THE BEHAVIOR OF DENSIFIED SOIL-WATER MIXTURES UNDER VERY ADVERSE WATER CONDITIONS

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SYNOPSIS

This paper presents and discusses the results of an investigation conducted on the Omaha Municipal Airport runways following the Missouri River flood of April 1943 which covered the airport site with 3 to 7 feet of water for from 10 to 17 days The investigation was made for the purpose of determining the effect of flood waters on the density and water content of the densified soil subbases and the soil-aggregate bases. The data obtained are of unusual interest because these runways are constructed on a former river bed composed of fine sands, silts, and heavy clays. The subbases consist of ordinary soil densified and from 6 to 12 in thick The bases consist of sand-gravel and binder soil, and are approximately 6 in thick

In making the survey samples of subbases and bases were taken at 500-ft intervals over the 22,000 lin. ft. of runways. At each location test samples were taken at the center line, at the quarter points, and near the edges Visual observations were made on the subgrade at all the locations and the water table was determined at 30 locations

All subbase and base samples were tested for density and moisture content In addition the plasticity indices were determined on all subbase samples. The samples were grouped according to the years (1936 thru 1942) which they represented and the data obtained for each year's construction were compared with the results obtained during construction by considering the plasticity indices, the maximum laboratory densities, and the optimum water contents of each sample and the degree of compaction required in the field for the respective year which the sample represents.

A summary of the results is as follows: (1) All subgrade soils were found to be saturated and the water was within 12 in. of the surface, (2) Ninety-seven subgrade samples were taken and of these only 14 had a density less than the minimum density specified for the year of its construction, and only 9 had a greater water content than the optimum content for the specified density; and (3) Of the one hundred twelve base samples taken only 12 had a lower density than the minimum specified density and only 8 had more water content than the optimum content for the specified density.

The tests as a whole support the authors' contention that the water holding capacity of compacted soils and soil-aggregate mixtures can be restricted.

In connection with the soil investigation a series of load bearing tests were made, by the circular rigid plate method, during the period immediately following the flood and repeated in the same spots four months later It was found that immediately following the flood the load bearing values were somewhat less than the pre-flood average, this decrease being due principally to the saturation of the subgrade Four months later, after the water table had dropped to the normal level and after the subgrade had a chance to lose most of its excess water, it was found that most of the locations tested had regained their pre-flood strength.

The stability of densified soil-water mixtures is, no doubt, the most important factor in designing low cost flexible pavements. No matter how strong the combination of subgrade, subbase, and base is at the time of construction, its future value depends on the amount of water that can enter the various layers. The truth of this statement is evidenced by the fact that the strength of a plastic soil mixture varies inversely as its water content; and that noncohesive mixtures cause heaving when frozen at saturation

Last year we presented a paper entitled "Some Physical Properties of Densified Soils",[1] in which we reported the results of our laboratory studies on the behavior of soil-water

[1] *Proceedings*, Highway Research Board, Vol. 22, p 460 (1942)

mixtures when submitted to the actions of drying, freezing, and absorption by capillarity. We pointed out very emphatically that the water holding capacity of these mixtures can be restricted by limiting their air-void content. We showed, by a number of examples, that fine grained soils, which contain less than about 3 5 per cent air-voids by volume after compaction to maximum density at optimum moisture, show no appreciable absorption by capillarity and that soil aggregate mixtures must contain less than about 1 5 per cent air-voids to resist absorption Our general conclusion on this particular point was to the effect that soil and soil-aggregate mixtures can be so selected and compacted as to limit their water holding capacities.

We are not unmindful of the fact that the water holding capacity of a soil-water mixture can be increased by the action of freezing. However, we showed last year that properly selected and densified fine-grained soil mixtures shrink on freezing, and that soil-aggregate mixtures will swell only slightly or show no volume change at all. Furthermore, all samples regained their original volume after thawing. From these tests we concluded that well prepared soil mixtures will produce neither detrimental heaving nor additional water holding capacity when frozen.

