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STABILIZING FINE SAND BY ADDING CLAY: LABORATORY WIND TUNNEL STUDY*

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Summary

Because of the need to develop inexpensive technology to stabilize highly erodible soils and arrest migrating sand dunes, this research was undertaken. Our objective was to evaluate the effectiveness of adding clay to very sandy soil to reduce wind erosion susceptibility. The study was conducted in a laboratory wind tunnel facility. In the first part of the study, various amounts of bentonite and kaolinite clay were added to a fine sand. The mixtures were wetted with simulated rain, and resulting aggregates were tested for mechanical stability. The aggregates' resistance to crushing increased greatly with increasing clay content. Because the bentonite was several times more effective than kaolinite, bentonite was used in the second part of the study. Trays were filled with various concentrations of bentonite-sand mixtures, wetted with simulated rain, dried, and tested in the wind tunnel with and without abrader at a free stream wind speed of 14 m s^{-1}. Without abrader (wind only), the soil loss increased with clay concentration. With an abrader of sand introduced into the wind tunnel upwind of the test section, cumulative soil loss from the tray with the untreated sample was 20 and 30 times more than that from the trays treated with 10 or 20 g bentonite per kg of sand. Wind erosion susceptibility of sandy soil was reduced greatly by adding small amounts of bentonite clay in this laboratory study.

1 Introduction

Desertification is a serious threat for the dry areas that make up one-third of the earth's land mass (HAGEDORN et al. 1977). For example, the Sahel region at the southern border of the Sahara desert in Africa is concerned with that problem (FORTER 1979, HAGEDORN et al. 1977). Migration of sand dunes is a critical desertification process, because it changes agricultural areas into wasteland and covers up everything with sterile sand. Active dunes exist on all continents, both along the coasts and inland. They may be very destructive and damaging, covering roads, fertile lands,

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bushes, trees, and buildings.

Dunes are composed basically of sand particles and, consequently, have low cohesion and lack structure. They occur generally under semi-arid and arid conditions, when the fragile ecosystems are destroyed for food, fuel, or fodder (HAGEDORN et al. 1977). Prevailing winds from a constant direction are the most important climatic element for the formation of sand dunes. Winds of velocity greater than 5.3 m/s can transport sand on dunes (HAGEDORN et al. 1977). No significant vegetation, except a few psammophytes will grow naturally on dunes because the soil is loose and sterile.

The first step in stabilizing dunes is temporary stabilization by any material that stops surface sand movement. The second step is biological stabilization, which consists of establishing a permanent vegetative cover (TROEH et al. 1980). That is no easy task because of the character of the soils and because the winds tend to uproot young plants or bury them with drifting sand. Temporary stabilization of the soils is necessary in order to protect young plants until they become sufficiently large to maintain themselves against the drifting sand.

Temporary stabilization may be done by use of vertical barriers or horizontal protection. Vertical barriers consist of fences of appropriate height, thickness, porosity, and arrangement (FORTER 1979, HAGEDORN et al. 1977, HAGEN et al. 1972, SKIDMORE & SIDDOWAY 1978), including parallel rows of shrubs perpendicular to the prevailing winds.

Horizontal protection involves applying water, oil (low-gravity asphaltic oil, high-gravity waxy oil, crude oil), chemical soil stabilizers (ARMBRUST & LYLES 1975, LYLES et al. 1974). Asphaltic oil does not penetrate into the ground. It lies on the top as a protective film or crust, which eventually hardens into a non-sticky surface. This crust is a thin and fragile layer, which is easily damaged during later field operations. When the film is broken, deflation immediately starts again. To increase the thickness of the crust and reduce the risk of fracturing, the asphalt sprayings must be repeated. High-gravity waxy oil is a cheap, longer lasting dune stabilizer, which penetrates to a depth of 10–20 cm. However, it remains sticky so later operations on the stabilized area are difficult (CHEPIL 1955). Crude oil used in Libya developed a crust 0.5 cm thick, which lasted about three years. An area of 5 to 15 ha could be stabilized in one day, at a cost of $420 per ha (HAGEDORN et al. 1977). In order to establish a permanent vegetation cover, only those oils that do not limit plant growth and emergence by their toxic effects and that do not form a cover that cannot be penetrated by water can be used. Another reason for stabilizing sandy areas is to maintain the quality of the environment (ARMBRUST 1977, TROEH et al. 1980).

