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APPLICATION OF CHEMICAL AND ELECTRICAL PARAMETERS TO PREDICTION OF ERODIBILITY

The laboratory study of the erosive behavior of remolded soils shows that the shear stress required to initiate erosion is significantly affected by the kinds and concentration of ions in the pore and eroding fluids and types of clay minerals. The kinds and amounts of clay minerals have been shown to be described by the dielectric dispersion of saturated samples. The composition of the pore fluid is described by the electrical conductivity and sodium adsorption ratio. A method for measuring the hydraulic shear stress necessary to initiate erosion has also been developed. This paper presents experimental data that demonstrate that the shear stress required to initiate erosion depends on sodium adsorption ratio, electrical conductivity, and the magnitude of dielectric dispersion.

Problems of potential erosion are found in unprotected road cuts, drainage ditches, embankments, and other surfaces from which vegetation has been removed. Resulting erosion and waterborne sediments restrict the capacity of the drainage system, and great amounts of water are lost by seepage and channel instability. Hence, factors affecting the erodibility of soil need study in order to identify, predict, and prevent erosion.

Table 1 gives a chronological listing of research performed on the effect of soil properties on the hydraulic erosion of soils. Some results indicate that erodibility depends on the bulk properties of soil (e.g., vane shear stress and soil density), whereas other results (14) indicate that surface erosion is independent of shear strength. Partheniades and Paaswell (27) hold that vane shear strength and plastic index do not accurately convey the state of soil at the surface and therefore are poor parameters for evaluating erodibility.

A widespread incidence of subsidence and piping failures was reported by Ingles and Aitchison (18), Aitchison and Wood (19), and Sherard, Decker, and Ryka (20). Such erosion behavior in the field was correlated with the composition of the pore fluid. The types of ions in the pore fluid have been quantified in terms of sodium adsorption ratio (SAR), which is calculated as

$$SAR = [Na]/\sqrt{0.5[(Ca^{++}) + (Mg^{++})]}$$

where (Ca^{++}), for example, indicates the concentration of individual ions in milliequivalents per liter. The amount of ions in the system is expressed by the conductivity of the soil extract.

Although subsidence and piping failures of embankments and canals have been explained in terms of SAR and pore fluid concentration and numerous studies have been carried out to study the influence of various soil properties on hydraulic erosion of soils, no systematic laboratory study has been reported to determine the influences of pore and eroding fluid compositions nor of type of clay mineral on soil erodibility.

This paper summarizes available laboratory data on the influence of pore and eroding fluid compositions on the erodibility of a soil (21, 22) and presents new data on the influence of the type of clay mineral on erodibility. A possible functional relationship among the shear stress required to initiate erosion, the composition of the soils, and the types of ions in the pore fluid is discussed. The erosion mechanisms for partially saturated clays, however, may be different and are not considered in this paper.

SAMPLES FOR TESTING

Materials

Results reported in this study were obtained on a local natural soil called Yolo loam. Its composition is 46 percent sand, 35 percent silt, and 19 percent clay. X-ray analysis showed that montmorillonite, kaolinite, mica, and vermiculite were the clay minerals present. The cation exchange capacity was 19.8 meq/100 grams of soil, and the pH was 8.2. Other properties of Yolo loam are as follows:

Property	Value (percent)
$CaCO_3$	0.4
Saturation	33.9
Liquid limit	46
Plastic limit	23

The extractable cations, in meq/100 grams of soil, are Ca^{++}, 9.7; Mg^{++}, 10.6; Na^{+}, 6.2; and K^{+}, 0.3. The water soluble ions, in meq/1 saturated extract, are Ca, 1.3; Mg, 2.4; Na, 6.6; and K, 0.1.

Yolo loam particles smaller than 50μ in size were replaced by kaolinite (hydrite R), illite grundite, and montmorillonite in order to examine the effect of the type of clay mineral on erodibility.

Sample Preparation

Samples of soil of 1.5 kg were mixed in 20-liter bottles containing 10-liter solutions of various SAR and salt concentrations. Samples were agitated from time to time to facilitate equilibrium between soil and solution. For samples of very high SAR, the soil was initially equilibrated with a higher concentration of NaCl than the final concentration to displace as much adsorbed Ca and Mg as possible and then filtered and equilibrated with the proper concentration of NaCl. The samples were filtered and consolidated for 2 weeks with increasing loads up to 32 kg. The effluent from the consolidated samples was used in analyzing the concentrations of Na, Ca, and Mg. The total electrolyte concentration was determined by measuring the electrical conductivity of the effluent solution. A portion of the consolidated samples was taken for determination of moisture content.

