

# Effects of Salts on Erosion Rate of Unsaturated Compacted Montmorillonite Clays

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Erosion rates of unsaturated compacted calcium montmorillonite and sodium montmorillonite clays were measured under a range of tractive shear stresses in a rectangular flume. The calcium montmorillonite was treated with calcium chloride and sodium carbonate to obtain samples with different chemical composition. Samples were compacted at nearly optimum water content under 700 Pa into sample containers with 160-cm<sup>2</sup> surface area and subjected to flowing water in the flume. The tractive stress on the bottom of the flume was determined by measuring the velocity distribution of the flow and using the Prandtl-von Karman equation. The tractive stress ranged from 1.67 to 12.9 Pa. The erosion rate of naturally occurring calcium montmorillonite was two orders of magnitude higher than that of sodium montmorillonite. When calcium montmorillonite was treated with 0.88 percent by dry weight sodium carbonate, the erosion rate was reduced to the same order as that of sodium montmorillonite. Addition of calcium chloride had no appreciable influence on the erosion rate of calcium montmorillonite. Empirical equations have been developed to estimate the erosion rate of compacted unsaturated montmorillonite clay as a function of sodium adsorption ratio and tractive stress.

Surface erosion by rainfall and flowing water can severely damage earth structures such as earth dams and highway embankments. These structures are often constructed from unsaturated compacted cohesive soils, and therefore an understanding of erodibility (relative susceptibility to erosion under an eroding force) of such soils is necessary for safe design of earth structures. Surface erosion can be caused by overtopping and by sheet or concentrated flow over embankments. The extent of erosion depends on the erosion resistance of the soil as well as the dynamics of the eroding flow. Certain soils in nature are highly erodible. Severe erosion damage to embankments in the form of deep gullies caused by rainfall has been reported by Sherard et al. (1).

In recent years the results of extensive studies (2-9) have shown that pore water chemistry plays an important role in erosion resistance of saturated consolidated cohesive soils. The influence of pore water chemistry (or salt additives) on erosion resistance (or erosion rate) of unsaturated compacted cohesive soils has not been fully investigated. However, earth structures are compacted and usually are in an unsaturated state, especially the surface layer that is exposed to rainfall and flowing water. An unsaturated soil may slake as the result of water penetrating the soil and increasing the pore air pressure. In this

case, the erosion mechanism will differ from that of saturated soils. Consequently, the relative contribution of salts to erosion rate also will differ for unsaturated and saturated soil.

The objectives of this paper are to describe the influence of sodium and calcium salts on the erosion rate of unsaturated compacted montmorillonite clays and to provide empirical relationships for estimating the erosion rate of such soils as a function of tractive stress and sodium adsorption ratio.

The information provided in this paper will help engineers to realize the influence of salts on the erosion rate of unsaturated compacted montmorillonite clays. The engineer will then select an appropriate soil for construction and maintenance of embankments or will stabilize the highly erodible soil with chemical treatment.

The empirical relationship can be used to evaluate the extent of erosion and the possibility of failure of an embankment by surface erosion.

## EXPERIMENTAL INVESTIGATION

The materials and method of investigation are briefly described in this paper. Detailed descriptions are presented by Shaikh (10).

### Materials

Two commercially available montmorillonites, a sodium montmorillonite (No. 200 Volclay bentonite) and a calcium montmorillonite (Panther Creek southern bentonite), were selected for this study. An X-ray diffraction analysis showed that both clays are composed of well-crystallized montmorillonite mineral. The physical properties of these minerals are given in Table 1.

### Chemical Treatment

Preliminary test results showed that the erosion rate of Ca-montmorillonite was about two orders of magnitude higher than that of Na-montmorillonite. The pore water chemistry was assumed to be the major cause of the difference in erosion rate. To verify this assumption, the Ca-montmorillonite was treated with calcium chloride and sodium carbonate. The pore water chemistry of the soil samples is characterized by sodium adsorption ratio [ $SAR = Na/0.5(Ca + Mg)$ ] and total dissolved salts ( $TDS = Ca + Mg + Na + K$ ) in a saturation extract. Treatment of Ca-montmorillonite with sodium salts may not

