SOME PHYSICAL PROPERTIES OF DENSIFIED SOILS

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SYNOPSIS

This paper presents laboratory data to substantiate the belief of the authors that the stability of densified soil mixtures can be measured by the behavior of these mixtures when submitted to drying, freezing and capillary water The samples examined by these tests include ten fine grained soils and six soil-aggregate mixtures The fine grained soils have liquid limits of 24 to 80 and plasticity indices of 5 to 52 The soil-aggregate mixtures are well-graded up to ½-inch, and the material passing the No 40 have liquid limits of from 21 to 38 and plasticity indices of from 6 to 21

The tests were made by compacting the soils to maximum density at optimum moisture in a standard Proctor mold The lineal changes due to drying and freezing were determined on the expelled specimen The effects of capillarity were determined by replacing the bottom of the Proctor mold with a perforated one and placing the whole assembly in water

The tests reveal that (1) All mixtures shrink on drying and the shrinkage increases as the optimum water content increases The lineal shrinkage on the samples examined varied from 0 1 to 4 3 per cent (2) The fine grained soils shrink on freezing and the shrinkage increases as the optimum water content increases whereas the soil-aggregate mixtures expand and the expansion increases as the ratio of water used at optimum to theoretical water required increases The maximum shrinkage obtained with fine grained soils was 1 0 per cent and the minimum 0 1 per cent With the soil-aggregate mixtures the expansion varied from 0 2 per cent to 0 5 per cent (3) None of the soil samples absorbed water appreciably by capillarity if the air void content at optimum moisture and maximum density did not exceed 3 5 per cent None of the soil-aggregate mixtures absorbed water if the air void content did not exceed about 1 0 per cent

Compacted water-soil mixtures have been used extensively in recent years in the construction of boulevards, highways, and airport runways They have proved most useful as subbases for the improvement of subgrades and as bases under bituminous wearing surfaces. Hand in hand with this construction program much research has been carried on, both in the laboratory and the field, to obtain information necessary for the economical design of durable pavements of this type. Some data are presented here on a number of physical tests which we have been using as a means of measuring stability.

From observations of field and laboratory tests and performances over a number of years we have come to the conclusion that flexible pavements can be most safely designed by considering the following factors

1. The load bearing value of the natural subgrade at its worst anticipated condition.
2. The rate at which the subgrade strength can be increased by placing upon it layers of densified soils, soil-aggregate mixtures or bituminous mixtures.
3. The stability of the densified mixtures
4. The relation between unit strength and size of testing plate.

Last year we presented data on factor No. 4[1] and this time we wish to discuss our methods for judging the durability of densified soils. At some future meeting we expect to discuss the other two factors and finally it is our intention to propose a complete method for the designing of roads and runways

[1] W H Campen and J R. Smith, "Measuring the Load Supporting Value of Flexible Pavements," *Proceedings*, Highway Research Board, Vol 21, p 142 (1941).

In evaluating the stability of densified soils the effects which might be produced when they are dried, frozen, or subjected to absorption by gravitational or capillary water must be considered It is well-known that soils after compaction in the region of maximum density and optimum moisture will shrink on drying This shrinkage can be great enough literally to cut the surface up into small segments. When this condition develops slab action and low supporting values greatly diminish with consequent rapid rutting and spalling.

Freezing may produce either shrinkage or swelling. If the shrinkage is excessive the results will be the same as described under drying Excessive expansion may produce buckling or even blow ups Furthermore, if freezing should produce a permanent volume increase the water holding capacity of the mass would be increased By this process, in the presence of water, the compacted mixture could lose its density and load bearing value very quickly.

The entrance of water into densified soil masses beyond the quantity needed for optimum moisture may produce two distinct effects. When the process of absorption merely replaces entrapped air a limited loss of load supporting value results. If absorption, however, produces swelling additional space is provided for holding water. This condition reduces load bearing value very rapidly and in addition may cause heaving immediately or when followed by freezing.

