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USE OF BENTONITE TO STABILIZE SANDY SOIL MATERIAL IN A WIND TUNNEL STUDY

by

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INTRODUCTION

When wind blows constantly on barren, dry, sandy soil surfaces sand dunes are formed and put into motion in the same direction as the prevailing wind. Their rate of movement is proportional to the velocity of the wind that makes them move. Active dunes exist on all continents, both along the coasts and inland. They may be very destructive and damaging, covering roads, fertile lands, bushes, trees, and builings.

After sand dunes have formed in an area, no significant vegetation will grow on them because the soils are totally loose and sterile. Dunes are composed basically of sand particles and consequently they have low cohesion and they lack structure.

Senegal, West Africa, is in the Sahel, an ecological zone at the southern margin of the Sahara Desert. One of several forms of desertification in Senegal is the formation and migration of sand dunes, both along the coast and inland. The coastal dunes, also called "living dunes" or "white dunes" are more critical because their causal agent is the trade winds blowing continuously from the anticyclone of the Azores in the Atlantic Ocean to the African continent. These winds bring in salty vapor which is the main factor limiting the list of plants that can grow on the coast (Giffard, 1974). When the winds reach the coast they blow over sandy and barren soils and dunes are formed and move inland. The sand dunes may cover productive land with a thick layer of sterile sand. As in the case of true desert of sand, like many parts of Sahara, only a few psammophytes can grow naturally on the dunes.

The northern coast goes from Saint-Louis to Dakar, over 185 km from North to South. The people living along this coast make a living with truck farming. When their productive land is covered, the farmers do not have anymore land to farm, anymore source of income, and the loss of this valuable land is a big economical loss for the country.

The first step in dune stabilization is the temporary stabilization by any material that stops surface sand movement until a vegetative cover is established. The second step is biological dune stabilization which consists of establishing a permanent vegetative cover, basically trees, but that is no easy task because of the character of the soils, and because the winds blow continuously, uprooting young plants or burying them if they are not protected against 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 is critical to the process of establishing vegetation and many techniques are available according to specific situations and economic considerations. The two techniques which have been used are vertical barriers and surface stabilization. Vertical stabilization is the use of fences or barriers made of local material. Parallel fences of shrubs are estabished perpendicularly to the prevailing winds. The other technique is to spray the soil surface with water, oil, chemical stabilizers or cover it with nets made from artificial threads.

Senegal is a developing country with limited financial resources; however, because of the importance of the area involved, cheaper methods of stabilizing the spreading sand dunes must be found. For years, efforts have been made to stop the advancement of sand dunes. The techniques that may presently be used are effective, but less expensive ways are necessary in order to protect other areas.

This research project was conducted to find the effectiveness of adding clay to stabilize dunes against wind erosion. Sand dunes stabilized with clay should be cheaper than the methods presently used in Senegal. Kaolinite and bentonite are relatively cheap and easy to find and to add to the top layer of the dune surface. The resulting crust may reduce wind erosion damage by stabilizing the dune sufrace.

Dry soil aggregates with higher mechanical stability are more resistant to wind erosion than aggregates with lower mechanical stability. The mechanical dry soil aggregate stability is a physical property of aggregates. The study reported here is a study of the behaviour of crusts under the influence of wind and abrasion caused by saltating particles in the test section of the wind tunnel.

REVIEW OF LITERATURE

Desertification is a serious threat for the dry areas which make up one third of the Earth's land mass (Hagedorn et al., 1977). In Africa, the Sahel region, the southern border of the Sahara desert, is concerned with that problem (Forter, 1979; Hagedorn et al., 1977). Migration of sand dunes is the most critical process of desertification because it changes agricultural areas into wasteland and covers up everything with sterile sand.

Dunes are piles of sand. There are a number of kinds of dunes, and many factors go into producing them - climate, vegetation, amount of sand available, and direction and strength of winds. Sand dunes move or migrate a number of meters a year.

The surface of sandy soils is never completely smooth and level, it is rippled. There is always a wind (moving air) and the sand is free to move. The action of the wind on the sand results in ripples that are miniature sand dunes which may become sand dunes (Knight, 1964; Throeh et al., 1980).

As stated by Skidmore (1978), sand dunes 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 ms^{-1} are effective for the sand transport on dunes (Hagedorn et al., 1977).

Stabilization of migrating dunes is done permanently with a vegetation canopy (Troeh et al., 1980). Before the vegetation is established, ways must be designed to protect the young plants against sandgrain abrasion, uprooting, and covering by sand until the plants are large enough to stabilize the dune. Temporary stabilization may be done by use of vertical barriers or horizontal protection. Vertical barriers consist of fences with appropriate height, thickness, porosity and arrangement (Forter, 1979; Hagedorn et al., 1977; Hagen et al., 1972; Skidmore and Siddoway, 1978).

Horizontal protection consists of protecting the surface against wind erosion by applying water, oil (low-gravity asphaltic oil, high-gravity waxy oil, crude oil) or chemical soil stabilizers (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 crust fracturing the asphalt sprayings must be repeated. High-gravity waxy oil is a cheap, longer lasting dune stabilizer; it penetrates to a depth of 10 - 20 cm, remains sticky and consequently later operations on the stabilized area are difficult (Chepil, 1955). Crude oil used in Libya develops a crust 0.5 cm thick and lasts about three years. An area of 5 to 15 ha could be stabilized in one day. Costs were calculated at $420 per ha (Hugedorn 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.

Chemical soil stabilizers can be used for short time protection against erosion until a plant cover has been established. They have been used also for the construction of military installations, airports, highways, houses, shopping centers, and industrial plants where vast areas were exposed to wind and water erosion.

Another goal for stabilizing sandy areas is to maintain the quality of the environment (Armbrust, 1977; Troeh et al., 1980).

Investigations were begun in 1959 to determine the amount of hay and wheat straw needed to control wind erosion on sandy soils (Chepil et al., 1963). Asphalt was used to bind the pieces of the mulch. Skimore (1978) pointed out the importance of crop residues in surface protection against wind erosion. Other natural materials for stabilization have been also applied directly to the soil surface (Chepil et al., 1963).

From these studies the desirable properties of an effective stabilizer were listed: permeability, possibility of seedling penetration, persistence of effectiveness and ease of application (Chepil and Woodruff, 1963). Costs for materials ranged from $475 to $4,750 per ha.