Our eight years' experience has taught us that most ordinary soils and mixtures can be properly densified by prevailing construction methods. True, there are some very plastic soils on the one hand and some very noncohesive silty soils on the other, which will not meet our requirements either in the laboratory or in the field These should not be used. There are some soils which should be satisfactory from a plasticity standpoint, but which contain an excessive amount of air-voids when compacted in the laboratory to maximum density at optimum moisture. However, the air-void content of these soils can be reduced in the laboratory by using more compactive effort, and if they are to be used in the field, more compactive effort will be required there also Local conditions will determine whether a soil, requiring excessive compactive effort, is more economical than one which compacts readily, but costs more to procure.

Last year we offered very little field data in connection with the laboratory tests This year we present the results of an investigation of the Omaha Municipal Airport runways. The investigation was made after a severe flood. Our principle purpose is to point out the behavior of the densified mixtures, insofar as water absorption is concerned

The runways were built on a former Missouri River bed. The original soil survey disclosed three distinct types of subgrade, clean fine sand, silt, and practically pure clay, as well as mixtures of these. These materials occur heterogeneously, both vertically and horizontally The site is between a lake, an old river channel, and the present river. The water in the river reaches a level higher than the surface of the runways nearly every year, at which time the water table under the runways comes to within three feet of the surface The runways are provided with a surface and subsurface drainage system, both of which parallel the paved strips.

The following is a typical cross section of the runway pavements.

(1) 12 in of subbase consisting of soils having plasticity indices of from 13 to 29.
(2) 6 in. of base consisting of a mixture of sand-gravel and soil binder.
(3) 2 to 3 in. of bituminous pavement

In April of 1943 the Missouri River flooded very badly and covered the entire airport site from 10 to 17 days to a depth of from 3 to 7 ft. As soon as portions of the runways were uncovered, we started our investigation, which lasted about two weeks.

The survey consisted of taking and examining samples of subbase and base at 500 ft intervals over the 22,000 ft. of the runway system Samples were taken at the center and 25 ft and 6 ft from the edges While the samples were being taken, visual inspection was made of the subgrade, and the water table was measured at about 30 locations.

Immediately following the flood and also four months later we made a series of load bearing tests in the runway areas The results of both series are included in this paper.

TESTS AND OBSERVATIONS

Subgrade and Water Table

The subgrade observations indicated that all deposits below the compacted subbases were affected by the flood waters Wherever sand occurred free water was present and where silts, clays, or other soil mixtures occurred, these were also saturated. The water table varied from 12 to 48 in., depending on the elevation of the surface and the imperviousness of the subgrade layers.

Subbase

The results of the subbase tests are shown in Tables 1 to 4, inclusive. The tests are grouped to represent construction during the years 1936 to 1942, inclusive. For each year or group of years the plasticity index, the maximum laboratory density, and the optimum moisture content are given for each different soil. The compaction requirements for each year and the corresponding minimum dry weights and maximum water contents, on

TABLE 1
TESTS MADE ON SUBBASE LAID IN 1936 AND 1937 CONSTRUCTION

Sample Number	Laboratory Tests					Field Tests[a]	
	Plasticity Index	Max. Proctor Density		95% Proctor Density		Density, lb per cu ft. dry	Moisture, %
		Lb per cu ft dry	Optimum Water, %	Lb per cu. ft dry	Water Content, %		
85	26	106	19.5	101	23.5	102.2	19.7
86	19	109	18.0	104	22.0	108	17.5
81	15	110	17.5	105	21.5	112.5	15.2
82	16	110	17.5	105	21.5	111.7	14.4
83	13	110	17.5	105	21.5	115	14.8
75	21	108	18.5	103	22.5	104.5	18.9
78	15	110	17.5	105	21.5	104	20.9
79	12	110	17.5	105	21.5	106.3	19.2
76	18	109	18.0	104	22.0	108.6	18
77	14	110	17.5	105	21.5	101.5	21.6
72	21	108	18.5	103	22.5	101.2	21
73	21	108	18.5	103	22.5	107.5	19.7
69	13	110	17.5	105	21.5	105.5	20.6
28	17	109	18.0	104	22.0	112	16.9
30	15	110	17.5	105	21.5	102.6	22.5
89	16	110	17.5	105	21.5	113.5	14.8
103	19	109	18.0	104	22.0	107.6	19.2
104	16	110	17.5	105	21.5	110.5	17.6
34	15	110	17.5	105	21.5	98.6	22.6
36	27	108	19.5	101	23.5	101.5	23.1
95	15	110	17.5	105	21.5	103	20.9
96	17	109	18.0	104	22.0	107	20.2
97	26	106	19.5	101	23.5	101	23.1
98	18	109	18.0	104	22.0	104	22.0
99	14	110	17.5	105	21.5	101	23.6
41	19	109	18.0	104	22.0	108	19.7
43	21	108	18.5	103	22.5	104.6	21.2
57	29	105	20.0	100	24.0	104.6	19.7
59	24	107	19.0	102	23.0	95	26.1
117	25	107	19.0	102	23.0	105	21.7
118	17	109	18.0	104	22.0	105	19.5
119	14	110	17.5	105	21.5	105	20.5