DESCRIPTION OF TESTS

Since the processes of drying, freezing and absorption are the natural enemies of densified soils it becomes of utmost importance to determine the quantitative effects of these destructive agencies by some laboratory methods. It is believed the following apparatus and methods accomplish this purpose.

Drying Test The sample is compacted in a standard Proctor mold, expelled and the diameter measured, allowed to dry at room temperature and measured daily until shrinkage ceases Thumb tacks are used as reference points and the cylinder is placed on a ½-in. screen and turned periodically to obtain uniform drying. Measurements are made with a gauge graduated in 1/10 mm. and shrinkage is based on the diameter before drying.

Freezing Test The sample is prepared as for drying, dipped in melted paraffin once or twice, and subjected to a temperature of 10 deg F. below zero for six hours or more The paraffin treatment prevents loss of water during the freezing period. The sample is measured before freezing, after freezing, and after thawing Lineal change is based on the diameter before freezing

Capillarity Test The sample is compacted and the mold base is removed and replaced with a similar one which has been perforated with $\frac{1}{16}$-in holes The mold assembly is placed in water so that about ½ in. of the bottom of the sample is submerged The water container and the sample are then placed in a moisture cabinet and allowed to remain for 7 days. Absorption is determined by weight on a gram scale Volume increase is measured by cutting off and weighing extruded material at the top of the mold. A piece of filter paper is inserted between the bottom of the sample and the perforated plate Care is taken to displace the air in the perforations while attaching the bottom plate. Absorption is expressed either as percentage of the dry weight of the sample or as percentage of the original volume of the sample.

Deformation Test The sample is compacted in 1½-in. layers in a mold 4 in. high and 8 in. in diameter with a tamper weighing 11 9 lb. The face of the tamper has an area of 12 sq in. and is applied 46 times through a distance of 18 in. This method of compaction gives the same results as the Proctor Method. The center of the sample, while still in the mold, is tested for load bearing values at deformations of about 0 1 in., 0 2 in., and 0.3 in. with a 2-in diameter bearing block. In making the test the bearing block is pressed into the sample to the approximate deformation desired and 2 minutes are allowed to elapse before actual deformation and load readings are taken Deformation readings are taken with a dial gauge graduated in 0 01 in and loads are taken with either a scale graduated in ounces or hydraulic gauges graduated in 10-lb divisions

TEST RESULTS

To show information on a wide variety of soils we are presenting data on ten soils and six soil-aggregate mixtures. Some physical characteristics of these materials are given in Tables 1 and 2 It will be

TABLE 1

CHARACTERISTICS OF SOILS

Soil No	1	2	3	4	5	6	7	8	9	10
Liquid limit	29	24	34	29	36	39	37	38	52	80
Plasticity index	5	9	10	11	16	18	18	19	30	52
Retained on No. 10 sieve, per cent	0	0	0	0	0	0	0	0	0	0
Retained on No 40 sieve, per cent	0	20	0	4	0	0	2	0	0	0
Retained on No 200 sieve, per cent	0	44	0	38	0	1	23	3	0	0
Sand	16	52	2		1	16		15	76	2
Silt	76	39	84		83	72		69	76	60
Clay	8	9	14		16	12		16	24	38
Optimum moisture, per cent	15	10 5	17	14	17 5	17 5	14	18 1	20	24 2
Maximum dry weights—lb. per cu ft	113 5	124 2	111 5	115 0	110 2	105 8	116 0	108 0	105 5	100 0
Air voids, per cent	5 1	2 9	3 2	3 6	2 9	5 4	3 7	4 4	2 8	1 2
Specific gravity	2 61	2 62	2 70	3 71	2 67	2 61	2 65	2 68	2 67	2 68
Public roads administration classification	A-4	A-2	A-4	A-7	A-7	A-7	A-7	A-7	A-7	A-7