The use of plant residues was investigated to determine the amount of hay and wheat straw to control wind erosion on sandy soils (CHEPIL et al. 1963). Asphalt was used to bind the pieces of the mulch. SKIDMORE & SIDDOWAY (1978) reviewed the importance of crop residues in surface protection against wind erosion. Other natural materials for stabilization also have been applied directly to the soil surface (CHEPIL et al. 1963). From these studies, some desirable properties of an effective stabilizer were determined: permeability, possibility of seedling penetration, persistence of effectiveness, and ease of application.

Studies were conducted (ARMBRUST & DICKERSON 1971, LYLES et al. 1974) to evaluate a number of materials commercially available for stabilizing soil against wind erosion. Four materials were tested in the field and 34 in the laboratory. These tests eventually led to establishing criteria for an acceptable product:

(i) to cost less than $123 per ha;

(ii) to have no adverse effect on plant growth;

(iii) to reduce erosion for at least two months;

(iv) to be easily applied.

A final list of five polymers and one resin-in-water emulsion met these criteria.

Polyacrilamide (PAM) has been used because it was simple to apply, had the ability to aggregate sandy soils, and was not toxic (DE BOODT & GABRIELS 1976). However, high costs limited its use and recently, attempts have been made to replace it with a cheaper product that would be equally effective. That product was iron sulfate plus urea formaldehyde (SHARMA & DE BOODT 1983). Costs of material and application remain the critical factors for use of stabilizing agents.

This research project was conductd to determine the effectiveness of adding clay to stabilize dunes against wind erosion. Stabilizing with clay should be cheaper than the methods presently used. Kaolinite and bentonite clays are relatively cheap and easy to find and to add the top layer of the dune surface.

Our hypotheses were:

1. The dry-aggregate stability of aggregates formed from clay and fine sand is dependent upon the clay concentration.
2. The stability of aggregates is dependent upon the number of wetting and drying cycles.
3. The stability of aggregates formed from a kaolinite and fine sand mixture is greater than the stability of those formed from a bentonite and fine sand mixture.

2 Materials and methods

A sample of Tivoli sand (Typic Ustipsamment, mixed, thermic) was taken from the surface (0–500 mm depth) of semifixed sand dunes near Hutchinson, Kansas. The particle size distribution of the soil was 97% sand (1.0–0.05 mm), 1% silt (0.05–0.002 mm), and 2% clay (<0.002 mm). Wyoming bentonite, commercially used for drilling mud in oil well development, was obtained from a vender in Great Bend, Kansas, and ceramic kaolinite was obtained from Macon, Georgia.

The clays were mixed with the fine sand in the following concentrations: 0, 10, 20, 30, 60, 120, and 240 g bentonite per kg of sand and 0, 10, 20, 30, 40, 50, and 60 g kaolinite per kg of sand replicated four times. Two hundred grams of clay and sand mixture were placed in plastic containers. All the containers of sand and clay were placed in a rainfall simulator, irrigated at an intensity of 2.5 cm hr^{-1} for 10 minutes, and then air-dried for 9 days. Rainfall was simulated by deionized water drops formed with 6.4 mm fulljet nozzles under a pressure head of 1 m and allowed to fall 10.4 m onto the clay-sand mixtures. Three samples of each clay-sand combination were passed through the same wetting - drying procedure for a second time, two for a third time, and one for a fourth time. After the last drying, dry soil aggregate stability was determined using the technique described by SKIDMORE & POWERS (1982), with an apparatus called the Soil Aggregate Crushing Energy Meter (SACEM) (BOYD et al. 1983).

The crushed material from the aggregates was passed through a 6.35 mm sieve and separated into fractions by sieving. The material was sieved for 10 seconds on a Tyler Portable Sieve Shaker (Model TX-24) equipped with eight sieves (4.76, 3.36, 2.0, 1.0, 0.5, 0.25, and 0.106 mm). The material passing through the 0.106 mm sieve was further separated with a 2-minute shaking on an Allen-Bradley Sonic Sifter (Model L3PF) equipped with 0.074, 0.053, and 0.030 mm sieves. The total aggregate surface area was calculated described by SKIDMORE & POWERS (1982). The dry aggregate stability index was calculated by dividing the work done in crushing the sample by the total aggregate surface area and the data reported in J m^{-2}.