TABLE 1 PHYSICAL PROPERTIES OF SODIUM AND CALCIUM MONTMORILLONITES

	Na-Montmorillonite	Ca-Montmorillonite
Median size ( $\mu\text{m}$ )	< 0.1	4
Specific gravity	2.70	2.77
Liquid limit	522	90
Plastic limit	41	50
Plasticity index	481	40
Optimum water content <sup>a</sup> (%)	34	47
Optimum dry density <sup>a</sup> ( $\text{g}/\text{cm}^3$ )	1.20	1.07

<sup>a</sup> From standard Proctor test.

produce a mineral analogous to the Na-montmorillonite, but such treatment will reduce the erosion rate of the Ca-montmorillonite by two orders of magnitude, to the same order of magnitude as that of Na-montmorillonite.

For chemical treatment of the Ca-montmorillonite, the amount of the salt required to reach a specific value of SAR or TDS in the saturation extract was estimated and dissolved in distilled water. Pure Ca-montmorillonite was then sprayed with the desired amount of the salt solution and mixed with distilled water to form a slurry paste. The samples were then kept in watertight plastic bags for 2 weeks and intermixed every day of the first week; water was added, if necessary, to keep the samples soft if the samples became hard as the result of chemical reactions. The samples were air dried and thoroughly ground. The values of SAR and TDS of the treated samples were measured and are given in Table 2.

The term "pure Ca-montmorillonite" or "Ca-montmorillonite" will be used to indicate the Ca-montmorillonite at its natural composition. The treated samples of Ca-montmorillonite will be referred to as "Ca-montmorillonite + percentage salt." The concentration of soluble cations in a saturation extract, TDS, SAR, and some other physicochemical properties of the clay samples (with and without chemical additives) are given in Table 2.

### Eroding Water

Tap water was used as eroding water, and each test was started with clean water. The quantity of total dissolved salts in the eroding water was less than 2.2 meq/L, and the pH of water

was 7.7. The temperature of the eroding water was maintained at  $18^\circ\text{C} \pm 1^\circ\text{C}$  by adding hot or cold water during testing.

### Sample Preparation

To compact the samples, the optimum water content of the clays was first determined by the standard Proctor test (values are given in Table 1). The air-dry samples were then sprayed with tap water to nearly optimum water content. For the first sample, an excess amount of wet soil was pressed into the sample container at 700 kPa pressure using a hydraulic press and a specially designed rectangular mold and piston. The surface of the sample was then trimmed flush with the top edges of the container. The wet weight of the remaining soil in the sample container was considered the "optimum wet weight." A sample containing material equal in weight to the optimum wet weight was pressed into the sample container until it produced a soil sample the surface of which was flush with the edges of the container. The rest of the samples were then prepared by pressing the optimum wet weight in the sample container until the surface of the sample was flush with the edges of the container. Compacted samples were stored in plastic bags for 24 hr before erosion testing.

### Testing Apparatus and Procedures

Erosion tests were performed using a rectangular Plexiglas flume 15.5 cm wide, 11 cm deep, and 250 cm long with adjustable slope. A schematic drawing of the flume and sample containers is shown in Figure 1. The sample containers were 15.2 cm long, 10.5 cm wide, and 2.25 cm deep. The flume floor was modified so that the surface of the sample was flush with the bottom of the flume. Water was recirculated in the system. The depth of flow ranged from 0.8 to 2.1 cm. The flow rate was measured by a precalibrated Venturi meter, and uniformity of flow depth was maintained by an upstream control. The velocity profiles along the flume at sections shown in Figure 1 were measured using a Pitot tube 0.3 cm in outside diameter connected to a pressure transducer and readout system.