TABLE 2

CHARACTERISTICS OF SOIL-AGGREGATE MIXTURES

Mixture No	1	2	3	4	5	6
Liquid limit	26	34	21	38	27	27
Plasticity index	7.5	21	6	12	12	13
Retained on ½-in screen, per cent	0	0	0	0	0	0
Retained on No 4 sieve	12	12	15	15	15	14
Retained on No 10 sieve	40	40	40	42	42	40
Retained on No 40 sieve	70	70	70	72	74	72
Retained on No 200 sieve	80	80	85	78	87	85
Retained on No 270 sieve	80 4	880 0	87	78 5	87 5	86
Specific gravity of solids	2 63	2 62	2 61	2 62	2 60	2 60
Optimum water, per cent	6	6 75	5 6	6 5	6	6 5
Maximum dry weight—lb per cu ft	139 5	137 5	140 5	138 2	139 5	138 8
Air voids, per cent	1 6	1 2	1 2	1 1	1 4	0 3
Public roads administration classification	A-2	A-6	A-1	A-4	A-2	A-2

observed that the soils have liquid limits of 24 to 80 and plasticity indices of 5 to 52. In the soil-aggregate mixtures the liquid limit varies from 21 to 38 and the plasticity index from 6 to 21. In these two tables are also shown the optimum moisture, maximum density and air content, by volume, of each sample The air content or air voids is included because it is the one factor which usually limits the extent of absorption by capillarity.

In Tables 3 and 4 are shown the lineal shrinkages due to drying. As far as soils are concerned the results show that as the optimum water varies from 10 5 to 24 2 the shrinkage varies from 0 5 per cent to 4 7 per cent respectively In general it may be inferred from these tests that the shrinkage is proportional to the optimum water but it should be emphasized that the only correct way to determine this property is to make a test The shrinkage also varies with the plasticity index but not as consistently as with the optimum water. As far as the soil-aggregate mixtures are concerned the shrinkage varies from 0 1 to 0 2 per cent and is not affected much by the optimum water or plasticity index as

TABLE 3

DRYING TESTS ON SOILS

Soil No	Composition			
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	Lineal shrinkage, per cent
1	103 5	112 7	4 9	0 5
1	118 0	108 8	4 3	1 2
2	95 5	124 2	3 9	0 5
3	97 0	111 5	2 3	1 0
3	109 0	109 0	1 7	1 7
4	96 5	114 2	5 3	0 6
5	103 5	110 0	2 2	1 2
6	100 0	105 8	5 4	1 8
7	101 5	106 0	3 5	0 9
8	99 0	108 0	4 0	1 4
9	100 0	105 5	2 8	2 6
9	113 5	102 5	2 0	3 7
10	100 0	100 0	1 2	4 3

TABLE 4

DRYING TESTS ON SOIL-AGGREGATE MIXTURES

Mixture No	Composition			
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	Lineal shrinkage per cent
1	100 0	139 5	1 6	0 2
1	115 0	137 4	0 8	0 5
2	96 5	136 0	2 8	0.2
2	117 0	133 5	1 6	1 0
3	103 5	140 4	1 2	0 1
4	103 0	137 3	1 1	0 1
5	105 0	138 8	0 6	0 1
6	97 0	138 5	0 6	0 1

long as a minimum of binder soil is used. On a number of the soil and soil-aggregate samples shrinkage tests were made after compaction at water contents higher than optimum and increased contraction occurred in every case.

in samples 2, 4, 5, and 7. In sample 2 the shrinkage was lowered from 0 2 per cent to 0.0 per cent as the moisture content was raised from 10.5 per cent (optimum) to 11 5 per cent.

The results of the freezing tests on soil-

TABLE 5
FREEZING TESTS ON SOILS

Soil No	Composition			
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	Lineal shrinkage per cent
1	103 5	112 8	4 9	0 1
2	100 0	125.2	2 1	0 2
2	109 5	121 9	2 7	0 0
3	97 0	111 5	2 3	0 3
4	96 5	114 2	5 3	0 6
4	109 0	112 0	3 8	0.4
5	103 5	110 0	2.2	0 5
5	123 0	105 5	0 3	0 3
6	100 0	105 8	5.4	1.0
7	106 0	114 8	3 1	0 7
7	115.0	113 3	2 2	0 2
8	99.0	108 0	4 0	0 5
9	100 0	105.5	2 8	0 8
10	100 0	100 0	1 2	1.0