[a] Field tests made in 1943 after flood waters had subsided.

TABLE 2
TESTS MADE ON SUBBASE LAID IN 1938 CONSTRUCTION

Sample Number	Laboratory Tests					Field Tests[a]	
	Plasticity Index	Max. Proctor Density		95% Proctor Density		Density, lb per cu ft dry	Moisture, %
		Lb per cu ft dry	Optimum Water, %	Lb per cu. ft dry	Water Content, %		
13	19.0	109	18.0	104	22.0	115.6	14.4
14	16.5	110	17.5	105	21.5	105.1	19.6
15	16.8	109	18.0	104	22.0	107.0	19.7
16	17.8	109	18.0	104	22.0	105.3	20.9
17	19.8	109	18.0	104	22.0	105.6	21.4
18	17.8	109	18.0	104	22.0	105.1	20.2
19	22.3	108	18.5	103	22.5	104.9	20.5
20	21.7	108	18.5	103	22.5	103.5	21.5
21	16.2	110	17.5	105	21.5	109.3	16.2
22	23.3	107	19.0	102	23.0	104.6	21.1
23	21.0	108	18.5	103	22.5	105.5	21.5
24	24.4	107	19.0	102	23.0	104.5	21.0
26	18.0	109	18.0	104	22.0	110.7	17.8

[a] Field tests made in 1943 after flood waters had subsided.

the wet side of the moisture-density curve, are also given. In arriving at the stability of the various soils, the actual dry weights and water contents obtained were compared to the minimum dry weights required and the corresponding maximum water contents. It should be pointed out that during construction all soils were compacted to the minimum requirements or better. The minimum compaction requirements, expressed as a percentage of the maximum Proctor density, were as follows For the years 1936, 1937, and 1938, 95 per cent; for the year 1941, 97 per cent, and for the year 1942, 100 per cent.

TABLE 3
TESTS MADE ON SUBBASE LAID IN 1941 CONSTRUCTION

Sample Number	Laboratory Tests					Field Tests[a]	
	Plasticity Index	Max. Proctor Density		97% Proctor Density		Density, lb per cu ft dry	Moisture, %
		Lb per cu ft dry	Optimum Water, %	Lb per cu ft dry	Water Content, %		
66	17.7	109	18 0	106	20.8	110	17.8
67	13 2	110	17 5	107	20 3	112 6	16.7
68	21 0	108	18 5	105	21 3	101 5	23.0
63	21 3	108	18.5	105	21.3	110 1	17.9
64	10.7	108	18 5	105	21 3	103 2	20 2
65	18.7	109	18 0	106	20 8	107 4	18.7
60	19 7	108	18 5	105	21 3	110 6	17.9
61	21 5	108	18 5	105	21 3	107 1	19 6
62	17 7	109	18 0	106	20 8	105 8	20 6
44	14.4	110	17 5	107	20 3	117 2	15 0
45	28.3	106	19 6	103	22 3	109 6	18 9
46	24 2	107	19 0	104	21 8	109 1	17 9
54	18 4	109	18 0	106	20 8	110 1	18 6
55	17 5	109	18 0	106	20.8	110 6	17 2
56	18 9	109	18 0	106	20.8	106 9	20 3
123	23 1	107	19 0	104	21 8	109.2	23.1
124	18 0	109	18 0	106	20 8	104 6	21 8
125	15 9	110	17.6	107	20 3	103 2	15 9
7	18 9	109	18 0	106	20 8	124.0	14 3
8	14 8	110	17.5	107	20 3	113 0	17.0
9	20 3	108	18 5	105	21.3	110 0	20 3
108	18 1	109	18 0	106	20 8	112 0	16 3
109	14 3	110	17 6	107	20 3	114 0	16 3
110	17 8	109	18 0	106	20 8	111 0	16 0
10	15 3	110	17 6	107	20 3	113 0	16.4
11	18 0	109	18 0	106	20 8	107 0	19.0
12	27 4	106	19 6	103	22 3	103 5	22.2
111	19 6	108	18 6	105	21 3	113 0	16.6
112	18 5	109	18 0	106	20 8	110 0	15 1
113	16 0	110	17 6	107	20 3	115 0	12 6
47	17 1	109	18 0	106	20 8	106 7	20 6
48	19 9	108	18 6	105	21.3	107 5	20.5
49	15 9	110	17 6	107	20 8	104 0	20 5
120	18 9	109	18 0	106	20 3	110 0	18 6
121	17 1	109	18 0	106	20 8	107 6	19.6
122	23 1	107	19 0	104	21 8	104 5	21 7
50	20 7	108	18 5	105	21 3	105 5	20 5
51	16 6	109	18 0	106	20 8	107 5	17 5
52	21 1	108	18 5	105	21.3	108 0	18 5
53	21 1	108	18 5	105	21 3	111 00	18 4

