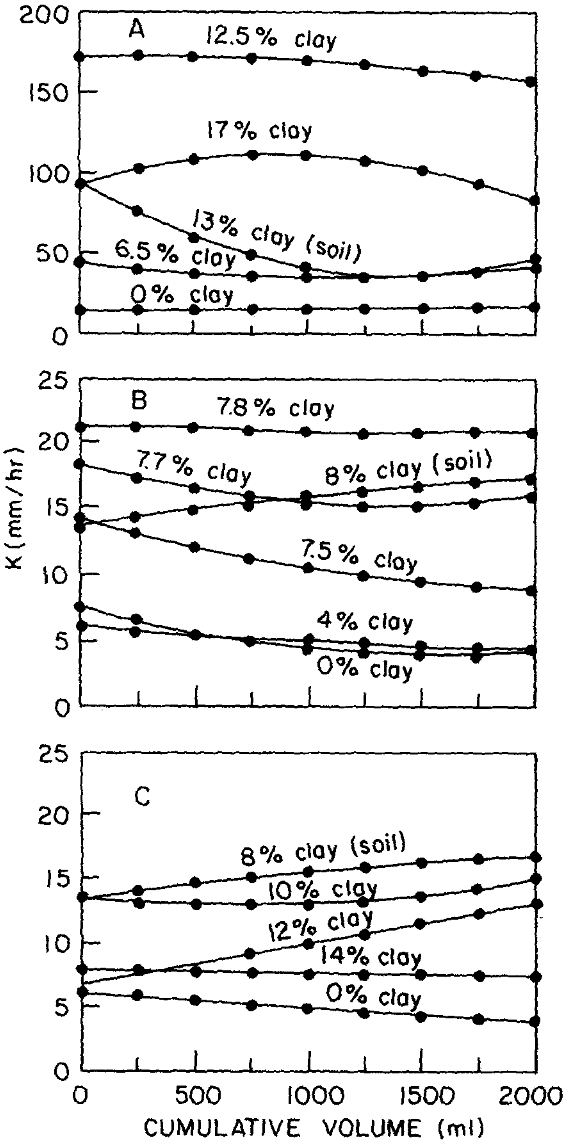

Figure 2. (A) Second-order polynominal regression plots of saturated hydraulic conductivities (k) of Vista soil containing different proportions of clay or sand + silt added to the soil. (Different percentages of clay.) (B) Hanford soil system containing different proportions of sand + silt (2–0.002 mm) added to the soil. (C) Hanford soil system containing different proportions of clay (<2 μm) added to the soil.

in Figures 2 and 3. Data for the natural unfractionated soils and for separated sand + silt are also included for comparison. All data were obtained using natural irrigation waters.

Despite the variability among replicates for some of the systems, certain trends are apparent. For the Vista soil (Figure 2A), mixtures having a small clay content (6.5% and 0%) yielded the lowest k, although the values for the 6.5% clay system were nearly the same as those for the natural soil toward the end of the measurement period. The mixtures having 17% clay (4% more than the natural soil) gave greater k values than for the unfractionated soil. The greatest k values, however, were obtained from the Vista soil mixture having a clay content reduced to 12.5% by addition of 4% sand + silt to the unfractionated soils.

For the Hanford soil mixtures (Figure 2B), a progressive decrease in k was noted for systems having the greatest clay contents (10%, 12%, and 14%) and

