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RELATION BETWEEN SWELLING AND ERODIBILITY OF COHESIVE SOILS[1]

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Abstract – Swelling of the soils containing clay minerals mixed with silica flour were determined as a function of pore fluid composition. For this purpose, portions of consolidated samples were trimmed into sections about 2–4 mm thick with areas of 6–8 cm^2. Duplicate sections were then placed on filter papers on sponges immersed in distilled water. Samples were weighed from time to time until a constant weight was reached. Swelling was expressed as grams of water uptake per 100 grams of oven-dried soil. The same samples were used to measure erosion rates. The erosion apparatus used was a rotating cylinder. Critical shear stress was obtained by measuring the erosion rate as a function of shear stress. Different types of clay minerals or the same clay under different conditions gave different magnitudes of swelling. The critical shear stress was related to the amount of swelling. Based on the results of this experiment, an empirical relationship between critical shear stress and swelling was developed.

INTRODUCTION

Problems of potential erosion are found in unprotected road cuts, drainage ditches, channels, embankments and other surfaces from which vegetation has been removed. The mechanism of surface cohesive soil erosion is basically a complex phenomenon between the structure of the soil and the nature of interaction between the pores and eroding fluids at the surface.

A recent laboratory study of the surface erosion of consolidated soils showed that the stress required to initiate erosion is significantly affected by the physico-chemical properties of the soil [3]. Among these properties, swelling of the soil was mentioned to be the most important one [10].

Any process in which water spontaneously enters a system and increases the volume of the system may be called swelling. Several proposals have been advanced to explain the forces active in swelling and the important factors influencing swelling. The main force which pushes clay particles apart at low electrolyte concentration is hydrostatic repulsive force [6, 8, 12] caused by the greater concentration of ions between the clay platelets than in the external solution. Other factors which have been shown to influence the swelling of clays are location and amount of substitution in the mineral lattices [5, 7],

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the type and amount of interlayer materials, the presence of organic acids, and the particle size and degree of crystallinity [9].

The purpose of this paper is to examine the influence of clay mineralogy and pore fluid composition on the swelling and its relation to the critical shear stress which is required to initiate erosion.

MATERIALS AND METHODS

Soils

Three kinds of artificial soils with different properties were selected. The soils were mixtures of sand, silt (silica flour) and clays. The clay mineral additives used were montmorillonite, illite and kaolinite. The montmorillonite type clay mineral was volclay bentonite (Na-form) from the American Colloid Co. The illite clay was obtained from the Illinois Clay Products Co., under the commercial name Grundite®. The kaolinite clay used was Hydrite-R® supplied by the Georgia Kaolin Co. The soils used in this experiment were mixtures of 60% by weight silica flour and 40% clays.

Sample preparation

Samples of silica flour together with clay mineral additives were mixed in 20-l. polyethylene bottles containing 10 l. of solutions of various SAR (sodium adsorption ratio) and salt concentrations. The chloride form of each cation (Na, Ca, Mg) was used. The samples were agitated from time to time to facilitate complete equilibrium between soil and solution. Samples were filtered and soil slurry was mixed to a uniform consistency and placed in a 3-in. diameter consolidation mold. The samples were consolidated with increasing load up to 0.75 g cm^{-2}. After consolidation was completed, the soil sample was ejected from the mold and trimmed to the required height. Portions of the trimmings were used for the swelling and electrical dispersion measurements.

The effluent obtained during the consolidation process was analysed for specific electrical conductivity and ionic concentration.

Swelling measurement

Portions of consolidated saturated samples were trimmed to sections of about 2–4 mm in thickness with areas of 6–8 cm^2. Duplicate sections were then placed on the sponges immersed in distilled water. A desiccator was used to prevent evaporation from the soil surface.

Samples were weighed from time to time until constant weight had been reached. Equilibrium for each concentration required approximately one week, unless dispersion became apparent. At the conclusion of water uptake, the pads were oven dried to determine the quantity of soil. Swelling results were expressed as g water uptake per 100 g oven-dried soil.

Erosion measurement

The apparatus used to measure the erosion rate as a function of shear stress on the sample was the rotating cylinder apparatus described in detail by Alizadeh and Arulanandan [1]. A cylindrical sample of soil was mounted concentrically inside a transparent cylinder that could be rotated at speeds up to 1500 rev/min. The annular space between the sample and the rotating cylinder was filled with distilled water. As a result of rotation of the outer cylinder, with the inner cylinder (soil sample) held stationary, the rotation of the fluid imparts a shear to the surface of the soil. The erosion loss was measured at each rev/min and the cumulative loss at each rev/min was determined as a function of time. Slopes of these lines yield erosion rates. The relation between erosion rate and shear stress was thus obtained. The intercept on the applied shear axis gave the critical shear stress (t_c).

Method of measuring the type and amount of clay minerals

An electrical method was used to characterize the soils. This method is based on applying an electric field to the soil-water system. A response is produced which can be measured in terms of resistance and capacitance. The measured value of capacitance can be converted into a quantity known as the dielectric constant, (ϵ_0).