An emulsion of polymerized styrene-butadiene latex and mineral oil was made available in the 1960's in England for dune stabilization. It provided a good surface film. Oil/latex, in the proportion of 9:1 at a rate of 357 lha^{-1}, was also effective in controlling wind erosion. The same material was used in Australia (Armbrust and Lyles, 1975). During the same time a California firm developed an emulsion of resin and water. A German firm developed a liquid plastic material. All these products were equally effective in controlling wind erosion (Armbrust and Lyles, 1975).

A study at Manhattan, Kansas, was conducted to evaluate a number of materials commercially available to stabilize soil against wind erosion (Armbrust and Dickerson, 1971; Lyles et al., 1974). Four materials were tested in the field and 34 in the laboratory (Armbrust and Dickerson, 1971; Lyles et al., 1974). As a result of these studies criteria were established for a product to be acceptable: (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 the criteria.

Polyacrilamide (PAM) was used because it was simple to use, had the ability to aggregate sandy soils and was not toxic (De Boodt and Gabriels, 1975). However, high costs limited its use, and more recently attempts have been made to replace it with a cheaper product that would be equally effective. That product has been found to be iron sulfate and urea formaldehyde (Sharma and De Boodt, 1983). Bentonite has also been used in India to reduce percolation loss on rice fields (Das and Dakshinamurti, 1975). Cost of material and application remain the critical factors for use of these materials (Lyles et al., 1969).

To estimate the stability of natural aggregates and aggregates formed from different soil conditioners and to be able to compare them a technique base on quantitative transfer of energy was developed by Skidmore and Powers (1982). By means of the technique it is possible to determine the relationship between the dry aggregate stability and the crushing energy, the relationship between dry aggregate stability and rupture stress. This improved technique has these desirable characteristics:(i) it measures the crushing energy quickly and accurately, (ii) the digital readout is provided in convenient units, and (iii) the instruments are efficient and portable (Boyd et al., 1983).

It has been stated that ridged surfaces and soil aggregation are the only means for controlling wind erosion under some circumstances (Lyles and Tatarko, 1982; Hagen and Armbrust, 1985). For temporary stabilization it is important to understand the four major simultaneous processes affecting soil loss from a crusted surface (De Boodt and De Vlaschaviner, 1982; Hage, 1984; Hagen and Armbrust, 1985; Troech et al., 1980). The processes are (i) removal of loose soil particles less than 0.84 mm, (ii) abrasion, (iii) suspension, (iv) trapping saltating particles.

For the first process, the removal of loose soil particles, E is expressed in units of kgm^{-2}. These particles are on the top of the crust surface; they are weakly bound or not bound at all. This process has been studied since 1964 and equations were developed lately (Hagen, L. J. and Armbrust, D. V., 1985)

$$E = m - n \ln(\%sc), \qquad (\%sc) > 10$$

where: m, n - coefficients which vary with windspeed,
%sc - percent soil cover of flat residues or clods.

For the second process saltation of loose soil starts the process of abrasion on the downwind soil surface (Chepil and Woodruff, 1963; Hagen, 1984; Troeh et al., 1980). Soil abrasion loss equals C_aQ where C_a is an average abrasion coefficient with units m^{-1}, and Q the total saltation flux passage in units kgm^{-1}.

For most aggregates and crusts there is an inverse relationship between the abrasion coefficients and the mechanical stability.

The third process is suspension which removes the finer particles that move above the saltation region (Hagen and Armbrust, 1985; Troeh et al., 1980). The soil suspension equals C_sQ where C_s is the suspension coefficient with units m^{-1}. The characteristics of C_s are not known, but C_s is less important than C_a (Troeh et al., 1980).

The fourth process is the trapping of saltating soil particles by ridged surfaces and large aggregates which has been called "the governing principle of surface roughness" by Chepil (Troeh et al., 1980).

In order to estimate the amount of soil loss from a crusted soil surface and to estimate the distance downwind at which the crust fails by breaking up, the following equation was developed (Hagen and Armbrust, 1985):

$$\frac{dQ}{dx} = E + C_aQ - ((n_o + g) - \frac{(n_o + g)}{Q} - g \ln Q)\, Q$$

where: Q - the horizontal flux;
E - loose soil, kgm^{-2};
n_o - initial ridge trapping efficiency;
g - constant;
C_a - average amount of soil abraded per unit flux, m^{-1}.

This equation can be used for unridged or ridged surfaces. For the unridged surface n_o equals zero and there is and exponential increase in soil flux passage.

By integrating this equation, the distance downwind where the crust fails can be calculated. To prevent failure of the crust, management parctices which results in trapping saltating particles and thereby reducing soil flux must be used (Hagen and Armbrust, 1985).

MATERIALS AND METHODS

A sampe of Tivoli sand (mixed, thermic Typic Ustipsamment) was taken from the surface (0 - 500 mm depth) of semifixed yellowish 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). We used Wyoming bentonite commercially used for drilling mud in oil well development. It was obtained from Great-Bend, Kansas and ceramic kaolinite obtained from Macon, Georgia. The clays were mixed with the fine sand.

The clay concentrations used were 0, 10, 20, 30, 60, 120, and 240 gkg^{-1} for bentonite and 0, 10, 20, 30, 40, 50, and 60 gkg^{-1} for kaolinite. Four samples were made from each concentration and one water cycle was made for each sample. Two hundred grams of clay and sand mixture were placed in each plastic container. All the containers of sand and clay were placed in the rainfall simulator and irrigated at an intensity of 2.5 cmhr^{-1} for ten minutes and then were air-dried for nine days. Three samples of each 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 determinations were made on aggregates using the technique described by Skidmore and Powers (1982) with an apparatus of Boyd et al. (1983) using what is called the Soil Aggregate Crushing Energy Meter (SACEM).