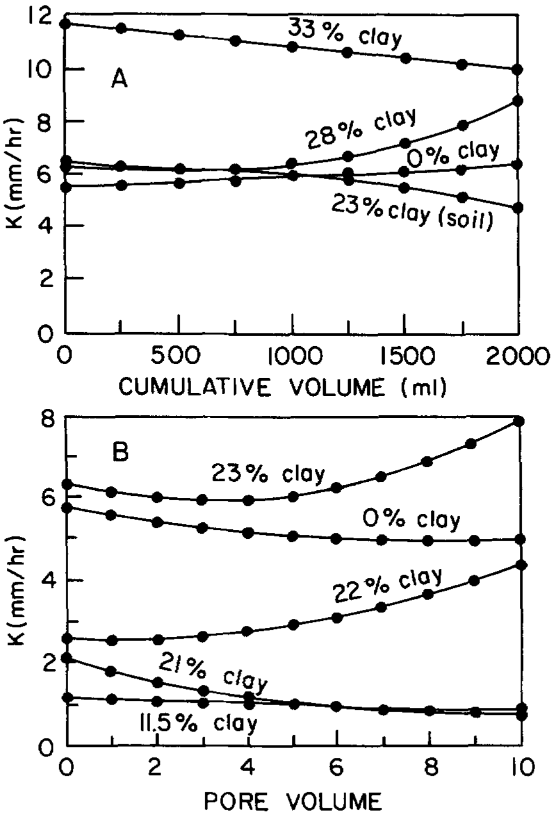

Figure 3. Second-order polynominal regression plots of saturated hydraulic conductivities (k) of Wyo soil systems containing different proportions of clay and sand + silt. (A) Systems having clay (<2 μm) added to the soil. (B) Systems having sand-silt added to the soil (through 10 pore volumes only).

for systems containing 7.7%, 7.5%, and 4% clay, compared with the unfractionated soil (8%) clay). The greatest k values were obtained for the Hanford soil systems having a clay content reduced to 7.8% by addition of 2% sand + silt to the unfractionated soil.

The Wyo soils systems (Figure 3) were the most difficult to work with due to the very slow rates of water movement. For this reason, only a few systems were continued for a time sufficient for passage of two liters of solution through the columns. The limited data for the Wyo systems suggest, however, that additions of clay to the 28% and 33% levels (i.e., in excess of the 23% clay in the unfractionated soil) increased k. The Wyo systems in which clay was removed (0% clay), however, yielded k values similar to those for the natural soil. Wyo systems having clay contents less than those of the unfractionated soil yielded progressively lower k (measured through 10 pore volumes) as the clay content was decreased.

Table 6. Mineral content of soil clay fractions.

Soil	Quartz and feldspars[1]	Kaolinite[2]	Mica[3]	KOH-soluble components[1]	Other[4]
			%		
Hanford	16	5	18	9	52
Vista	15	36	20	11	18
Wyo	10	29	18	5	38

[1] Noncrystalline silica, alumina and/or aluminosilicates. Method of Jackson (1956).

[2] Estimated by differential thermal analyses.

[3] Determined by chemical method average of duplicate analyses. Method of Jackson (1969).

[4] Dominantly expandable phylosilicates (smectite, vermiculite); by x-ray powder diffraction.

DISCUSSION AND CONCLUSIONS

The Vista soil and fraction mixtures (Figure 2A) consistently yielded relatively high k, compared with the Hanford (Figures 2b and 2c) and Wyo (Figure 3) soils. These results suggest that the relatively even distribution of particles among the fractions of sand, silt, and clay contributed to the creation of a greater proportion of larger conducting pores in the Vista soil or, conversely, that the preponderance of mineral particles in the fine sand, very fine sand, and coarse silt fractions of the Hanford soil and in the medium-silt, fine-silt, and clay fractions of the Wyo soil limited the proportions of larger conducting pores.

The rates of movement of water through separated sand + silt fractions of the Vista and Hanford soils were very low compared with movement through the unfractionated soils, suggesting that the dominant sand and silt in these two soils formed a compact matrix, in the absence of clay, with relatively few large conducting pores. The small quantities of clay in the unfractioned Vista and Hanford soils apparently produced a less compact matrix than that created by the packing of sand and silt. Additions of sand + silt to reduce the clay content to 7.8% in the Hanford soil systems and additions of clay to the 17% level in the Vista soil systems resulted in increases in k. For the Vista soil, the highest k values were attained for the systems containing 12.5% clay. Further additions of clay (to as much as 14%) to the Hanford soil resulted in lower k values than for the unfractioned soil.

The Wyo soil systems also responded to variations in clay content. Additions of clay to more than 23% in the unfractionated soil increased k, whereas systems having a clay content less than that of unfractionated soil gave lower k values.

Thus, the k values of the Vista, Hanford, and Wyo soils were apparently conditioned by the relative proportions of mineral size fractions. From data thus far obtained, changes in clay content apparently caused significant changes in k for the three soils. The hypothesis that particle-size distribution and particle-packing densities are major factors contributing to slow water movement in these soils is strengthened by these results. The analysis of variance on the final values of k for the three soils (Table 2) shows that clay content did indeed affect k, but not for very small changes in the clay content.

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