Chemical Analyses

Concentrations of Na, Ca, and Mg in the effluent solutions were determined with a Perkin-Elmer Atomic Absorption spectrophotometer, Model 303, equipped with a digital concentration readout unit. All solutions were made up to contain 500 ppm Cs, 0.2 percent La, and 1 percent HCl as the supporting interference-suppressing electrolytes. An air-acetylene flame was used for Ca and Mg, whereas an air-propane flame was used for analysis of Na.

TESTING PROCEDURE

Erosion Measurement

The erosion apparatus used is a modification of the rotating cylinder test apparatus of Masch, Espey, and Moore (26). Cylindrical specimens, 3 in. in diameter by 4 in. long, were prepared by consolidation from slurries. The specimen was supported by a mandrel and placed concentrically in a plastic outer cylinder. A photograph and a cross section of the apparatus are shown in Figures 1 and 2. The annular space between the sample and the outer cylinder is filled with the eroding fluid, which in this study is distilled water. The outer cylinder is then rotated at a uniform speed for a measured time, and the shear stress τ on the surface of the sample is determined by the torsional displacement of the inner cylinder.

Erosion was determined from the difference in weight before and after the applied stress. Fresh eroding fluid was used after each weighing. Erosion was measured after various periods at each speed of rotation (shear stress), and the erosion rate was computed from a graph of erosion versus time (Fig. 3). This was repeated at increasing speeds of rotation to determine erosion rates for different shear stresses. The relation between erosion rate and shear stress obtained on samples of Yolo loam is shown in Figure 4. This figure shows that the data do fit a linear relationship, suggesting that the eroding mechanism is the same over the range of applied stresses. Figure 5 shows specimens before and after erosion.

The shear stress required for zero erosion rate, which is the intercept on the applied shear axis, is defined as the critical shear stress τ_0.

Method of Measuring the Type and Amount of Clay Minerals

A method of describing the amount and type of clay without destroying the soil sample has been developed in our laboratory (23, 24). This method makes use of the electrical properties of a soil sample, such as dielectric dispersion $\Delta\epsilon_0$. The dielectric dispersion is the difference in the dielectric constant measured at, say, about 10^6 and 10^8 Hz. Dielectric constants of various clay-sand mixtures and various clay types are shown in Figures 6 and 7. These and other data show that different clays and different sand-clay mixtures have different amounts of dielectric dispersion in the frequency range at which the measurements were carried out. It has also been shown that the dielectric dispersion is nearly independent of the water content of the sample as shown in Table 2. Table 3 shows that $\Delta\epsilon_0$ is a function of the amount of clay and type of clay.

RESULTS OF EROSION MEASUREMENTS

Effect of the Type and Amount of Sorbed Ion on Erodibility

The critical shear stresses obtained from the intercepts of plots such as that shown in Figure 4 are shown in Figure 8. Figure 8 shows the effects of both the salt concentration in the pore fluid and the SAR on the shear stress required to initiate erosion of Yolo loam when distilled water was used as the eroding fluid. A detailed study of this nature might yield a relationship of the form $\tau_0 = f(\text{SAR}, \sigma_p)$, where σ_p is the conductivity of the pore fluid (a measure of the salt concentration).

Data shown in Figure 8 indicate that τ_0 increases with a decrease in SAR of the salt concentrations of the pore fluid studied. Further, τ_0 increases with increased salt concentration in the pore fluid at any SAR. These effects are expected if one considers the degree of flocculation of the soil. As SAR increases or total salt concentration in the pore fluid decreases, soil flocculation decreases, with interparticle bonds weakening and surface soil particles detaching more easily (21).

Effect of Composition of the Eroding Fluid

Figure 9 shows how the NaCl concentration of the eroding fluid affects erosion rates. The soil sample used in each case was a saturated Yolo loam having the same SAR, the same NaCl concentration in the pore fluid, and the same water content. τ_0 increased as NaCl increased in the eroding fluid. This result shows that erosion rates depend also on the composition of the eroding fluid. Hence, $\tau_0 = f(\text{SAR}, \sigma_p, \sigma_e)$, where σ_e is the conductivity of the eroding fluid. These results show that erosion also depends on the osmotic pressure gradient between the pore and eroding fluids.