When the dielectric constant of a liquid is measured as a function of frequency in the radio frequency range, it is found that ϵ does not vary [2]. When one considers a two-component system, such as the soil-water system, it is observed that current density (ratio of conductivity to dielectric constant) varies for each frequency since the ratio of conductivity to dielectric constant is different for each of the two components. Therefore, charges will be accumulated at the interface between the clay particles and the surrounding solution. Since this build-up of charges takes more time as the frequency increases, there will be less time for the charges to accumulate at the interface, and at this point, the dielectric constant becomes independent of the frequency. This change in ϵ_0 with frequency is generally referred to as electric dispersion. The total amount of decrease in measured dielectric constant is defined as the magnitude of dielectric dispersion, $\Delta\epsilon_0$. The magnitude of $\Delta\epsilon_0$ depends primarily upon the type and the amount of clay, and other factors have secondary effects [2]. In this study, dielectric dispersion was measured and used as a quantitative index for soil characterization.

Electrical properties of the samples were measured shortly after the erosion test was completed. The measurements were made over the frequency range of 10^6 and 10^8 Hz with an RX meter type 250 (Boonton Radio Corp., Division of Hewlett-Packard, N. J.). A description of the equipment and the measurement techniques are given by Arulanandan and Smith [4] and Smith [11].

RESULTS AND DISCUSSION

In order to evaluate the swelling and critical erosion stress of different soils as affected by the water phase, two variables were considered: (1) total salt concentration, and (2) sodium adsorption ratio.

The concentrations used were 0.250, 0.125, 0.050 and 0.005 N, where N refers to the normality of pore fluid. At any concentration, various SAR (from 1 to 100) were used. The critical shear stress and swelling were measured for each sample. The results are shown in Tables 1, 2 and 3.

The results show that soils with high concentrations of ions in the pore fluid did not swell except at very high values of SAR, while at low concentration the lower water uptake (swelling) is high and independent of SAR. The results also show that, in general, the critical shear stress increases with increasing salt concentration or decreasing SAR.

Table 1. Effect of pore fluid composition on swelling and critical shear stress of montmorillonitic soils (40% clay content)

Concentration (m equiv/l.)	SAR	Water uptake (g/100 g)	t_c (dyne/cm^2)
250	21.0	98	13.2
250	35.0	135	8.4
250	74.0	295	7.8
125	4.0	15	28.4
125	27.0	150	7.6
125	45.5	248	4.0
125	92.0	302	0.6
50	4.6	21	24.6
50	36.0	203	4.0
50	48.0	330	1.6
50	85.0	362	0.0
5	2.8	273	5.0
5	25.0	350	0.8
5	48.0	384	0.0
5	89.0	395	0.0

Table 2. Effect of pore fluid composition on swelling and critical shear stress of illitic soils (40% clay content)

Concentration (m equiv/l.)	SAR	Water uptake (g/100 g)	t_c (dyne/cm^2)
250	2.0	11	27.8
250	50.0	17	12.6
250	52.0	22	7.4
250	70.0	30	6.8
125	3.5	13	24.0
125	25.0	22	7.0
125	46.0	28	4.0
125	77.0	29	1.4
50	4.5	15	19.8
50	20.0	25	4.0
50	44.0	28	1.6
50	88.0	30	0.4
5	2.3	25	4.8
5	25.0	30	0.8
5	49.0	32	0.0
5	70.0	39	0.0

These results are consistent with fundamental theories of colloidal clay chemistry. According to the double-layer theory, the higher the salt concentration of bulk solution, the greater is the attractive forces between clay particles. At low ion concentrations of pore fluid the soil is more swollen, and water molecules can enter between the clay plates and separate them. Thus at low concentrations or high SAR, clay particles are readily dispersible and will be easily removed by flowing water.

Table 3. Effect of pore fluid composition on swelling and critical shear stress of kaolinitic soils (40% clay content)

Concentration (m equiv/l.)	SAR	Water uptake (g/100 g)	t_c (dyne/cm^2)
250	3.5	9	23.0
250	22.0	11	11.0
250	50.0	10	9.0
250	81.0	12	7.8
125	2.8	9	20.0
125	25.0	12	6.0
125	50.0	10	4.6
125	93.0	13	2.0
50	5.2	10	15.8
50	25.0	11	5.0
50	41.0	13	2.6
50	97.0	14	0.6
5	4.5	12.5	5.0
5	26.0	13	2.4
5	54.0	15	0.8
5	86.0	20	0.0

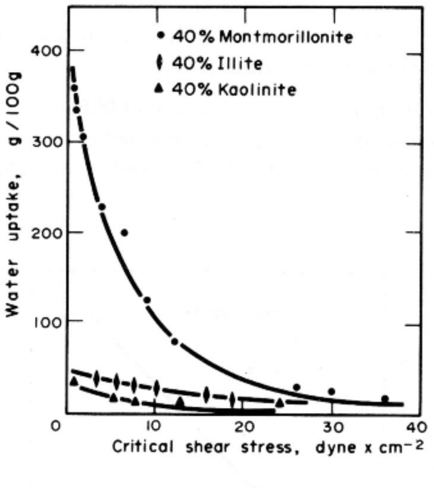

Fig. 1. Plot of critical shear stress vs water uptake.