The tractive stress ( $\tau$ ) exerted on the flume bottom was estimated by measuring the velocity profiles and using the Prandtl-von Karman equation for smooth channels (11, pp. 168, 200),

TABLE 2 CHEMICAL PROPERTIES OF MONTMORILLONITE CLAY SAMPLES USED IN EXPERIMENTAL INVESTIGATION

Clay	Paste pH	Conductance (mmhos/cm)	Concentration of Cations in Saturation Extract (meq/L)					SAR	% Sat.	Exchangeable Cations (meq/100 g)					
			Ca	Mg	Na	K	TDS			Ca	Mg	Na	K	CEC	ESP
Na-montmorillonite	9.8	1.8	1.2	0.6	18.7		20.5	19.8	755.6	20.1	7.00	53.70	0.90	84.8	63.30
Ca-montmorillonite	8.2	0.7	5.9	1.2	0.7		7.8	0.4	96.6	70.9	8.10	0.46	1.00	82.8	0.56
Ca-montmorillonite + 0.80% $\text{CaCl}_2$			242.0	32.2	5.4	3.5	283.0	0.5	89.5	74.8	3.00	0.06	1.19	79.1	0.10
Ca-montmorillonite + 1.60% $\text{CaCl}_2$			374.0	39.9	6.9	4.6	425.0	0.5	93.5	83.0	2.90	0.14	1.24	87.3	0.20
Ca-montmorillonite + 0.22% $\text{Na}_2\text{CO}_3$			2.3	0.9	5.0	0.3	8.5	3.9	145.8	68.7	7.89	3.66	1.21	81.5	4.50
Ca-montmorillonite + 0.88% $\text{Na}_2\text{CO}_3$			0.8	0.5	9.3	0.1	10.7	11.4	208.5	53.3	7.75	21.63	1.18	84.0	25.80

NOTE: Ca, Mg, Na, K = calcium, magnesium, sodium, and potassium cations; TDS = total dissolved salts =  $\text{Ca} + \text{Mg} + \text{Na} + \text{K}$ ; SAR = sodium adsorption ratio =  $\text{Na}/[0.5(\text{Ca} + \text{Mg})]^{1/2}$  in (meq/L)<sup>1/2</sup>; % Sat. = percent saturation, water content of the paste used for saturation extract; CEC = cation exchange capacity; and ESP = exchangeable sodium percentage, 100 Na/CEC.

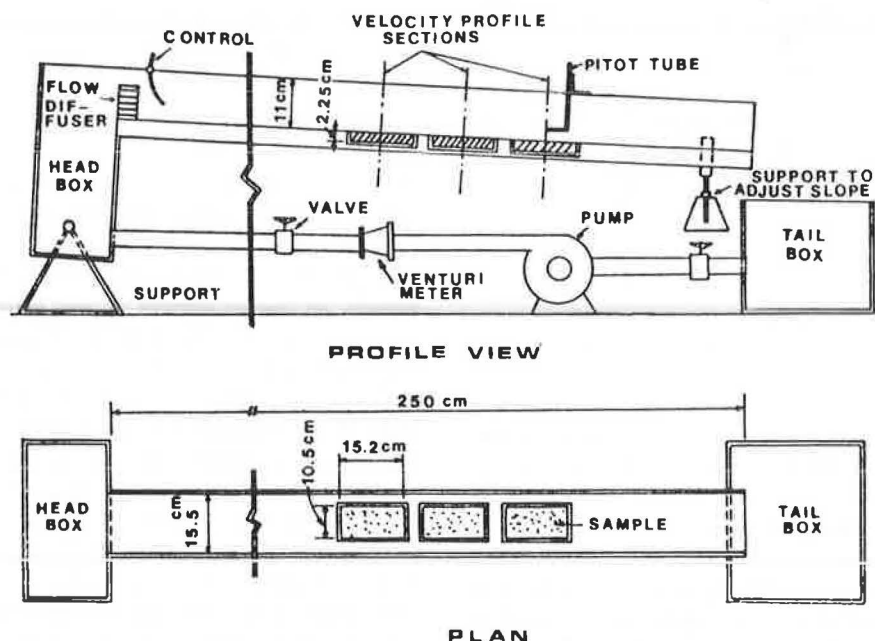


FIGURE 1 Flume and sample containers.

$$V/V_* = 5.5 + 5.75 \log (V_* y/\nu) \quad (1)$$

where

- $V_* = (\tau/\rho)^{1/2}$  is shear velocity,
- $V$  = velocity at depth  $y$  in the turbulent region,
- $\rho$  = density of water, and
- $\nu$  = kinematic viscosity of water.