The effects of the amount and types of ions in the pore and eroding fluids on erosion are discussed further elsewhere (21).

Table 1. Research performed on the effect of soil properties on hydraulic erosion of soils.

Investigator	Soil Properties Studied
Lutz (1)	Physical properties of soils that affect permeability and dispersion
Anderson (2)	Dispersion ratio
Sundborg (3)	Particle size
Dunn (4)	Vane shear strength
Smerdon and Beasley (5)	Plasticity index, dispersion ratio, mean particle size, percentage of clay
Laflen and Beasley (6)	Effect of compaction-void ratio
Moore and Masch (7)	Scour index (as function of Reynolds number)
Partheniades (14)	Surface erosion independent of shear strength
Flaxman (9)	Unconfined compressive strength
Carlson and Enger (10)	Vane shear strength, plasticity index, soil density
Abdel-Rahman (8)	Plasticity index, dispersion ratio, particle size, percentage of clay
Rektorik (12)	Moisture content at compaction, vane shear strength, void ratio exchangeable calcium-sodium ratio
Berghager and Ladd (13)	Effect of cohesive intercept (shear strength for zero effective normal stress at failure)
Grissinger (15)	Bulk density, temperature, antecedent water, type of clay, orientation of clay materials
Mirtskhulava (16)	Eroded aggregate size, cohesive force, effect of water weight on particle
Liou (17)	Influence of electrolyte concentration, pH, and temperature on hydraulic erodibility of pure clays

Figure 1. Rotating cylinder erosion test apparatus.

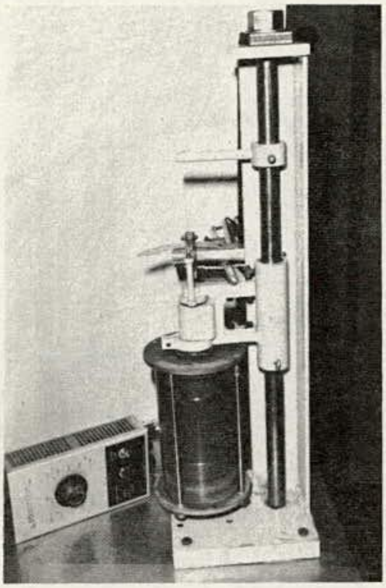


Figure 2. Cross-sectional view of the rotating cylinder test apparatus.

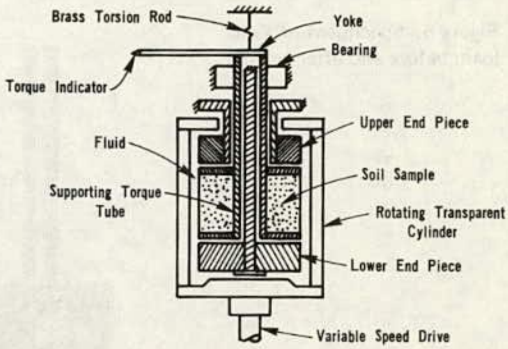


Figure 3. Relationship between erosion and time at different speeds of rotation (Yolo loam, 0.006N, SAR = 1.6).

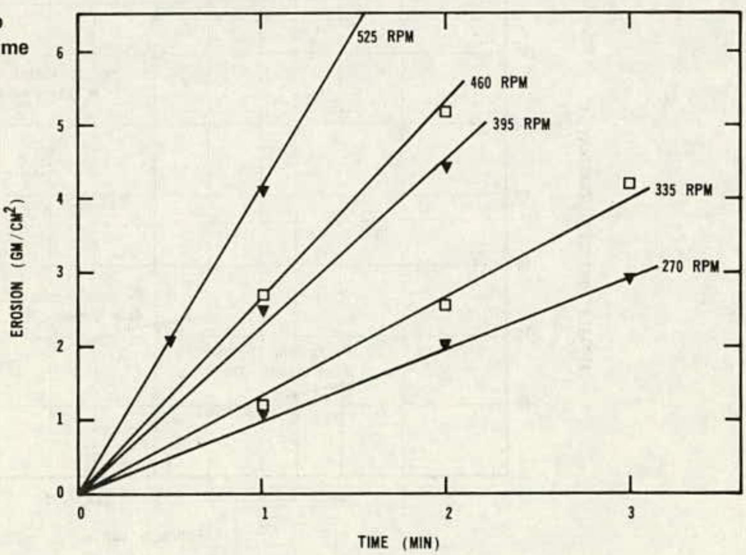


Figure 4. Relationship between erosion rate and shear stress for different SAR (Yolo loam, ~0.1N, water content ≈28 percent).