TABLE 6
FREEZING TESTS ON SOIL-AGGREGATE MIXTURES

Mixture No	Composition			
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	Lineal expansion, per cent
1	100 0	139.5	1 6	0 2
1	115 0	137.4	0.8	0 5
2	96 5	136 0	2 8	0 0
2	117 0	133 5	1.6	0.2
3	98 0	140 0	1 8	0.6
4	104 5	137 2	0.8	0 3
5	105 0	138 8	0.6	0 5
6	97.0	138 5	0 6	0.2

In Tables 5 and 6 are given the results of all freezing tests. Looking at Table 5 it will be noticed that in general the shrinkage increases as the plasticity index increases when the samples are compacted at or very near optimum moisture. It should be observed also that as the moisture content is raised above optimum, shrinkage decreases. This is brought out

aggregate mixtures present a quite different picture. Here the general tendency is toward expansion From these few typical tests the following trends are apparent (1) The expansion is governed by the plasticity index of the material passing the No. 40 sieve. This is brought out in samples 1 and 2 in which the grading up to the No. 270 sieve is the same but sample 2 is much more plastic. Sample 1 with a plasticity index of 7.5 has an expansion of 0.2 per cent whereas sample 2 has a plasticity index of 21.0 and no expansion or contraction. Sample 3 which is well graded but has a low plasticity index has the largest expansion of all the samples. (2) Expansion is also governed by the percentage of material passing the No. 40 sieve when the plasticity index is about the same Samples 5 and 6 bring this out. By increasing the amount passing the No. 40 sieve from 26 to 28 the expansion is lowered from 0.5 per cent to 0 2 per cent. All soil and soil-aggregate mixtures returned to their original volumes after thawing.

The results obtained with the freezing test deserve some special attention due to the fact that some mixtures contract while others expand at optimum water content In our opinion the following considerations explain the behavior of the fine grained soils: The water in these soils certainly exists as very thin films These films may be either in the form of plain water or frozen water as some have suggested. It can be shown by calculations based on the expansion coefficient of quartz, water, air and ice that the shrinkages obtained greatly exceed the theoretical results. We, therefore, conclude that these films possess very high coefficients of contraction and that the degree of contraction varies with the thickness of the film.

It is believed that the expansion of the soil-aggregate mixtures can be explained by pointing out that they contain more water than can be accounted for by the requirements of the binder at optimum and the absorption of the aggregate As an example sample 4 consists of 77.5 per cent sand-gravel having an absorption of 0.5 per cent and 22 5 per cent soil binder requiring 17 5 per cent water at optimum The final mixture requires 6 5 per cent water at optimum whereas theoretically it should require 4.4 per cent. These calculations show that the binder soil is quite wet and for this reason will, no doubt, expand on freezing It can be shown also that the degree of volume change depends on the degree of wetness.

Water may affect densified plastic soils by entering from the top, sides, or bottom either by gravity or capillarity. In this study special attention has been given to the affects of capillary water entering from the bottom, in the belief that the affects from other directions and by gravity can be judged from this test. In Tables 7 and 8 are given the results of all tests made. It will be noticed that the fine grained soils when compacted at optimum moisture contain from 2 2 to 11 8 per cent air voids. Samples 2, 3, 4C, 5, 7, and 9, all contain 3 4 per cent or less and absorbed less than 0 5 per cent water by weight during the test Samples 1, 6, and 8 all contain more than 4 4 per cent voids and absorbed from 0 75 to 1.5 per cent water by weight. All these tests show that soil masses containing air voids will absorb some water The first group shows that the absorption is negligible if the air voids are below 3.5 per cent It should be pointed out also that even after prolonged absorption the soil samples still contain from 2 to 3 per cent air voids

Samples 4A and 4B were prepared purposely with high voids to create a condition whereby swelling as well as absorption might occur. The only case of swelling occurred with sample 4A. The soil actually grew out of the mold and a volume increase of 1.77 per cent developed.