It was not possible to obtain aggregates from the untreated sand (0% bentonite and 0% kaolinite), and from 10 gkg^{-1} of kaolinite concentration because the mixtures were very soft. We studied three aggregates from each sample; the diameter of each aggregate was about 12 - 13 mm. The energy required to crush the aggregates, the initial breakforce, the diameter, and mass of the aggregates were determined. The crushed material was placed on a 6.35 mm sieve. The material that did not go through the sieve was put back on the SACEM and procedure repeated until the aggregate was broken into pieces less than 6.35 mm in diameter. All the material was then put in the top of a set of eight nested sieves with hole widths of 4.76, 3.36, 2.83, 2.0, 1.0, 0.5, 0.25, 0.106 mm. The nest of sieves was shaken for ten seconds with a Tyler Portable Sieve Shaker, Model TX-24. The material that passed through the 0.106 mm sieve was placed on a set of smaller sieves with hole widths of 0.074, 0.053, 0.038 mm and shaken for two minutes with an Allen-Bradley Sonic Sifter, Model L3PF. The material on each sieve was also weighed.

The crushing energy of each aggregate was calculated by dividing the energy in joules read on the SACEM by the aggregate mass in kilogram and the results given in Jkg^{-1}. The densities of the aggregates were determined using aggregates coated with paraffin by the method of Blake (1965). The pipette method for particle size distribution analysis of the sand was performed Day (1965). The total aggregate surface area was calculated by the method given by Skidmore and 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 Jm^{-2}. It can be used to measure resistance of aggregates and crusts to abrasion from wind erosion. The rupture stress was calculated by the method of Skidmore and Powers (1982). The units used were kilopascals. They measure the resistance of aggregates to crushing energy at the first break of the aggregates.

For the second step of the study larger containers were used, wind tunnel trays with dimensions 122.4 x 20.4 x 5.1 cm . The clay used was bentonite. The clay concentrations were: 0, 10, 20, 30 gkg^{-1}. The sand and the bentonite were mixed with a masons mixer. After the trays were filled with the clay and sand mixture, the samples were wetted in the rainfall simulator at an intensity of 2.5 $cmhr^{-1}$ for ten minutes and then ovendried at a temperature of 37°C to constant weight. We filled five trays for each concentration level. Four of the trays were used for the wind tunnel study and one for the dry aggregated stability and depth of crust studies. 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 and the tunnel operated at wind velocity of 14 ms^{-1} for five minutes. The trays were weighed again and the soil loss calculated. Next, the test tray was placed at the same section and 1.300 kg Tivoli fine sand was placed at a distance of two meters upwind of the test tray. This sand will be called the abrader. Between the tray and the abrader fine sand particles were stuck to the tunnel floor with adhesive spray. The tunnel was operated at the same wind velocity of 14 ms^{-1} until abrader was blown over the test section of the wind tunnel. This procedure was repeated six times on each sample. Then the procedure was repeated twice with six kilograms of abrader. Each time the loss of soil from the tray was recorded.

The experimental design for Part I was completely randomized with two clay types kaolinite and bentonite. There were seven clay concentrations for each clay type: 0, 10, 20, 30, 60, 120, 240 gkg^{-1} for bentonite and 0, 10, 20, 30, 40, 50, 60 gkg^{-1} for kaolinite.

There were four replications for each clay concentration and one wetting-drying cycle for each replicated sample. 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.

At 10 gkg^{-1} kaolinite concentration the mixture was so soft that it was not possible to make aggregates out of it.

A regression analysis was performed on the crushing energy of aggregates enriched with kaolinite with two independent variables: concentration (20, 30, 40, 50, 60 gkg^{-1}) and water cycles (1, 2, 3, 4). A regression analysis was also performed on the crushing energy of aggregates enriched with bentonite with two indipendent variables: concentration (10, 20, 30, 60, 120, 240 gkg^{-1}) and the same water cycles (1, 2, 3, 4).

A more detailed study was done on aggregates enriched with bentonite. The same procedure was used adding two more concentrations 40 and 50 gkg^{-1}. So we got 32 observations with five independent variables: aggregate mass, aggregate diameter, bentonite concentration, water cycles, and initial break force. The backward and stepwise procedures were used.

The completely randomized design was used for the second part. For the same mixture, the samples were assigned randomly to the five trays. The data obtained were analysed by analyses of variance (ANOVA) and the regression analysis. The tests for interaction effects were performed using F tests and the means were compared with one another using LSD. To model the response of soil loss to the additions of bentonite, a regression analysis was performed. The analyses were done by SAS Programs.

RESULTS AND DISCUSSION

The experiment was conducted in two steps. We used the results of the first step to conduct the second one. At the beginning of the first step we made four hypotheses. The expeperiment showed that two of these hypotheses were true and two false.

Part I. Aggregating Fine Sand by Adding Kaolinite and Bentonite

The hypotheses were as follows:

1. The dry-aggregate stability of aggregates formed from clay and fine sand is dependent upon the clay concentration.
2. The stability of aggregates formed from clay and fine sand is dependent upon the process of wetting and drying cycles.
3. The stability of aggregates formed from kaolinite and fine sand mixture is greater than the stability of those formed from bentonite and fine sand mixture.
4. The crushing energy of the aggregates and the concentration of clay in the mixture from which the aggregates were formed are linearly related.

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

The regression analysis performed on the crushing energy of aggregates enriched with bentonite (see Table 2) gave the same results for both F test and T test. That means that the resistance of aggregates enriched with both kaolinite and bentonite to crushing energy depended upon the clay concentration and not upon the wetting-drying cycles, i.e., the first hypothesis was true (see Fig. 2) and the second hypothesis false. The same result was obtained with the regression analysis of the crushing energy of bentonite aggregates. 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 and initial break-force). Except the bentonite concentration, the backward and stepwise procedures eliminated all the independent variables at 0.50 level. That means that the resistance of aggregates enriched with bentonite to breaking by external forces depended on the bentonite concentration.