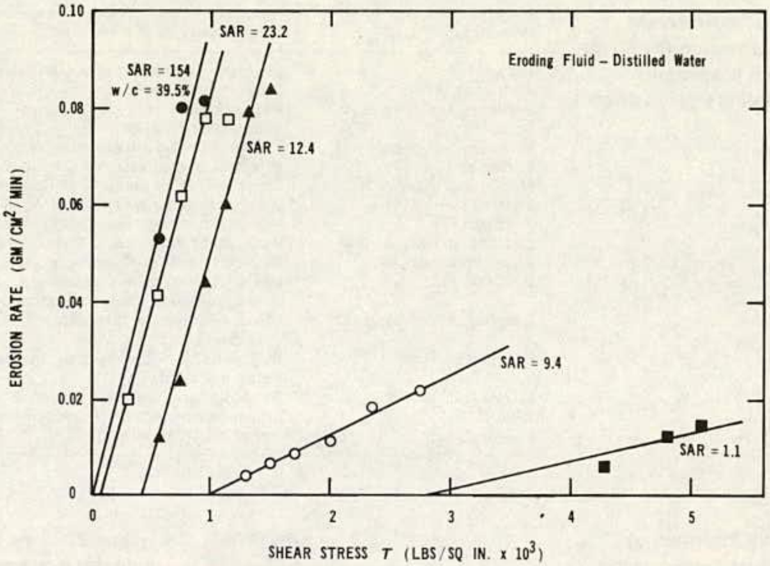


Figure 5. Specimens of Yolo loam before and after erosion.

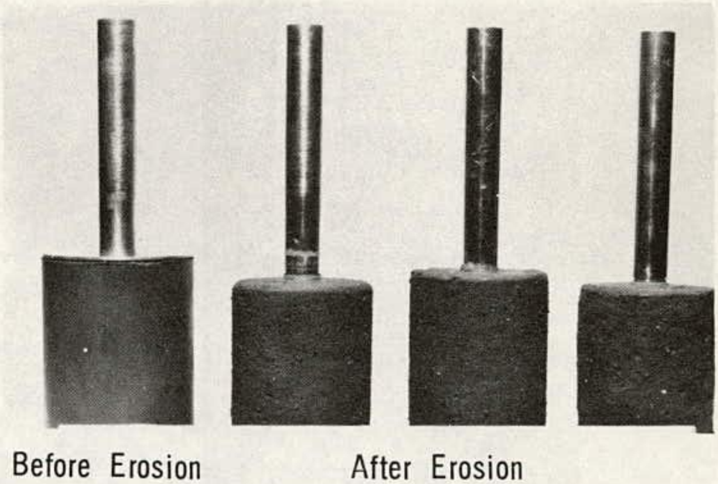


Figure 6. Effect of clay type on electrical dispersion.

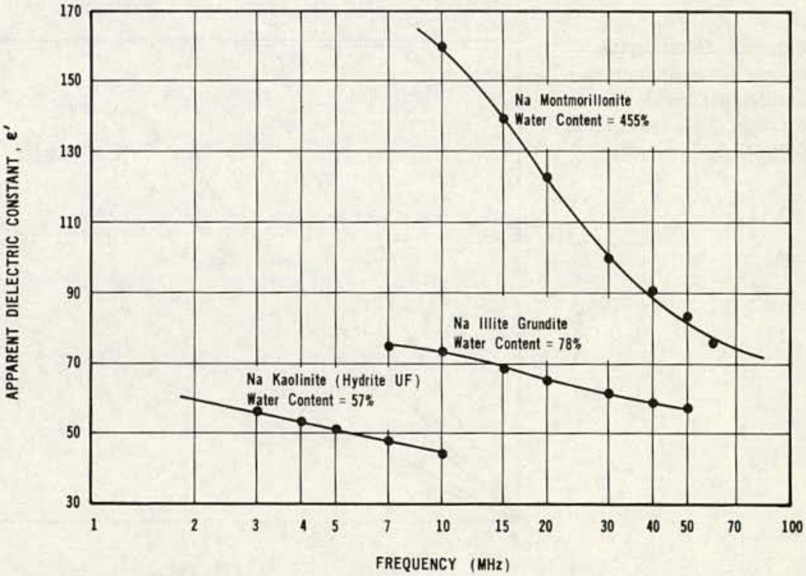


Figure 7. Effect of clay content on dielectric dispersion of illite grundite.