The tractive stresses were determined for five locations across and along the flume and then averaged. The average of tractive stress values obtained by this method was in close agreement with the value of  $\tau$  obtained using duBoys' equation (11),

$$\tau = \gamma R \sin \alpha \quad (2)$$

where

- $\gamma$  = unit weight of water,
- $R$  = hydraulic radius, and
- $\alpha$  = angle between the flume and the horizontal surface.

For small flow depth and high slopes where velocity profile measurement was not possible, the tractive stress was estimated by Equation 2.

For each soil sample a total of nine tests were conducted at three flume slopes and three time durations. To reduce the testing time, the flume was designed so that as many as three samples could be tested during the same run. For Ca-montmorillonite samples for which the erosion rate was relatively high, only one sample per run was used. In this case, the rest of the sample locations in the flume were filled with dummy samples made of Plexiglas. For Na-montmorillonite samples for which the erosion rate was relatively low, three samples were placed

in the flume for each run. In each test, samples were removed at different time intervals starting with the downstream sample. In initial test runs, all three samples were removed at the same time and tests were conducted for different periods of time. The erosion rates obtained by these two procedures were nearly identical and within the range of measurement errors for each soil sample. The close agreement of erosion rate values of a sample at different time intervals suggests that using three samples in each run did not greatly influence the erosion rate of the samples. The amount of erosion (weight loss) is defined as the difference between the dry weights of the samples before and after testing. The values of weight loss are per unit surface area.

## EXPERIMENTAL RESULTS AND DISCUSSION

In addition to erosion tests, the reaction of the clay samples to still water was observed. In this section the reaction of Na-montmorillonite and pure Ca-montmorillonite to still water will be discussed. Then the erosion test results will be presented and discussed.

### Behavior of Clays in Still Water

One sample of each pure clay, identical to the samples prepared for the erosion tests, was immersed in water for 10 min and the reaction was recorded. The Na-montmorillonite sample did not show appreciable swell, although dispersion of the surface particles was noticed. The surface of the sample became sticky, as was the case in the erosion tests. The Ca-montmorillonite sample, however, swelled and its thickness increased by about 50 percent. Upward flow of entrapped air in a few locations carried water-laden Ca-montmorillonite upward. The depth of penetration of water into the Na-montmorillonite sample was less than 1 mm; water completely penetrated the Ca-montmorillonite sample.

The behavior of the Ca-montmorillonite in still water is characterized by slaking. Slaking is the breakdown of soil on immersion in water. When an unsaturated soil specimen is immersed in water, the water will penetrate the specimen under the driving force of the matrix and osmotic potential. The air in the voids will be trapped between menisci of the entering water, and air pressure will increase as the water fills the voids. The entrapped air will then exert an enormous pressure causing a rapid increase in void size and disintegration of the soil (12, p. 146; 13, p. 174; 14, pp. 1-7).

### General Observations for Erosion Tests

The mechanism of erosion was observed to vary for the different clay samples tested. The Na-montmorillonite eroded particle by particle. At the beginning of each test the recirculating water was clear and gradually became cloudy indicating the gradual detachment of the clay particles from the sample surface and their suspension in water. The pattern of erosion of the Na-montmorillonite samples was similar to that shown in Figure 2. The three samples shown in this figure represent various erosion times. Except for the dips at the upstream and downstream ends, the sample surface remained flat and smooth after erosion. The form of erosion at the upstream and downstream ends of the samples is believed to be the result of eddies that developed from changes in roughness of the flume bed when the bed changed from the Plexiglas to a soil sample surface. The erosion time of the Na-montmorillonite samples ranged from 30 to 120 min, and the erosion depth varied from 1 to 6 mm. The depth of penetration of water in the samples during the erosion tests was less than 1 mm.