TABLE 1
ANALYSIS OF VARIANCE TABLE FOR KAOLINITE

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

** Significant at 0.01 level

$R^2 = 0.827$

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter=0	Prob>|T|
Intercept	1	1.04	0.57	1.82	0.0853
Water	1	0.18	0.14	1.30	0.2103
Concentration	1	96.58	10.80	8.94	0.0001

TABLE 2
ANALYSIS OF VARIANCE TABLE FOR BENTONITE

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

** Significant at 0.01 level

$R^2 = 0.687$

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter=0	Prob>|T|
Intercept	1	9.58	7.09	1.35	0.1914
Water	1	1.43	2.39	0.60	0.5553
Concentration	1	226.38	33.44	6.77	0.0001

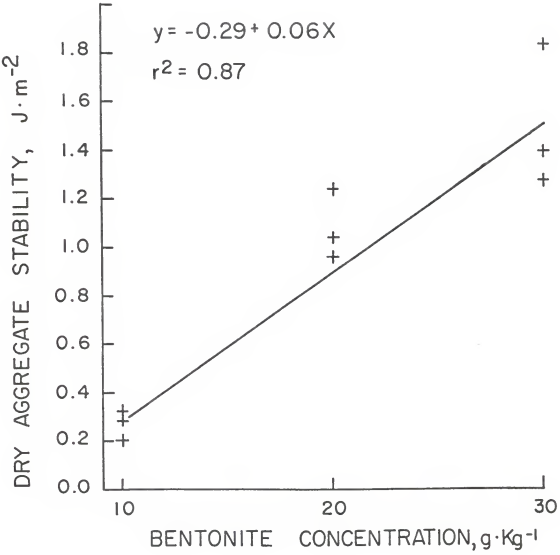


Fig. 1 The relationship between bentonite concentration and dry-aggregate stability.

Aggregates from bentonite and fine sand mixture were 4 - 5 times more stable than those from kaolinite and fine sand mixture at the same clay concentration (see Table 3). At the kaolinite concentration of 10 gkg^{-1} the crust was very soft, the sand particles did not stick together and we could not make aggregates out of it. This points out that our third hypothesis is false. The difference between bentonite and kaolinite is in the binding type of the unit cells. Bentonite is a 2:1 type clay minerals with shrink-swell capability. When wet, it traps many sand particles. Kaolinite is a 1:1 clay minerals with rigid hydrogen bonding between unit cells. The fourth hypothesis is true in the range of 10 to 30 gkg^{-1} of bentonite concentration. In this range we have a straight line relationship between the resistance of aggregates to crushing energy and the bentonite concentration (see Fig. 2). The dry-aggregate stability index and the crushing energy were highly correlated (see Fig. 3), as were the dry-aggregate stability index and the rupture stress (see Fig. 4). Aggregate densities were measured only for the bentonite clay (see Table 4). They were used for the calculation of the total aggregate surface area. From this surface area, the aggregate stability index was calculated. The densities also were used to calculate the rupture stress (see Table 5).

TABLE 3

CRUSHING ENERGIES OF AGGREGATES ENRICHED WITH BENTONITE AND KAOLINITE

Clay Added	Crushing Energy	
	Bentonite	Kaolinite
gkg^{-1}	Jkg^{-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

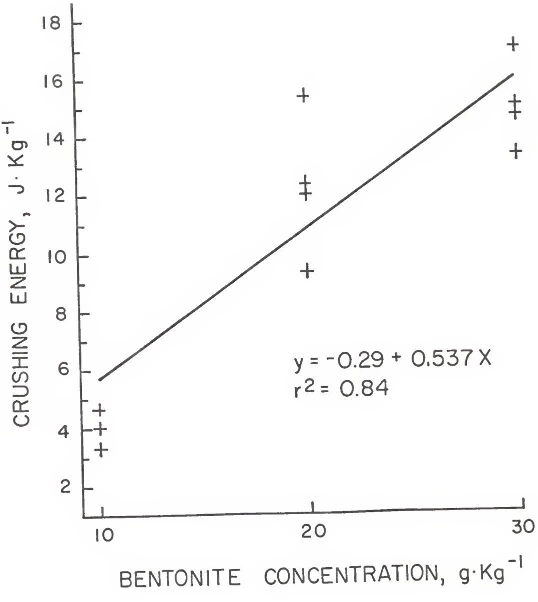


Fig. 2 The relationship between bentonite concentration and the crushing energy.

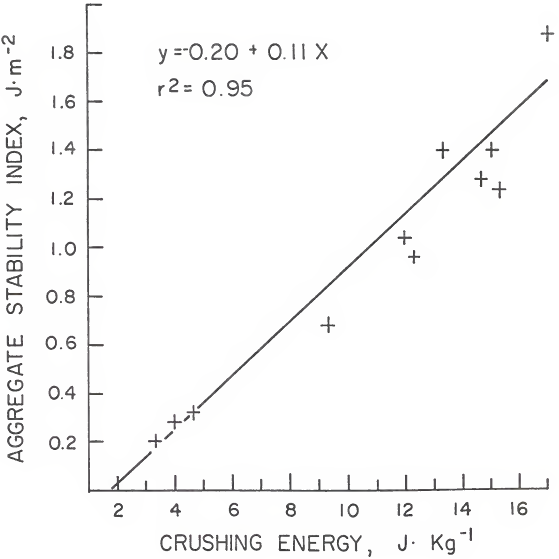


Fig. 3 The relationship between the crushing energy and the dry-aggregate stability index.

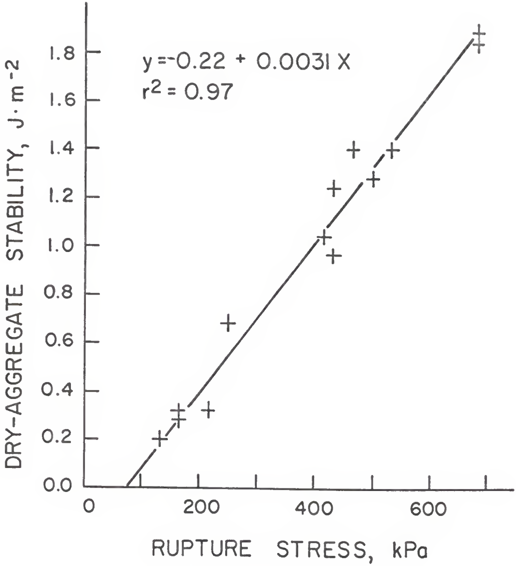


Fig. 4 The relationship between rupture stress and dry-aggregate stability index.