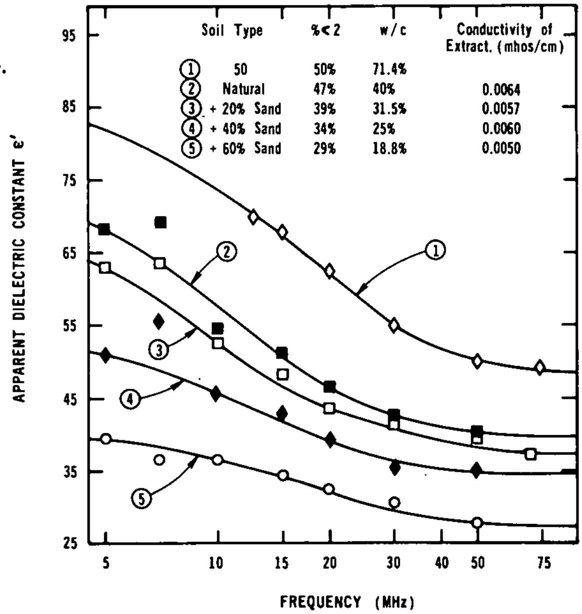


Table 2. Effect of water content on dielectric dispersion.

Soil Type	Water Content (percent)	$\Delta\epsilon_o$
Montmorillonite	260.0	127.0
	361.0	128.0
	455.0	112.0
Illite grundite	48.6	24.0
	52.0	26.0
	78.0	25.0
Kaolin UF	51.2	16.0
	81.0	17.5
	80.2	14.5

Table 3. Effect of type and amount of clay on dielectric dispersion.

Soil Type	Water Content (percent)	$\Delta\epsilon_o$	Percentage of Clay
Montmorillonite plus sand	260.0	123	100
	230.0	103	80
	255.0	98	60
	182.0	57	20
Illite grundite plus sand	40.0	30	47
	31.5	27	39
	25.0	17	34
	18.8	12	29
Kaolin UF plus sand	70.0	14	100
	45.0	4	80
	39.3	5	60
	35.4	8	50

Figure 8. Relationship between critical shear stress and SAR for different concentrations of Yolo loam.

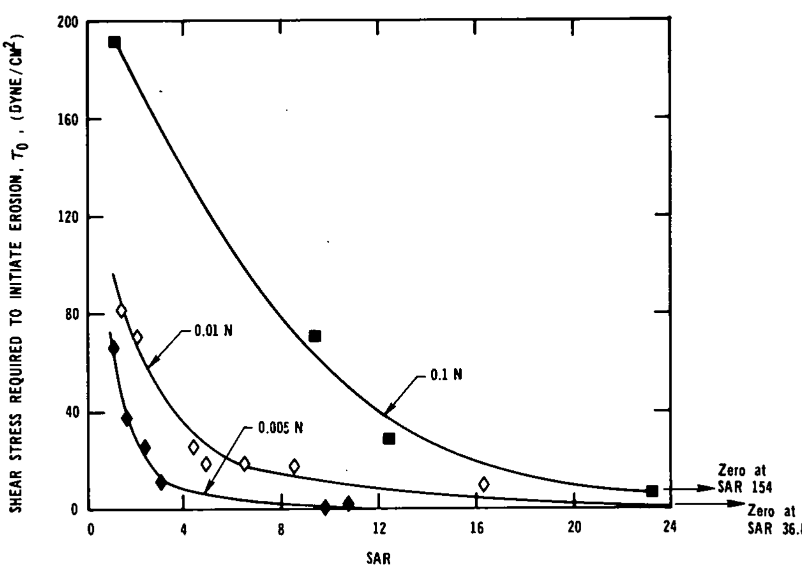


Figure 9. Relationship between erosion rate and shear stress for different concentrations of eroding fluid (Yolo loam, SAR ≈35, σ = 2.0 mmho/cm, pore fluid = 0.02N, water content = 40 percent).