The crushing energy of each aggregate was calculated by dividing the energy in joules read on the SACEM by the aggregate mass in kilograms, and the results were in J kg^{-1}. Densities were determined using aggregates coated with paraffin (BLAKE 1965). Particle size distribution analysis of the sand was done by the pipette method (DAY 1965). Finally, rupture stress was calculated by the method of SKIDMORE & POWERS (1982) in which they measured themaximum force on the aggregates at the initial break of the aggregates.

The experimental design for Part I was completely randomized with two clay types, kaolinite and bentonite. After the test for interaction showed that the water cycles had small effect on the resistance of aggregates to crushing energy, the water levels were considered as replications in later analyses.

For Part II of the study, Tivoli sand and Wyoming bentonite clay were used again. They were mixed with a mason's mixer in concentrations of 0, 10, 20, 30 g of clay per kg of sand. Five wind tunnel trays (122.4 × 20.4 × 5.1 cm) were filled with each concentration of the clay-sand mixture and wetted in the rainfall simulator at an intensity of 2.5 cm hr^{-1} for 10 minutes and dried at 39°C to constant weight. The trays were level on the floor of the raindrop tower during rain simulation. Four of the trays were used for wind tunnel testing and one for aggregate stability and depth of crust measurements. The depth of crust was measured with a caliper.

The wind tunnel study consisted of two steps. First the trays were weighed and placed in the wind tunnel test section, then exposed to a wind velocity of 14 m s^{-1} for 5 minutes. The trays were weighed again, and the loss of loose material was calculated. Next, the tray was returned to the tunnel and 1.300 kg Tivoli fine sand (the abrader) was placed 2 meters upwind of the test tray. Between the tray and the abrader, fine sand particles were stuck to the tunnel floor with an adhesive. The tunnel was operated at 14 m s^{-1}, until abrader was blown over the test section of the wind tunnel. This procedure was repeated six times on each tray. Then the procedure was repeated twice with 6 kilograms of abrader. Each time, the loss of soil from the tray was recorded. The soil loss data were analyzed by analysis of variance (ANOVA) and by regression analysis. The tests for interaction effects were performed using F tests and the means were compared with one another using LSD.

3 Results and discussion

The F test (see tab. 1) showed that the crushing energy of the aggregates enriched with kaolinite depended upon either the clay concentration or the wetting - drying cycles or both. The T test showed that the wetting and drying cycles did not affect resistance of aggregates to crushing, therefore, our second hypothesis was false for kaolinite.

The regression analysis performed on the crushing energy of aggregates enriched with bentonite (tab. 2) gave similar results. Therefore, the resistance of aggregates enriched with bentonite to crushing energy also depended upon the clay concentration and not upon the number of wetting-drying cycles, i.e., the first hypothesis was true and the second hypothesis was false. The F test showed that the crushing energy for 32 observations depended on one or more of: aggregated mass, aggregated diameter, bentonite concentration, water cycles, or initial break-force. Except for the bentonite concentration, the backward and stepwise regression procedures eliminated all independent variables at the 0.50 level. This reaffirmed that the resistance of aggregates enriched with bentonite to breaking by external forces depended on the bentonite concentration only.

Aggregates from the bentonite and fine sand mixture were 4–5 times more stable than those from the kaolinite and fine sand mixture, at the same clay concentration (tab. 3). At the kaolinite concentration of 10 g kg^{-1}, the crust was very soft, the sand particles did not stick together. Thus, our third hypothesis was false. A major difference between bentonite and kaolinite is in the type of clay lattice. Bentonite is a 2:1 expanding type clay mineral with shrink-swell capability. Kaolinite is a 1:1 clay mineral with more rigid hydrogen bonding between lattices.

Crushing energy appears to be linearly related to clay concentration. Linear regression equations of data (tab. 3) had r-square values of 0.97 and 0.99 for bentonite (fig. 1) and kaolinite, respectively.