[a]Field tests made in 1943 after flood waters had subsided

TABLE 4
TESTS MADE ON SUBBASE LAID IN 1942 CONSTRUCTION

Sample Number	Laboratory Tests			Field Tests[a]	
	Plasticity Index	Max Proctor Density		Density, lb per cu ft	Moisture, %
		Lb per cu ft dry	Optimum Water		
1	15 0	111	17 5	110 0	17 8
2	15 0	111	17 5	107 0	19 7
3	15 0	111	17 5	111 0	17 4
4	15 0	111	17 5	111 0	17 5
5	15 0	111	17 5	111 0	17 5
6	15 0	111	17 5	111 0	17 6
105	15 8	111	17 5	115 0	15 0
106	14 4	111	17 5	113 0	16 2
107	16 4	111	17 5	112 0	17 4
114	19 3	111	17 5	114 0	14 4
115	15 3	11'	17 5	111 0	17 3
116	14 7	111	17 5	113 5	16 0

[a] Field tests made in 1943 after flood water had subsided

Summary of the Subbase Results

1936 & 1937 Twenty-four out of 32, or 75 per cent, of the samples had a dry weight equal to 95 per cent or more of maximum density. Nineteen of the samples showed densities of from 92 to 94 5 per cent and 6 per cent showed a density of about 84 per cent Twenty-eight out of 32, or 87 5 per cent, of the samples contained as much or less water than their maximum requirement. All these soils showed an air-void content of about 2 per cent when compacted in the laboratory.

1938. Thirteen samples were taken on the 1938 work. All the samples showed the minimum dry weight requirements and did not exceed the maximum water requirements. These soils contained about 2 per cent air-void content when compacted in the laboratory.

1941. Thirty-five out of 40, or 87.5 per cent, of the samples tested showed dry weights equal to or higher than the required 97 per cent of maximum density and 12.5 per cent of the samples showed 94 to 96 per cent of maximum density. Ten per cent of the samples showed water contents higher than the maximum required. These soils showed

TABLE 5
CHARACTERISTIC OF SOIL-AGGREGATE MIXTURES USED FOR BASE

	For years 1936, 1937 & 1938	For years 1941 & 1942
Liquid Limit	34	26
Plasticity Index	21	7 5
Retained on 1 inch screen, %	0	0
Retained on No 4 sieve, %	12	12
Retained on No 10 sieve %	40	40
Retained on No 40 sieve, %	70	70
Retained on No 200 sieve, %	80	80
Retained on No 270 sieve, %	88 0	80 4
Specific gravity of solids	2 62	2 63
Optimum water, %	7 5	6
Maximum dry weight, lb per cu ft	135 0	138 0
Air Voids, %	1 5	1.4

an air-void content of about 3 per cent when compacted in the laboratory

1942. Of the 12 samples tested only one sample failed to give the proper density and moisture content. The soil used is a loess and contained about 2 8 per cent air-voids when compacted to maximum density at optimum moisture.