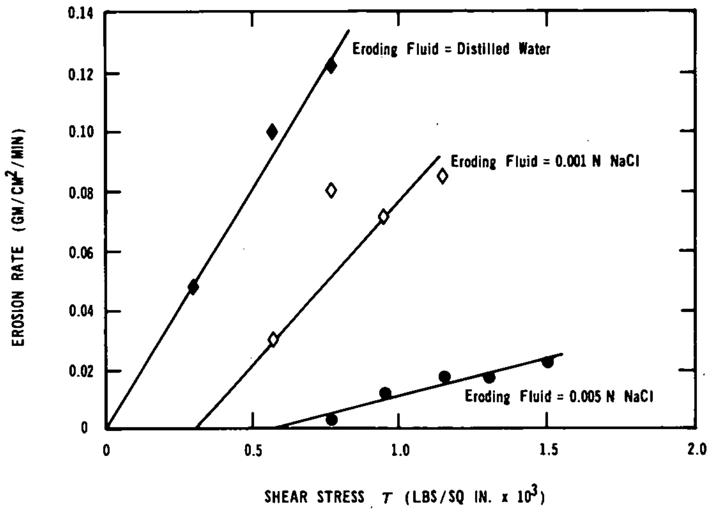


Figure 10. Effect of clay type on dielectric dispersion.

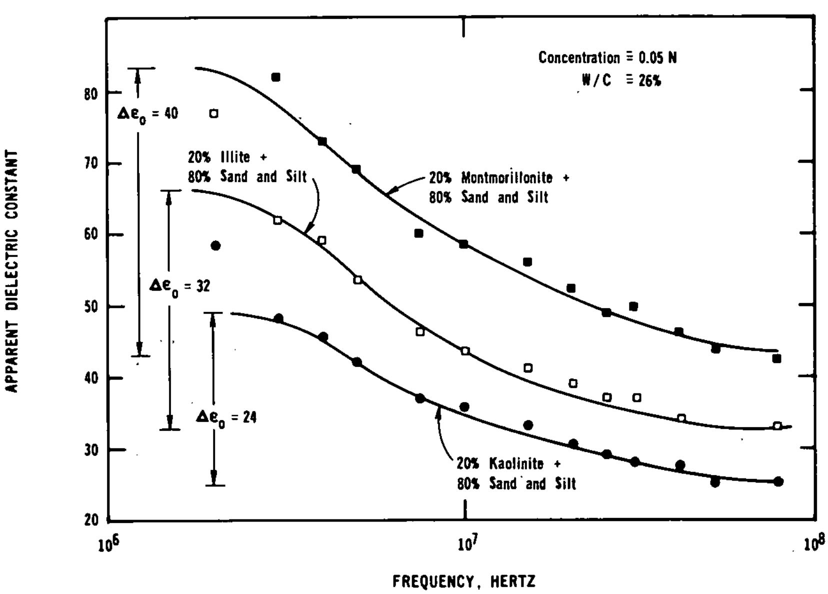


Figure 11. Relationship between τ_o and SAR for different clay types.