4 Part II. Wind tunnel study of bentonite crust

The simulated rainfall consolidated the clay-sand mixture and formed a crust on the surface. Some loose sand grains rested on the surface and were free to be moved by the wind, other particles were partially imbedded and weakly consolidated. The remaining particles were firmly cemented with the bentonite. Beneath the consolidated zone, there was a layer of unchanged mixture of sand and bentonite. During the wetting process, water did not infiltrate to this layer, and it remained unconsolidated.

During wetting of the mixture in the rain tower, the greater the clay content, the earlier runoff started. Runoff removed fine clay particles and left large sand particles loose on the crusted surface. At the lower bentonite concentrations, the crust surface was packed by the raindrop impact, while at the higher concentrations, the surface remained rather smooth with loose sand particles on top (photo 1). The loose sand grains were less than 1.0 mm diameter, so they were easily blown away without abrader. The

Source	DF	Sum of Squares	Mean Square	F Value
Model	2	38.09	19.04	40.84*
Error	17	7.92	0.46	
Total	19	46.02		

Variable	DF	Parameter Estimate	Standard Error	T for H_o: Parameter = 0
Intercept	1	1.04	0.57	1.82
Water	1	0.18	0.14	1.30
Concentration	1	96.58	10.80	8.94*

* Significant at 0.01 level

Tab. 1: *Regression analysis for* $y = a + bx_1 + cx_2$. *Y is resistance to crushing;* x_1 *and* x_2 *are wetting-drying cycles and kaolinite concentration, respectively.*

Source	DF	Sum of Squares	Mean Square	F Value
Model	2	7974.96	3987.48	23.09*
Error	21	3626.58	172.69	
Total	23	11601.54		

Variable	DF	Parameter Estimate	Standard Error	T for H_o: Parameter = 0
Intercept	1	9.58	7.09	1.35
Water	1	1.43	2.39	0.60
Concentration	1	226.38	33.44	6.77*

* Significant at 0.01 level

Tab. 2: *Regression analysis for* $y = a + bx_1 + cx_2$. *Y is resistance to crushing;* x_1 *and* x_2 *are wetting-drying cycles and bentonite concentration, respectively.*

Clay Added	Crushing Energy Bentonite		Kaolinite	
g kg^{-1}	J kg^{-1}		J kg^{-1}	
10	4.25	0.63*		
20	12.12	2.43	3.27	0.37
30	14.99	1.01	4.12	0.34
60	46.50	5.10	6.98	0.82

* Standard deviation

Tab. 3: *Resistance to crushing of aggregates enriched with bentonite and kaolinite.*

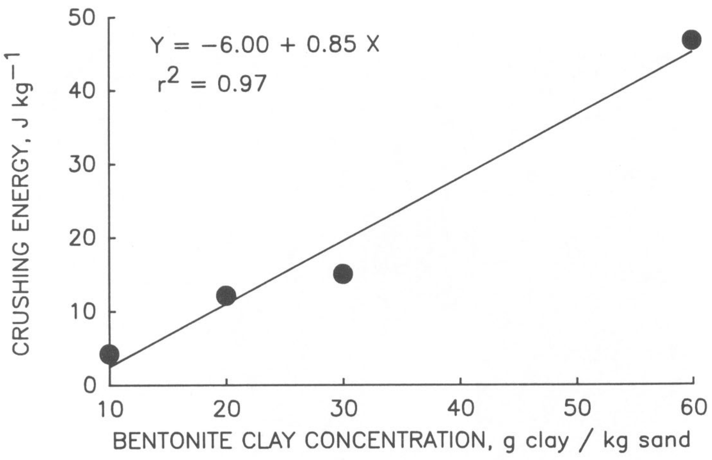


Fig. 1: *Aggregate resistance to crushing as influenced by adding bentonite clay to sand.*