The erosion pattern of the Ca-montmorillonite varied with the chemical additives. No specific erosion pattern was observed for samples of pure Ca-montmorillonite because it had a high erosion rate, two orders of magnitude higher than that of Na-montmorillonite. An erosion pattern of the pure Ca-montmorillonite is shown in Figure 3. Most of the pure Ca-montmorillonite samples eroded in large masses. The samples of the Ca-montmorillonite with 0.80 and 1.60 percent  $\text{CaCl}_2$  eroded mainly in flaky aggregates; flakes as large as 15 mm were

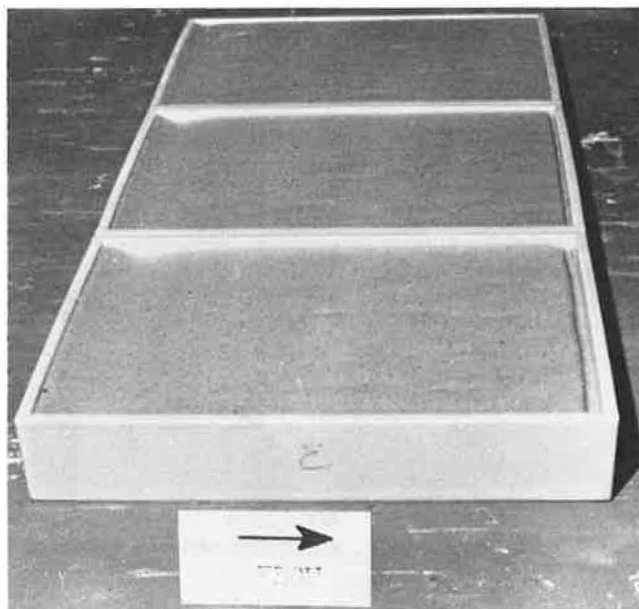


FIGURE 2 Erosion pattern of Na-montmorillonite samples (three different times of erosion increasing from top to bottom).

observed. The Ca-montmorillonite treated with 0.22 percent  $\text{Na}_2\text{CO}_3$  eroded in soil aggregates. The erosion pattern of the Ca-montmorillonite with 0.88 percent  $\text{Na}_2\text{CO}_3$  was similar to that of the Na-montmorillonite with an erosion rate on the same order of magnitude as that of the Na-montmorillonite. The erosion time of the pure Ca-montmorillonite samples ranges from 45 sec to 4 min. After the erosion tests were completed, the remaining clays in the sample containers were completely saturated.

### Erosion Test Results

A typical relationship between weight loss and erosion time for unsaturated compacted clay samples is shown in Figure 4. Erosion rates for given tractive stresses also are shown in

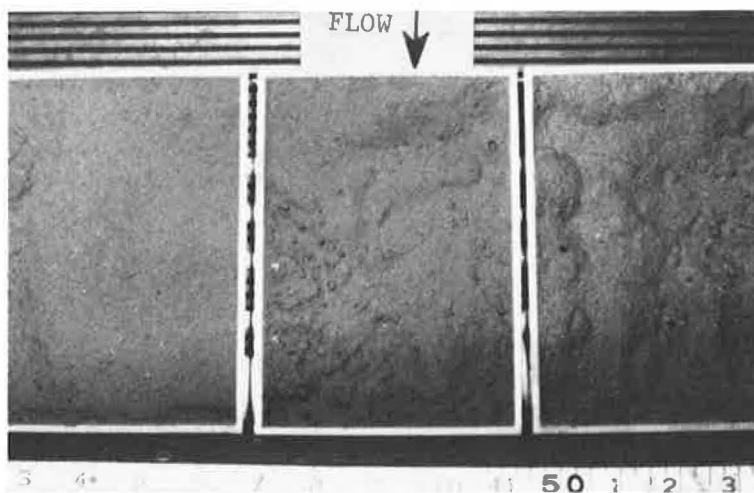


FIGURE 3 Erosion pattern of Ca-montmorillonite (three different times of erosion increasing from left to right).