In Table 8 are given the results of the capillary test on five soil-aggregate mixtures. These tests show that the absorption of water is negligible when the samples are compacted to maximum density at or near optimum water content. Sample 2 shows much higher absorption than the other samples because it was compacted at a water content well below optimum.

To show the importance of controlling the water holding capacity of compacted

TABLE 7

Absorption by Capillarity on Soils

Soil No	Composition			Absorption		
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	By weight, per cent	By volume, per cent	Voids after absorption, per cent
1	103 6	113 3	4 5	1 27	2 3	2 2
2	97 0	125 0	2 9	0 22	0 44	2 46
3	97 0	111 5	2 3	0 30	0 5	1 8
4A	86 5	109 3	11 8	5 90	10 4	1 4
4B	95 0	112 5	7 0	1 90	3 5	3 5
4C	99 5	115 3	3 6	0 48	0 87	2 53
5	103 5	110 0	2.2	0 30	0 5	1 7
6	100.0	105 8	5 4	1 50	2 5	2.9
7	105 0	115 9	3 4	0 35	0 65	2 75
8	100 0	107 5	4 4	0 75	1 3	3 1
9	100 0	105 5	2 8	0 40	0 7	2 1

TABLE 8

Absorption by Capillarity on Soil-Aggregate Mixtures

Sample No	Composition			Absorption		
	Water, per cent of optimum	Dry weight, lb per cu ft	Air voids, per cent	By weight, per cent	By volume, per cent	Voids after absorption, per cent
1	100 0	139 5	1 6	0 3	0 6	1 0
2	96 5	136 0	2 8	0 6	1 1	1 7
3	103 5	140 3	1 8	0 29	0 65	1 15
4	106 5	137 0	0 8	0 24	0 52	0 28
5	98 5	138 6	1 6	0 39	0 87	0 73

TABLE 9

Characteristics of Soil Mixtures Used in Figure 1

	Soil No				Soil-aggregate sample No	
	A	B	C	D	E	F
Liquid limit	80	50	32	43	32	43
Plasticity index	52	30	16	20	16	20
Pass ½-in screen					100	100
No 10 sieve					60 0	60 0
No 40 sieve	100	100	100	100	27 0	27 0
Silt	60	39	29	35	6 0	7 0
Clay	38	24	18	21	3 6	4 2
Optimum moisture, per cent	24 2	18 0	12 4	17 0	6 7	7.0
Maximum dry weight, lb per cu ft	100	110	121	100	136 0	135 0

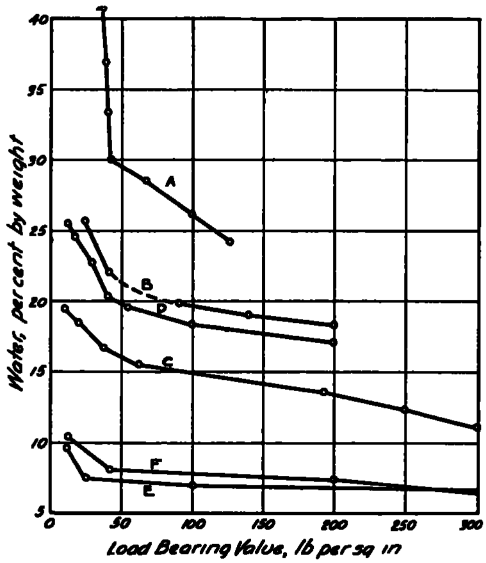

Figure 1. Relations Between Load Bearing Value and Moisture Content

APPLICATION

In applying the results obtained by these three methods for design of surfaces one must first consider the conditions to which the roadway will be subjected For instance if the densified layers are likely to be subjected to the influence of water plus freezing, they should contain very low voids at optimum and should show very little volume change on freezing If they might lose most of their water, they should show low shrinkage on drying If they might be subjected to water but no freezing, they need to be low in air voids but the volume change on freezing would not be important.