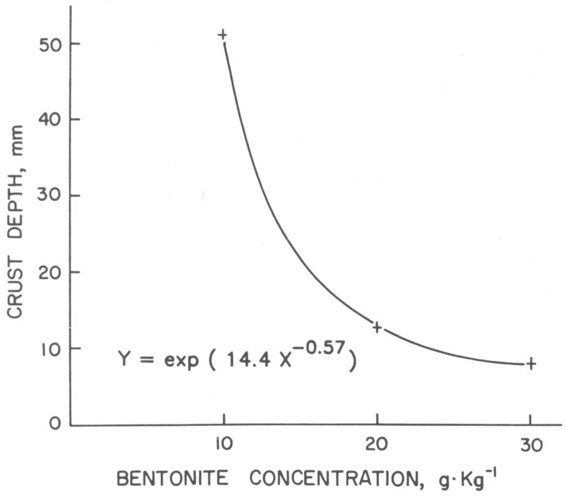
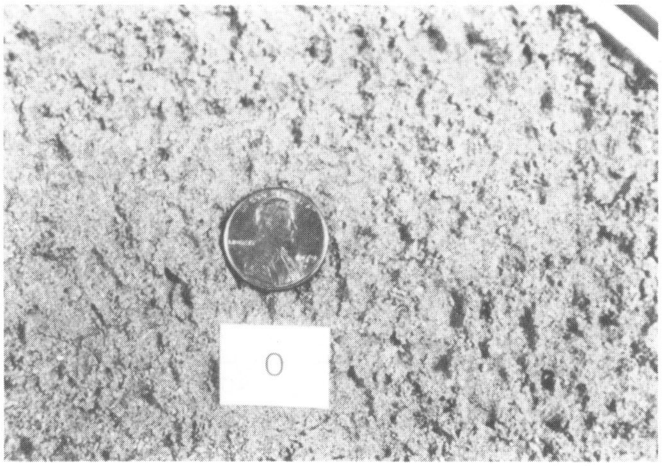


Fig. 2: *The relationship between bentonite concentration and crust depth.*

weakly trapped particles also were blown away with the first abrader impacts. As these particles were blown away, the crust became more and more stable.

As the bentonite clay concentration increased, infiltration decreased, thus decreasing the depth of water penetration and crust thickness (fig. 2).

During wind erosion from the trays, there were two kinds of soil loss: loose soil loss and loss by abrasion. The loose material on the surface blew off quickly with wind only, and the surface stabilized. Even the sand-only treatment did not erode at 14 m s^{-1} free stream wind speed. The amount of loose material on the surface increased with increased concentration of bentonite, contrary to our expectations (fig. 3). The intercepts of the curves in fig. 4 do not agree with



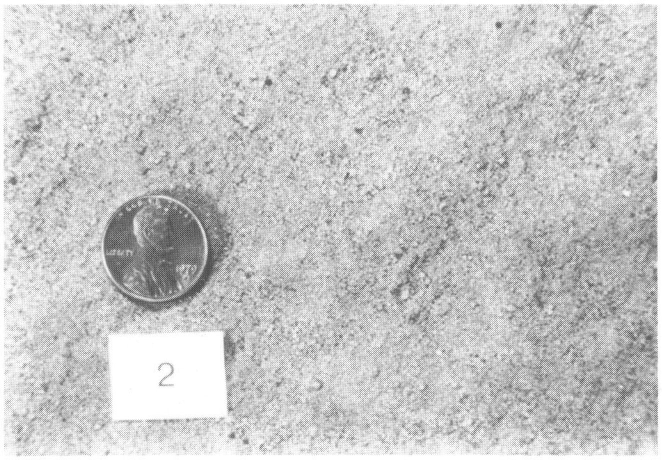


Photo 1: *Configuration of surface after rainfall treatment: (0) sand only, (2) 20 g bentonite/kg sand.*

the wind-only data of fig. 3. Although the surfaces of the mixtures having the least amount of clay eroded less with wind only, they were so fragile that with abrader they eroded more than surfaces with higher clay contents.

The higher the clay content, the smoother and firmer the surface crust, resulting in more clean, loose sand grains resting on the smooth crust surface ready to be blown off. At lower bentonite concentrations, the crust surface was pocked by raindrop impact during the wetting process (photo 1).