TABLE 4
AGGREGATE DENSITIES

Bentonite Concentration	Bulk Density
gkg^{-1}	gcm^{-3}
10	1.61 ± 0.00*
20	1.57 ± 0.00
30	1.58 ± 0.06

* Standard deviation

TABLE 5
CRUSHING ENERGY, STABILITY AND RUPTURE STRESS OF AGGREGATES OF TIVOLI FINE SAND ENRICHED WITH BENTONITE CLAY

Clay Added	Crushing Energy	Aggregate Stability Index	Rupture Stress
gkg^{-1}	Jkg^{-1}	Jm^{-2}	kPa
10	4.25 ± 0.63*	0.28 ± 0.00	173.62 ± 35.33
20	12.12 ± 2.43	0.98 ± 0.06	381.98 ± 49.68
30	14.99 ± 1.01	1.49 ± 0.13	548.40 ± 95.05

* Standard deviation

Part II. Wind Tunnel Study of Bentonite Crust

After the rainfall treatment the crust formed was composed of one consolidated block (see Fig. 5) on the surface of which there were some sand grains that were free to move and that we called loose sand (1). Other particles were weakly stuck to the block (2), and the third group of particles was composed of the grains that were firmly cemented together with the bentonite (3) and formed the consolidated crust. Beneath the crust 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.

When clay particles are wetted, they increase their surface area and trap the soil particles, but some of the sand grains on the surface are weakly trapped or not trapped at all. These sand grains make up the loose soil. During the process of wetting of the mixture in the rain tower, the greater the clay content the earlier runoff starts. Runoff removes the finest clay particles and leaves the larger particles that will form the loose soil on the crust surface. At the lower bentonite concentrations the crust surface is ridged by the rain drop impact, while at the higher concentration the surface is rather smooth with loose sand particles on top. The loose sand grains are less than 0.84 mm diameter, so they are blown away when a wind stronger than 5.3 ms^{-1} passed over. The weakly trapped particles also are blown away with the first saltation impacts. As these particles are blown away the crust becomes more and more stable.

We wanted to find out both the depth of incorporation of the bentonite needed and the concentration that would form a mixture permeable enough so water might infiltrate and wet the whole depth of mixture. The wetted depth, after drying, forms the crust that controls wind erosion.

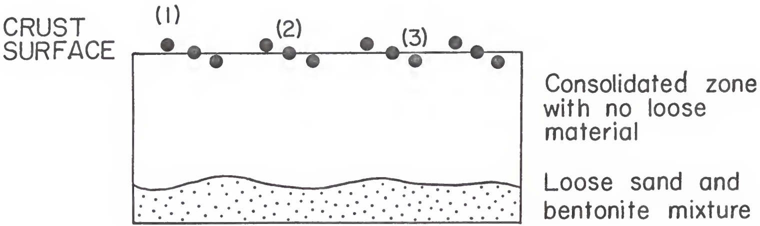


Fig. 5 Configuration of crusted surface after rainfall treatment with loose sandgrains (1), weakly held grains (2), and firmly cemented grains (3).

As the clay concentration increased, the crust depth decreased (see Fig. 6).

We expected that as the bentonite concentration increased, the amount of loose soil particles on the surface of the crust would decrease. We expected also that during the wind erosion process, the amount of soil lost from the tray would increase with the increase of the quantity of abrader. Finally, we speculated that the grater the mechanical stability of the crust formed, the lower would be the loss of soil by abrasion.

During wind erosion from the trays, there were two kinds of soil loss: loose soil loss and loss by abrasion. The loose soil loss E was a linear function of the bentonite concentration with a positive slope (see Fig. 7). That was the opposite of what we expected. The zero intercept model gives a R^2 of 0.93 and is the best model for the loose soil loss given the bentonite concentration.

During the wetting process, the finest clay particles at the surface of the tray are either carried away by runoff or taken below the surface, so only sand particles remain on top and form the loose soil. The higher the clay content, the more clay particles migrate downward and/or are carried away, and the more we have loose soil at the crust surface which is rather smooth. At the lower bentonite concentrations, the crust surface is ridged by the rain drop impact during the wetting process (see Fig. 8). These ridges lower the loose soil loss.

In order to describe the abrasion loss, it is useful to define an abrasion coefficient C_a. Let L be the cumulative abrader passage in kgm^{-1}. An abrasion coefficient than can be defined as

$$C_a = \frac{dL}{dQ}$$

If L is a linear function of Q, C_a is the slope of the line and a constant. As shown in Fig. 9, C_a was constant in the consolidated crust, but somewhat larger at the surface where there were

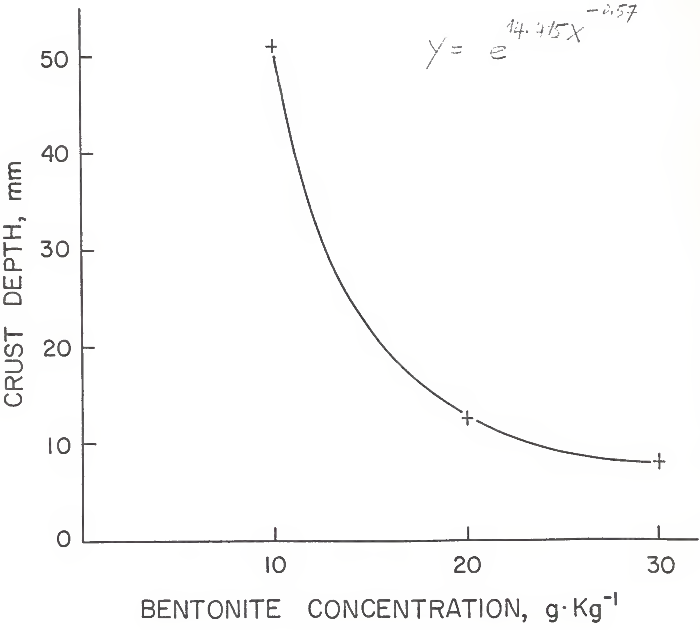


Fig. 6 The relationship between bentonite concentration and crust depth.