In designing roadways we assume that they will be subjected to all three agencies mentioned. We, therefore, have been staying within the limits shown in Table 10

TABLE 10
SPECIFICATIONS FOR DENSIFIED SOILS

	Subbases	Bases
Lineal shrinkage on drying, per cent	Not over 1 5	0 2
Lineal expansion on freezing, per cent		Not over 0 2
Lineal shrinkage on freezing, per cent	Not over 0 7	
Absorption by capillarity, percentage by weight	Not over 0 5	Not over 0 3
Air voids by volume	Not over 3 5	Not over 1 5
Degree of compaction, percentage of maximum density—minimum	98	100

soil mixtures a number of strength tests made by our deformation method are included. The properties of the soils are shown in Table 9 The results of the tests are shown in graphic form on Figure 1 All these mixtures show an abrupt loss of strength when the water content reaches a certain point For example sample F has a strength of 200 lb per sq. in. at 7 5 per cent moisture and only 42 lb at 8.1 per cent moisture As another example sample C has a strength of 193 lb at 13.5 per cent moisture and only 62 lb at 15 5 per cent All these strength tests were made at ⅛-in. deformation

In setting up the foregoing limits the following results and observations were taken into consideration

1 The sensitiveness of soil mixtures to water
2 The checking and cracking of compacted soils in the field
3 The failure of roads and runways due to the entrance of water from the top or bottom.
4 The abundance and ease of compaction of soils with low volume change characteristics.
5. Performance of roads and runways

SOME DESIGNS

In the last seven years we have designed a number of airport runways The selection of soils for subbases and bases for some of these parts will show how these limits are applied On part of the Omaha Airport site there was an abundance of soil No. 1 but it was not used because of the high air voids content at optimum water and maximum density even though the volume changes were low on drying and freezing Instead we used soil No 3 which had to be hauled four miles In selecting a binder for the base for the same project in 1936 we decided to use soil No 9 because the final mixture (soil-aggregate mixture No. 2) showed low volume changes when submitted to drying and freezing. (See Tables 1 and 2)

When designing the runways on the Kearney (Nebraska) Airport we were asked to use soil No. 6 for the subbase if possible. We rejected it because of its high void content at optimum moisture Soil No 8 was also available but at first it was also rejected because of high air voids It was finally accepted, however, after it was demonstrated in the field that it could be densified to a low air void content by more compactive effort On this same project soil-aggregate mixture No 3 was prepared to meet the grading requirement of a government agency. Mixture No 4 was finally used, however, because it was more economical and had a lower expansion on freezing

FIELD OBSERVATIONS

During the period covered by the laboratory research we have had opportunity to correlate this work with the construction and performance of the Omaha Airport Runways. This airport was started in 1936 and substantially completed in 1938. Since its site was an old river bed it offered unusual opportunities for studying the behavior of stabilization by compaction. The subgrade both horizontally and perpendicularly consists of heavy clays, silts, sands, and combinations of all these. As a whole the site is very wet and the water table comes to within 3 ft. of the finished surface nearly every year. The load bearing value of the natural subgrade with a 216-sq in. plate at ¼-in deformation ranges from 15 lb. per sq. in. upwards

The average cross section of the finished runways shows 12 in. subbase, 6 in. base and either 2 or 3 in of hot mixed bituminous mixtures. The subbase materials have characteristics similar to soil No. 5, Table 1, and the base is similar to soil-aggregate mixture No. 2, Table 2. The subbase was compacted to at least 97.0 per cent of maximum density and the base to at least 100 per cent

Tests have been made yearly to determine the density and moisture content of the subbase and base. The subbase does not change from year to year but the base increases in dry weight per cubic foot and decreases in percentage of water. Both subbases and base are practically saturated with water continually.

These runways show no signs of distress There are no transverse or longitudinal cracks, heaving or settlement. All indications are that the compacted layers are stable.

CONCLUSIONS

The tests and observations presented lead to the following conclusions:

1. The stability of densified soils and soil-aggregate mixtures can be measured and predicted in the laboratory by their behavior when subjected to drying, freezing and capillary water.
2. Apparatus and methods have been designed for measuring these behaviors.
3. By the use of these tests soils can be selected and compacted to resist one or more destructive agency.