The sand-only surface pocked by the raindrops was more resistant than sur-

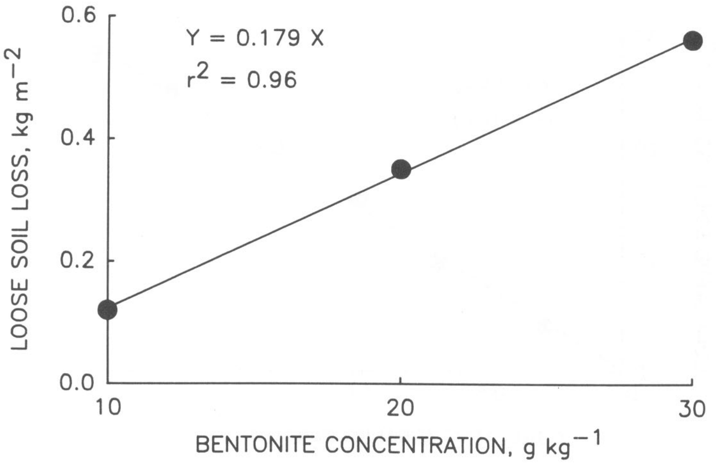


Fig. 3: *The relationship between loose material (blown off by wind only) and bentonite concentration.*

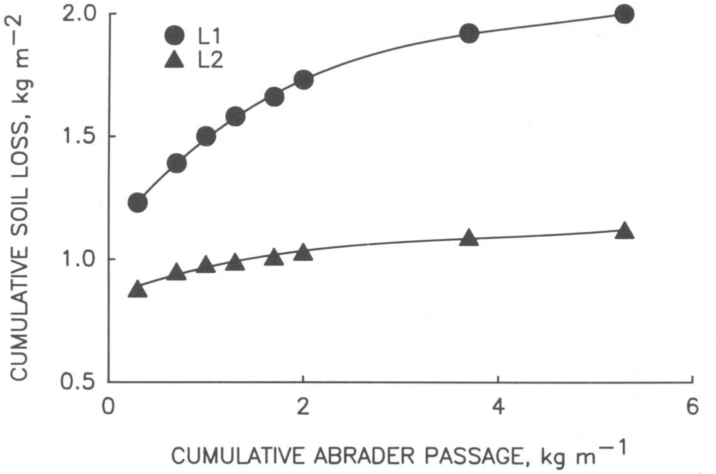


Fig. 4: *Cumulative soil loss from wind tunnel tests as influenced by abrader passage. L1 and L2 are for bentonite concentrations of 10 and 20 g per kg of sand, respectively.*

faces with clay to loss of material from wind only. The washed sand grains resting on the smooth slightly crusted surface of the clay-sand mixture were easily blown off. But when abrader was introduced, cumulative soil loss from the tray with untreated sand (fig. 5) far exceeded soil loss from the trays with bentonite added (fig. 4). With 2 kg m^{-1} of abrader passage, the cumulative soil loss was 30 kg m^{-2} from the untreated tray compared to only 1.5 and 1.0 kg m^{-2} from the tray with 10 and 20 g bentonite per kg sand, respectively.

As abrasion continued, the difference in loss between the treated and untreated

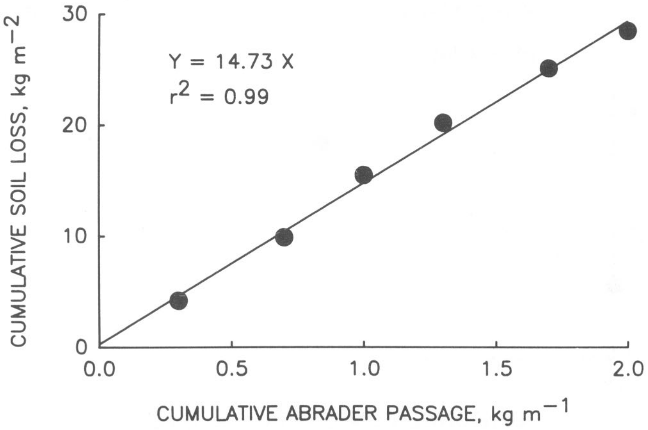


Fig. 5: *Cumulative soil loss from wind tunnel tests as influenced by abrader passage with no bentonite added.*

trays got even larger. The surface treated with bentonite tended to stabilize (fig. 4). Whereas, the slope of the cumulative soil loss vs cumulative abrader passage for the untreated tray continued to rise (fig. 5).

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