The plot between swelling and critical shear stress (Fig. 1) shows that the high swelling corresponds to the low critical shear stress. Swelling is a very sensitive parameter for montmorillonitic soils. For example, at zero shear stress, the water uptake for the montmorillonitic sample was as high as 400% of its dry weight. Illitic and kaolinitic soils, however, did not swell more than 40 and 20%, respectively.

Redrawing the same plot on semi-log paper resulted in a straight line for each type of

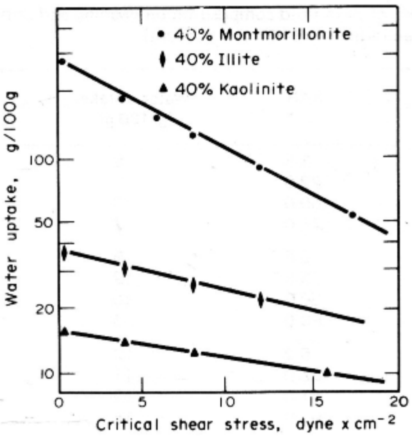

Fig. 2. Plot of critical shear stress vs water uptake.

clay (Fig. 1). A general equation for these lines can be written as follows:

$$t_c = (1/b)(n_1 - \log s) \quad (1)$$

where s = percentage of swelling as defined in g water uptake per 100 g of dry soil; b = slope; and n_1 = geometric intercept on the y axis.

In Fig. 2, the value of b is $(8.5)10^{-3}$, $(15.5)10^{-3}$ and $(38.5)10^{-3}$ for kaolinitic, illitic and montmorilonitic soils, respectively. These values resulted in straight lines when plotted as a function of dielectric dispersion ($\Delta\epsilon_0$) (Fig. 3). Based on these figures, the relationship

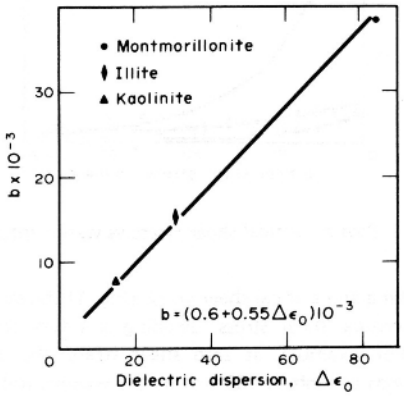

Fig. 3. Plot of b vs dielectric dispersion.

between b and $\Delta\epsilon_0$ is as follows:

$$b = (0.6 + 0.55\Delta\epsilon_0)\,10^{-3}. \tag{2}$$

Another plot was also drawn between geometrical intercept points and $\Delta\epsilon_0$ for each type of clay (Fig. 4). The equation between n_l and $\Delta\epsilon_0$ can be written as follows:

$$n_l = (1/40)\,(\Delta\epsilon_0 + 30)\,. \tag{3}$$

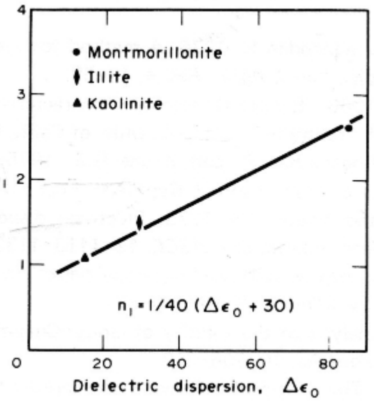

Fig. 4. Plot of n_l vs dielectric dispersion.

Therefore, equation (1) will be in the following form:

$$t_c = \frac{1}{(0.6 + 0.55\Delta\epsilon_0)}\,(750 + 25\Delta\epsilon_0 - 1000 \log s). \tag{4}$$

In this equation, the critical shear stress is inversely related to the amount of swelling and therefore, it might be possible to use the swell parameter as an index for predicting erodibility of cohesive soils.

CONCLUSIONS

The influence of compositional and environmental parameters, such as the type of clay fraction and composition of pore fluid, on the swelling and critical shear stress of cohesive soils were investigated. The following conclusions based on experimental results are obtained:

1. Different types of clay minerals or the same clay under different conditions give different magnitudes of swelling.
2. Total salt concentration and SAR of the soil are important factors controlling the swelling behavior of the soil.

3. The functional relationship between t_c and swelling (percentage water uptake) are found to be as follows:

$$t_c = \frac{1}{(0.6 + 0.55\Delta\epsilon_0)} (750 + 25\Delta\epsilon_0 - 1000 \log s)$$

where s is the percentage of water uptake.

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