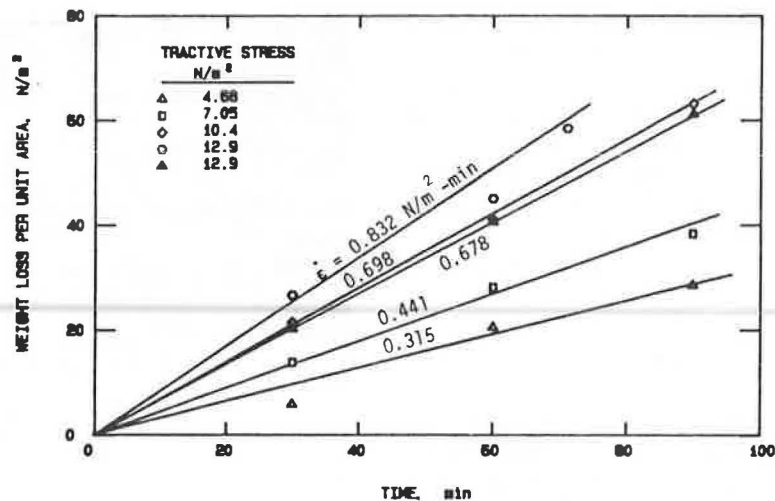


FIGURE 4 Weight loss per unit area versus time for Na-montmorillonite compacted at 34.5 percent water content.

Figure 4. Values of weight losses and erosion rates are per unit surface area. In addition to the tests discussed in this paper, a series of tests was conducted on compacted samples at various water contents and percentages of clay. The test results for all samples are presented elsewhere (10). For most of the samples, weight loss varied linearly with time. The slope of the line relating weight loss to time is defined as the erosion rate. The erosion rate values were determined by using a linear least-squares fit of the data and by imposing the restriction that the lines must pass through the origin as shown in Figure 4.

The erosion rate for Ca-montmorillonite was about two orders of magnitude higher than that for Na-montmorillonite. An erosion rate of 53 N/m<sup>2</sup>/min for Ca-montmorillonite versus 0.315 N/m<sup>2</sup>/min for Na-montmorillonite under tractive stress of 4.7 Pa was observed. To investigate the cause of such erosional behavior, the Ca-montmorillonite was treated with CaCl<sub>2</sub> and Na<sub>2</sub>CO<sub>3</sub> and the erosion rates of the treated samples were measured. Calcium chloride was used to increase the TDS and sodium carbonate was used to increase the SAR.

The relationships between erosion rate and tractive stress for the Na-montmorillonite samples and all of the Ca-montmorillonite samples are shown in Figure 5. The relationships between erosion rate and tractive stress may be expressed as

$$\dot{\epsilon} = C\tau \quad (3)$$

where

- $\dot{\epsilon}$  = erosion rate in N/m<sup>2</sup>/min,
- $\tau$  = tractive stress in N/m<sup>2</sup>, and
- $C$  = erosion rate coefficient in min<sup>-1</sup>.

The linear relationships between erosion rates and tractive stresses are determined by a least-squares fit of the data when lines pass through the origin. Values of the erosion rate coefficient ( $C$ ), TDS, and SAR for the clay samples tested are given in Table 3.

The coefficient ( $C$ ) for Ca-montmorillonite and Ca-montmorillonite + CaCl<sub>2</sub> is 11.8/min, which is 184 times greater than the erosion rate coefficient of 0.064/min for Na-montmorillonite. When Ca-montmorillonite was treated with Na<sub>2</sub>CO<sub>3</sub>, its erosion rate decreased by two orders of magnitude. The erosion rate of the Ca-montmorillonite + 0.88% Na<sub>2</sub>CO<sub>3</sub> samples approached that of the Na-montmorillonite samples (with an erosion rate coefficient of 0.138/min compared with 0.064/min for Na-montmorillonite). The data points shown in Figure 5 for pure Ca-montmorillonite and for Ca-montmorillonite + CaCl<sub>2</sub> fall in the same region. These data points are scattered, but they indicate that the addition of CaCl<sub>2</sub> had no appreciable influence on the erosion resistance of the Ca-montmorillonite tested.

The relationship between  $C$  and SAR is shown in Figure 6. These results indicate that the Ca-montmorillonite samples with SAR = 0.4 were much more erodible than were the Na-montmorillonite samples with SAR = 19.8. When the SAR of the saturation extract was increased, the Ca-montmorillonite became less erodible and its erosion rate decreased by almost two orders of magnitude. Note that the concentration of salts in the saturation extract of Ca-montmorillonite changed slightly when treated with Na<sub>2</sub>CO<sub>3</sub>, but such a small change will not significantly influence erodibility. Therefore the changes in erosion rate are attributed only to the changes in SAR as shown in Figure 6.