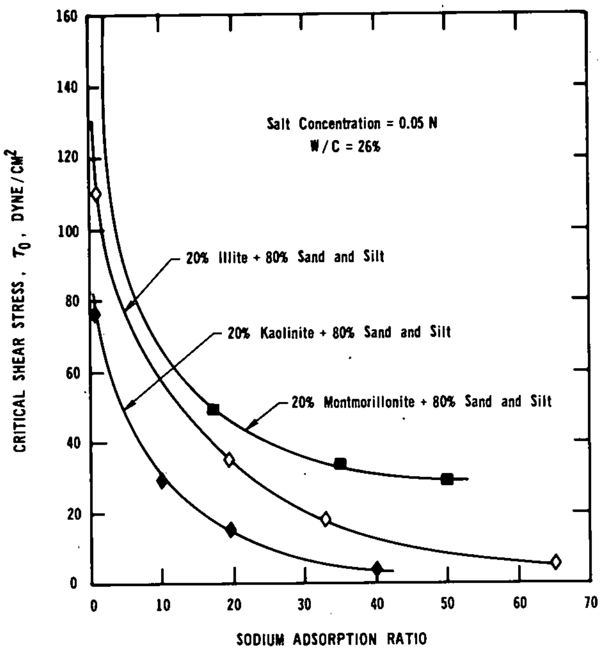
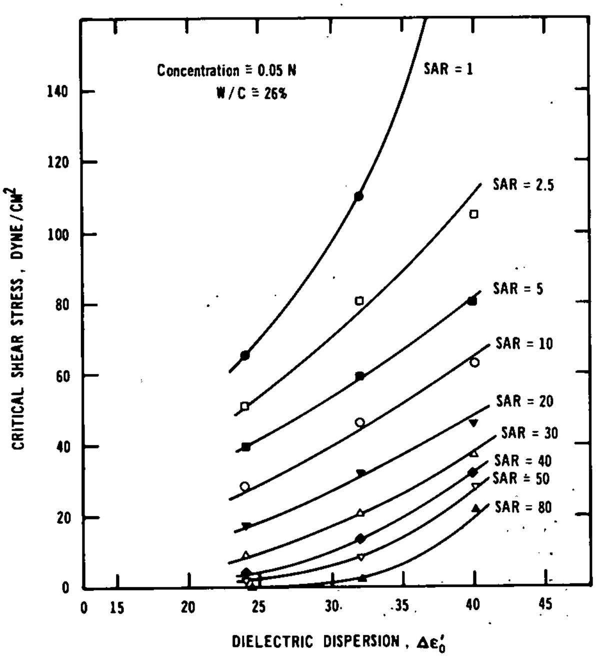


Figure 12. Relationship between dielectric dispersion and critical shear stress as a function of SAR at one typical concentration.



Effect of the Type of Clay Mineral on Erodibility

The type and amount of clay minerals, structure, and particle orientation can be characterized by electrical properties (24) as indicated by the results shown in Figure 6. The magnitude of dielectric dispersion $\Delta\epsilon_0$ for the kaolinitic, illitic, and montmorillonitic clays used in this study are 24, 32, and 40 respectively (Fig. 10). The magnitude of dielectric dispersion is a measure of the average compositional and environmental property of clay-water-electrolyte system, which can be used to characterize a soil without destroying or separating the soil mass into different sizes. Existing methods such as the use of plasticity index or activity or both cannot, however, evaluate the average compositional and environmental property of consolidated intact or undisturbed soils.

The results shown in Figure 11 demonstrate the effect of SAR on the shear stress required to initiate erosion (τ_0) for the three different types of clays at a water content of 25 percent and concentration of pore fluid of 0.05 N. The results show that a highly swelling montmorillonitic clay at a given SAR and concentration and at this composition is less erodible than an illitic or kaolinitic clay.

Relationship Between Dielectric Dispersion, Sodium Adsorption Ratio, and Critical Shear Stress

A quantitative evaluation of the type and amount of clay is made in terms of the electrical parameter, $\Delta\epsilon_0$; the type of ions in the pore fluid is determined by SAR; and the value of τ_0 is determined from erosion measurements. The relationship between SAR, τ_0, and $\Delta\epsilon_0$ for a given water content and concentration of pore fluid is shown for the three clays in Figure 12. The results show that, as the value of $\Delta\epsilon_0$ increases and SAR decreases, the resistance to erosion increases at a given concentration of the pore fluid.

The results presented in Figures 8 and 9 show that the concentration of electrolyte in the pore and the eroding fluids will have significant influence on the results shown in Figure 12. The effect of the most important parameters on erodibility has been shown by the data presented, and it would appear that a nomograph that could be used to predict the erodibility of a soil based on SAR, $\Delta\epsilon_0$, conductivity of pore fluid σ_p, and conductivity of eroding fluid σ_e could be developed.

CONCLUSIONS

The erosive behavior of consolidated cohesive soils was studied. It was found that both the types and concentrations of ions in the pore and eroding fluids and types of clay minerals have dominant effects on soil erosion.

The types and amount of clay minerals and soil structure can be determined by dielectric dispersion measurements; the type and amount of pore and eroding fluid compositions can be determined by SAR and electrical conductivity. Functional relationships between τ_0 and $\Delta\epsilon_0$, SAR, σ_p, and σ_e are currently sought in order to develop a nomograph for prediction of erodibility of soils and also for use in model analysis of erodible areas.

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