$Y = 0.209X^{-0.684} + 1.9923 \times 10^{-6} X^{3.553}$

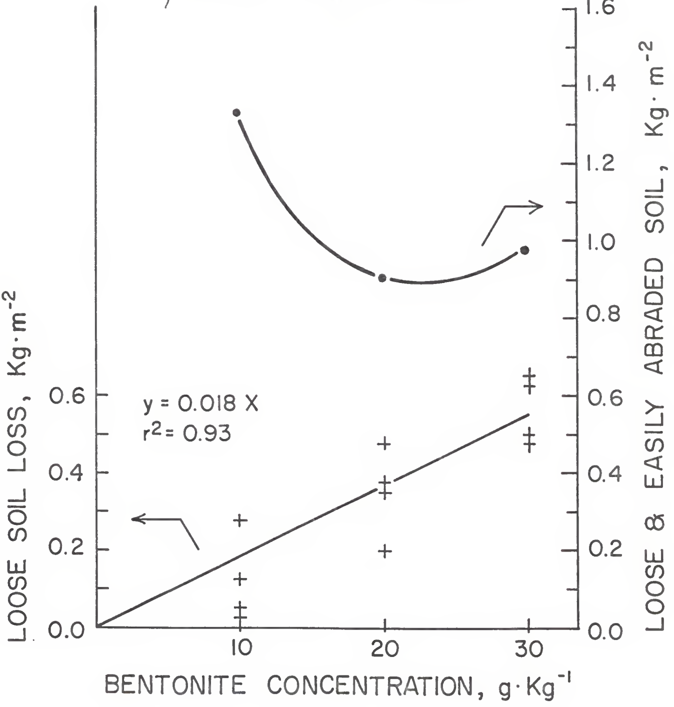
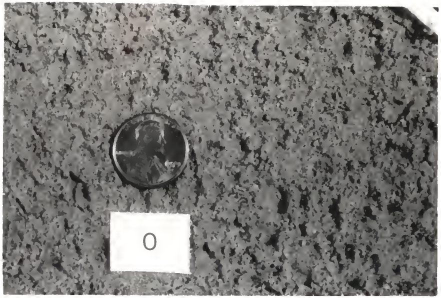


Fig. 7 The relationship between bentonite concentration loose soil, loose and easily abraded soil.

Fig. 8 Configuration of Crust Surface
After Rainfall Treatment.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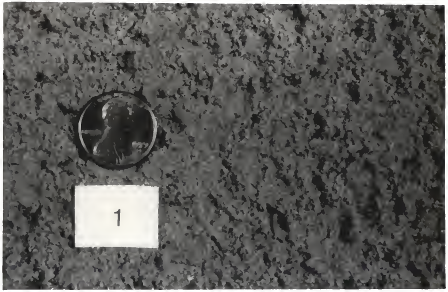
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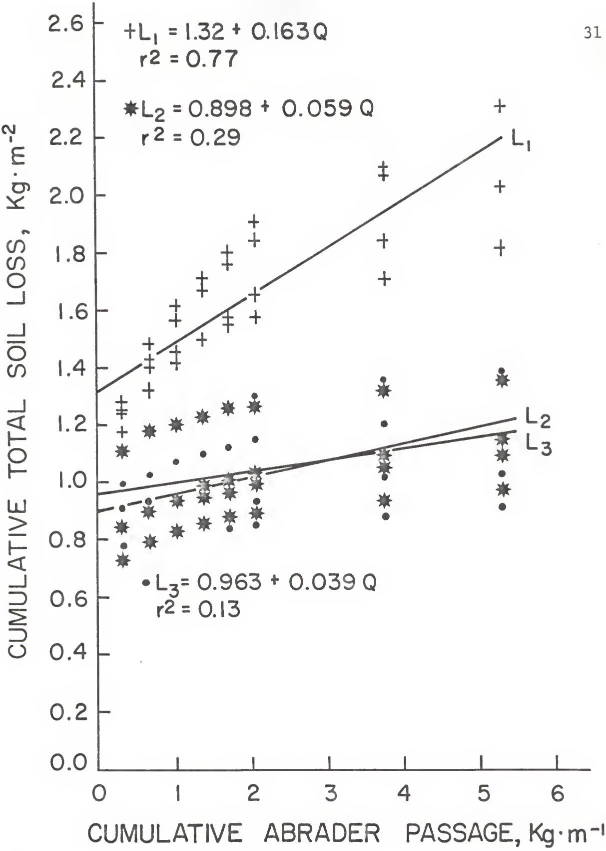

Fig. 9 The relationship between the cumulative abrader passage and the cumulative total soil loss for 10, 20, 30 gkg^{-1} bentonite.

some weakly held sand grains. To simplify analyses of the problem, the weakly held sand loss (defined at the zero abrader passage in Fig. 9) was added to the loose sand loss and C_a was treated as a constant.

The cumulative loose soil and easily abraded soil from the crust surface decreased as the bentonite concentration increased (see Fig. 7).

For the control treatment (see Fig. 10) the relationship between the cumulative abrader passage and the cumulative total soil loss was linear with a bigger slope than 10, 20, and 30 gkg^{-1} bentonite concentration. The coefficient of abrasion was $C_a = 7.67$ m^{-1}. It is over 30 times higher than the coefficient of abrasion for 10, 20, and 30 gkg^{-1} bentonite concentration.

Although the loose soil loss for 0 gkg^{-1} bentonite was very low, the easily abraded soil loss was very high, hence, the sum of these two results was high, 5.94 kgm^{-2}.

Because it is difficult to measure abrasion coefficients, dry-aggregate stability was tested as a predictor of the abrasion coefficient. By looking at Fig. 11 it can be seen that as the dry-aggregate stability index increased, the soil lost from abrasion decreased as did C_a and the regression equation of the function is

$$C_a = 0.056\ S_a^{-0.846}$$

with a $R^2 = 0.999.$

Finally, we want to calculate the maximum length of surface one can expect to have covered by a stable crust after wind erosion has ceased. In order to do the calculations, let us apply the law of conservation of mass to a control volume above a field segment (Fig. 12). The amount of sand coming over the segment when a wind blows is the cumulative abrader passage Q in kgm^{-1}. The amount of sand leaving the segment is

$$Q + \frac{dQ}{dx}$$

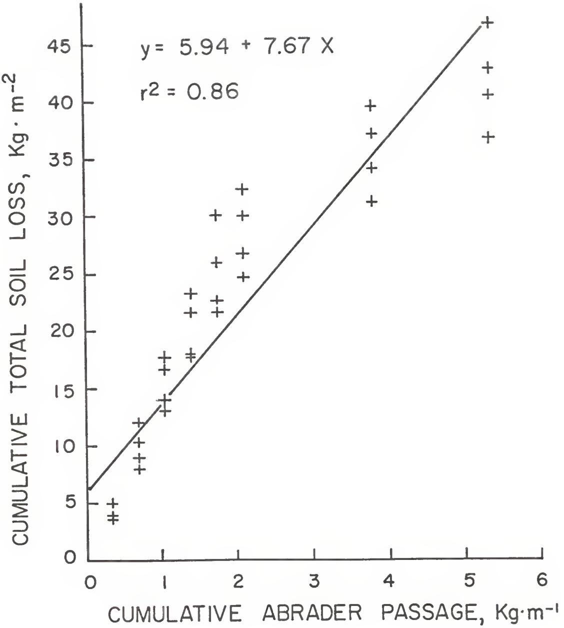

Fig. 10 The relationship between the cumulative abrader passage and the cumulative total soil loss for 0 gkg^{-1} bentonite.