The relationship between the erosion rate coefficient ( $C$ ) and SAR from Figure 6 may be expressed as

$$C = 4.41 (\text{SAR})^{-1.34} \quad (4)$$

Here  $C$  has units of min<sup>-1</sup>. The erosion rate ( $\dot{\epsilon}$ ) can then be estimated for a given tractive stress ( $\tau$ ) using Equation 3.

Slaking was the cause of the high erosion rate of the Ca-montmorillonite in this study. Slaking is the breakdown of soil aggregates on immersion in water. Ca-montmorillonite with a low SAR has a flocculated fabric and therefore is highly permeable. As a result, water easily penetrates the clay and slaking

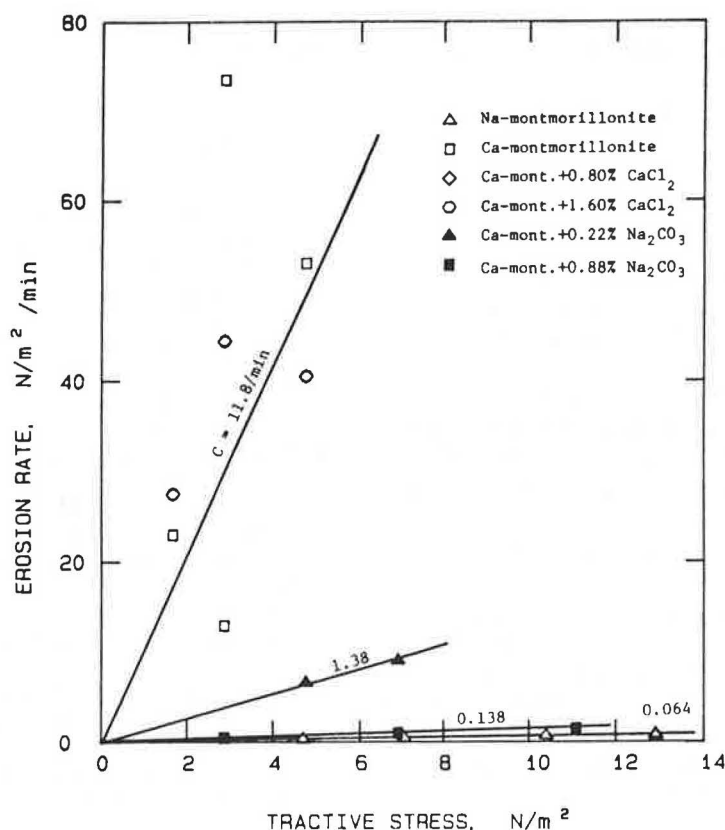


FIGURE 5 Erosion rate versus tractive stress for unsaturated compacted montmorillonite clays.

TABLE 3 CHEMICAL PROPERTIES OF THE SATURATION EXTRACT AND EROSION RATE COEFFICIENT FOR THE CLAY SAMPLES TESTED

Type of Clay	TDS <sup>a</sup> meq/L	SAR <sup>a</sup> (meq/L) <sup>1/2</sup>	Erosion Rate Coefficient C (min <sup>-1</sup> )
Na-montmorillonite	20.5	19.8	0.064
Ca-montmorillonite	7.8	0.4	11.8
Ca-montmorillonite + 0.80% CaCl <sub>2</sub>	283.0	0.5	11.8
Ca-montmorillonite + 1.60% CaCl <sub>2</sub>	425.0	0.5	11.8
Ca-montmorillonite + 0.22% Na <sub>2</sub> CO <sub>3</sub>	8.5	3.9	1.38
Ca-montmorillonite + 0.88% Na <sub>2</sub> CO <sub>3</sub>	10.7	11.4	0.138

<sup>a</sup>From the saturation extract.

occurs. Na-montmorillonite has a dispersed fabric with a low permeability and therefore water cannot easily penetrate the soil. Hence, the soil does not slake and erosion occurs only by detachment and removal of clay particles at the sample surface.

The results of this study were in agreement with those reported by Grissinger (15), who measured the erosion rate of unsaturated compacted soil mixtures containing Na-montmorillonite and Ca-montmorillonite. His results showed that the erosion rate of the soil containing Ca-montmorillonite was about 20 times greater than that of the soil containing Na-montmorillonite. Grissinger used a method of compaction

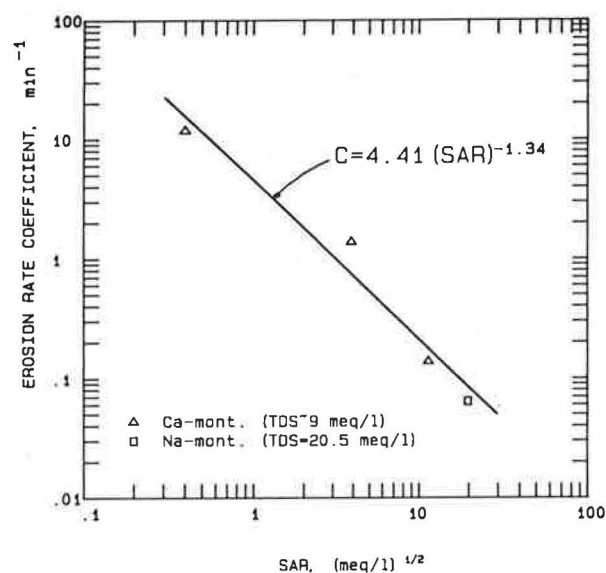


FIGURE 6 Variation of erosion rate coefficient (C) as a function of SAR for unsaturated compacted montmorillonite samples.

similar to the one used in this study and performed his erosion tests in a flume.

The influence of SAR on the erosion rate of the compacted unsaturated montmorillonite clays was the opposite of results of erosion studies (2-5, 8, 16) on saturated consolidated clays. The erodibility of saturated consolidated clays has been found

to increase with increasing SAR (5). The erosion rate of unsaturated compacted clays decreased with increasing SAR.

## APPLICATION OF RESULTS IN HIGHWAY ENGINEERING

A concern in highway engineering is erosion damage to highway embankments caused by rainfall and overland flow. Knowledge of the factors that control the erosion resistance of compacted unsaturated soils makes it possible to identify highly erodible soils and develop methods of controlling or reducing the erosion rate of such soils. The results of this study indicate that salt additives (or pore water chemistry) are the controlling factors of erosional behavior of montmorillonite clays. The erosion rate of a highly erodible Ca-montmorillonite can be reduced by two orders of magnitude by treating it with less than 1 percent by weight  $\text{Na}_2\text{CO}_3$ .

Empirical equations (Equations 3 and 4), which can be used to estimate the erosion rate of compacted montmorillonite clays, are developed in this study. From Equation 4 the erosion rate coefficient ( $C$ ) can be determined for a montmorillonite clay with a known value of SAR. Equation 3 can be used to estimate the erosion rate of the clay as a function of applied tractive stress. Therefore the extent of erosion during a runoff event can be predicted if the applied tractive stresses are assumed and flow duration is known.

## CONCLUSIONS

The results of this study have shown that the primary factor influencing the erodibility of unsaturated compacted montmorillonite clays is soil pore water chemistry. The pore water chemistry is characterized by the total dissolved salts (TDS in meq/L) and sodium adsorption ratio (SAR in meq/L<sup>1/2</sup>) of a saturation extract. The erosion rate of the Ca-montmorillonite (with SAR = 0.4 and TDS = 19.8) was two orders of magnitude higher than that of the Na-montmorillonite (with SAR = 19.8 and TDS = 20.5). The erosion rate coefficient ( $C$ ) (the increase in erosion rate per unit increase of tractive stress) decreased with increasing SAR.  $C$  of the Ca-montmorillonite decreased by almost two orders of magnitude, from 11.8 to 0.138/min, when the SAR increased from 0.4 to 11.4. The erosion rate coefficient of the Ca-montmorillonite approached the value of  $C$  of the Na-montmorillonite when the SAR of the Ca-montmorillonite approached the SAR of the Na-montmorillonite. The erosion rate of compacted montmorillonite samples may be

expressed as a power function of SAR and a linear function of tractive stress.

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