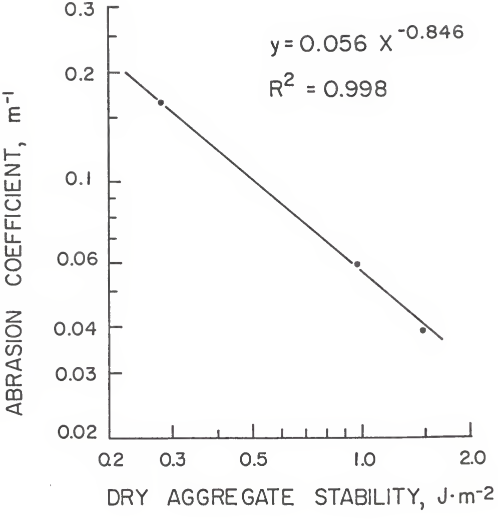

Fig. 11 The relationship between the dry-aggregate stability and the abrasion coefficient.

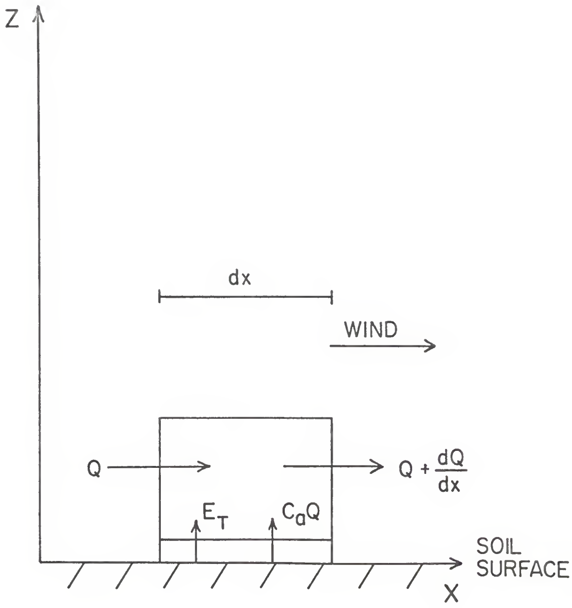

Fig. 12 Law of conservation of mass applied to soil movement by wind.

The loss from the surface of the segment then equals

$$Q + \frac{dQ}{dx} - Q = \frac{dQ}{dx}$$

In fact, the surface loss equals the summation of the loose sand and easily abradable sand E_T, plus the loss from abrasion (C_aQ), i.e., the loss (L) from the segment is described by the linear equation

$$L = \frac{dQ}{dx} = E_T + C_aQ$$

In this equation, the abrasion coefficient is $C_a = \frac{dL}{dQ}$.

The loss for single bentonite concentration is described as follows:

1. For 0 gkg^{-1} bentonite (check) (see Fig. 10)

   $$L_o = 5.94 + 7.67\ Q$$
   $$C_{a_o} = 7.67$$

   The loss increases as the amount of soil abrader increases (see Fig. 8).

2. For 10 gkg^{-1} bentonite

   $$L_1 = 1.32 + 0.163\ Q$$
   $$C_{a_1} = 0.163$$

3. For 20 gkg^{-1} bentonite

   $$L_2 = 0.898 + 0.059\ Q$$
   $$C_{a_2} = 0.059$$

4. For 30 gkg^{-1} bentonite

   $$L_3 = 0.963 + 0.039\ Q$$
   $$C_{a_3} = 0.039$$

For 20 and 30 gkg^{-1} bentonite, the slope of the simple linear regression model is small; hence, the model does not explain much of variance in the experimental data.

The soil loss for 30 gkg^{-1} bentonite is larger than the one for 20 gkg^{-1} at the beginning of the study because the presence of more loose soil grains on surface. At the point $Q = 3.25\ kgm^{-1}$ the two losses are equal, and from this point the normal pattern starts, the 30 gkg^{-1} bentonite concentration becomes more stable, after the loose soil is removed.

The loss from 10 gkg^{-1} bentonite was always larger than the loss from 20 gkg^{-1} and 30 gkg^{-1}.

From the linear equation of loss from a control volume

$$L_d = E_T + C_a\ Q_d$$

the amount of soil abrader needed to destroy the crust (Q_d) can be calculated:

$$Q_d = \frac{L_d - E_T}{C_a}$$

where L_d can be computed from the loose soil E, the crust depth (D), and the crust bulk density (r):

$$L_d = E + D\ r$$

The total soil loss (L_d) and the flux of soil abrader before crust failure for single clay concentration are as follows:

1. For 10 gkg^{-1} bentonite

$$L_{d1} = 0.1175\ kgm^{-2} + 0.051\ m \times 1610\ kgm^{-3} = 82.22\ kgm^{-2}$$

$$Q_{d1} = \frac{L_{d1} - E_{T1}}{C_{a1}} = \frac{82.22 - 1.32}{0.163} = 496.32\ kgm^{-1}$$

2. For 20 gkg^{-1} bentonite

$$L_{d2} = 0.36375 + 0.013 \times 1568 = 20.74\ kgm^{-2}$$

$$Q_{d2} = \frac{20.74 - 0.898}{0.059} = 336.30\ kgm^{-1}$$

3. For 30 gkg^{-1} bentonite

$$L_{d3} = 0.5595 + 0.00832 \times 1578 = 13.6 \ kgm^{-2}$$

$$Q_{d3} = \frac{13.69 - 0.963}{0.039} = 326.30 \ kgm^{-1}$$

We can now compute the maximum length of crusted surface (l_d) which will erode before the crust failure using the law of conservation of mass:

$$\frac{dQ}{dx} = E_T + C_a Q$$

$$\int_0^{Q_d} \frac{dQ}{E_T + C_a Q} = \int_0^{l_d} dx$$

The starting zero assumes that there is no incoming soil to the stabilized region.

$$l_d = \frac{1}{C_a} \left[\ln \left(\frac{E_T + C_a Q}{E_T} \right) \right]$$

The maximum length of stabilized surface (l_d) which can erode before the crust failure, for single clay concentration is as follows:

1. For 10 gkg^{-1} bentonite

$$l_{d_1} = \frac{1}{0.163} \ln \left(\frac{1.32 + 0.163 \times 496.32}{1.32} \right) = 25.34 \ m$$

2. For 20 gkg^{-1} bentonite

$$l_{d_2} = \frac{1}{0.059} \ln \left(\frac{0.898 + 0.059 \times 336.30}{0.898} \right) = 53.20 \ m$$

3. For 30 gkg^{-1} bentonite

$$L_{d_3} = \frac{1}{0.039} \ln \left(\frac{0.963 + 0.039 \times 326.30}{0.963}\right) = 68.00 \text{ m}$$

The higher concentrations of bentonite give the longer lengths of stabilized region before the crust starts to fail (see Fig. 13).

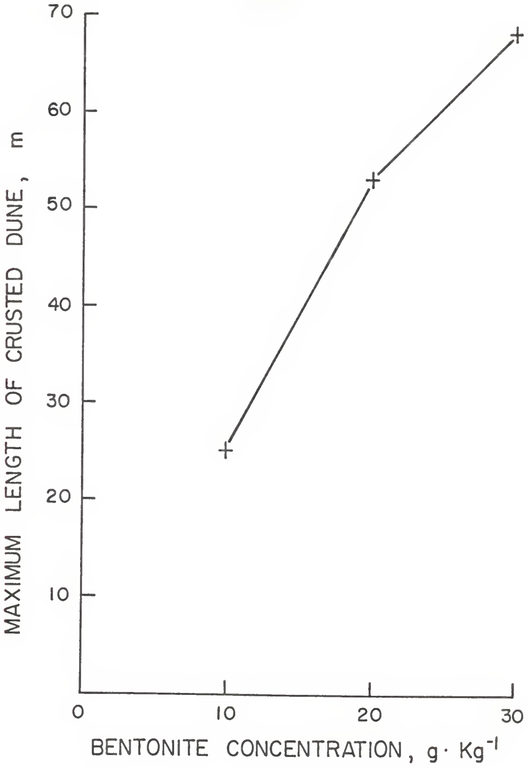

Fig. 13 The relationship between bentonite concentration and maximum length of stabilized crust.

SUMMARY AND CONCLUSIONS

Bentonite is a better cementing agent than kaolinite for aggregating sand. It might be more efficient to use bentonite rather than kaolinite for soil stabilization.

From physical and practical view point, bentonite incorporation should be limited within the range of 10, 20, and 30 gkg^{-1} because beyond this range the mixture of sand and bentonite does not get wet therefore there will be no crust. In that range, the resistance of aggregates enriched with bentonite to breaking by mechanical forces is proportional to the bentonite content of the mixture . When the bentonite concentration of the mixture with fine sand increases, the amount of loose soil particles on crust surface and easily abraded soil increases and the soil loss by abrasion decreases.

The effectiveness of using bentonite to produce a stable crust in attempting to stabilize sand dunes will depend upon the depth of incorporation and concentration.

The maximum length of stabilized crust that may be eroded before crust failure increaes with the increase of bentonite content in the range of 10 to 30 gkg^{-1}. We speculated that in applying the results of this study to practical operations of stabilizing sand dunes the following procedures might be followed.

A bentonite concentration of 20 gkg^{-1} with a depth of incorporation of 2 cm can be used for dune stabilization, a zone uphill of 53 m long will be stabilized on each longitudinal dune. The top of the dune should be left barren, so more sand will roll down in the relatively stable zone, at the foot of the dune leeward, a barrier of 0.50 m will be set at the beginning of the crusted surface to make sure that no sand is coming on the stabilized area. The choice of this bentonite concentration is dictated by the later field operation of planting
During these operations the crust will be broken and on the

field surface there will be aggregates big enough so that what Chepil called the "governing principle of surface roughness" will control wind erosion until the plants are big enough to cover the dune surface. Aggregates from 10 gkg^{-1} bentonite concentration might be too soft and get broken during planting operations. Crust formed from 30 gkg^{-1} bentonite concentration is the hardest of all three crusts, but it might be too shallow.

A large number of plants per hectar will be required to have an early cover of surface dune by plants.

The mixing will be done with a rotor tiller and wetting of the mixture will be done immediately after the operation of incorporation.

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USE OF BENTONITE TO STABILIZE SANDY SOIL MATERIAL IN A WIND TUNNEL STUDY

by

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B.S., University Cyrille and Method
Skopje, Yugoslavia, 1978

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MASTER OF SCIENCE

Department of Agronomy

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ABSTRACT

Migration of sand dunes threatens food production and degrades the environment wherever it occurs.

This research was undertaken to evaluate use of clay to stabilize sand surface temporarily.

Different concentration of bentonite (0, 10, 20, 30 gkg^{-1}) were mixed with fine sand. The mixture was wetted with a simulated rainfall and dried; the mechanical stability of the crust was studied both with the Soil Aggregate Crushing Energy Meter (SACEM) and the wind tunnel.

A straight line relationship was found between the resistance of aggregates to crushing energy and the bentonite concentration. An inverse relationship between the dry aggregate stability and the coefficient of abrasion was found. The infiltration depth decreased inversely to the bentonite content, so did the thickness of the crust. The amount of loose soil on the crust surface was found to increase with the bentonite concentration while the flux of abraded soil particles was greatest when the added bentonite concentration was low. Our results indicate that bentonite may be useful for temporary sand dune stabilization by incorporating 20 gkg^{-1} in the surface layer and forming a 2 cm crust over a distance of 53 m downwind.