Base

The base mixture used in 1936, 1937, and 1938 consisted of 80 per cent sand gravel and 20 per cent binder. The gradation and other characteristics of this mixture are given in Table 5 The maximum density at optimum moisture for this mixture was 135 lb per cu. ft. During construction it was compacted to a minimum dry weight of 133 lb. which equals 98 5 per cent of maximum laboratory density. The results of the base tests for these years are shown in Table 6. This table shows that 54 out of 63, or 86 per cent, of the samples had a dry weight of 133 lb. or more. Eleven per cent of the samples had a density of 96.5 per cent to 98 per cent and 3 per cent of the samples had a density of 91 5 per cent to 94.5 per cent. Eighty-nine per cent of the samples had a water content of 7.5 per cent or less.

TABLE 6
TESTS MADE ON BASE LAID IN 1936, 1937, AND 1938 CONSTRUCTION

The material used for the base course during these years had a Maximum Proctor Density of 135 lb per cu. ft dry and an Optimum Water Content of 7 0 per cent. Specifications required the material to be compacted in the field to a minimum of 135 lb per cu ft. dry.

Field Tests[a]			Field Tests[a]		
Sample Number	Density, lb per cu ft (dry)	Moisture, %	Sample Number	Density, lb per cu ft (dry)	Moisture, %
	1936			*1937*	
28	139.0	5 7	81	137 5	5 5
29	138 0	6 1	82	137.5	5 9
30	137 0	5.2	83	135 5	7.8
89	135 0	7 3	78	138 0	6 0
90	135 0	5 8	79	139 5	5 4
91	137 5	6 1	80	140 0	6 0
31	139 5	5 6	75	134 5	5.8
32	138 0	4 8	76	140.0	5 6
33	139 0	5 4	77	131 5	7 5
92	135 5	6 1	72	130 5	10 6
93	138 5	6 1	73	137 5	6 2
04	143 0	4 4	74	148 0	5 5
34	140 0	4 9	69	133 5	6 1
35	134 0	7 4	70	135 0	7 0
36	138 5	5 3	71	129.5	6 8
95	139 0	4 7	57	131 5	7 3
96	137 0	4 6	58	127.5	9 6
97	142 0	4 7	59	132 0	7 9
38	138 5	4 1	117	134 5	7 0
39	139 0	3 4	118	133 0	6 5
40	137 0	5 0	119	123 5	11 5
98	138 5	5 4			
99	138 0	5 6		*1938*	
100	138 0	4 7	16	134 0	6 3
41	140 0	4 7	17	136 0	6 5
42	141 0	4 1	18	137 0	6 1
43	142 0	4 8	19	139 5	4 7
			20	139 0	6 0
	1937		21	137 0	5 7
87	135 0	6 5	22	132 5	5 7
88	138 5	6 3	24	140 0	4 6
84	130 0	8 9	37	140 0	5 2
85	130 5	7 7	26	139 5	5.2
86	136 0	5 8	27	141 0	4 9

[a] Field tests made in 1943 after flood water had subsided

In Table 7 are given the results of tests made on base constructed during 1941 and 1942. This base mixture consisted of 80 per cent sand-gravel and 20 per cent loess soil This mixture gives a maximum dry weight of 138 lb. per cu ft at an optimum moisture content of 6 5 per cent. Other characteristics of this mixture are given in Table 5 During construction it was compacted to a minimum dry weight of 137 pounds which equals 99 3 per cent of maximum laboratory density. Forty-six out of 49, or 94 per cent, of the samples taken during this investigation had a dry weight of 137 lb. or more and only one sample contained more than 6.5 per cent moisture. Six per cent of the samples had a density of 96.5 per cent.

In connection with these soil tests an effort was made to determine the manner in which

TABLE 7

TESTS MADE ON BASE LAID IN 1941 AND 1942 CONSTRUCTION

The material used for the base course during these two years had a Maximum Proctor Density of 140 lb. per cu. ft dry and an Optimum Water Content of 6 5 per cent The specifications required a minimum field density of 137 lb per cu ft dry.

Sample Number	Field Tests[a]		Sample Number	Field Tests[a]	
	Density, lbs per cu ft (dry)	Moisture, %		Density, lbs per cu ft. (dry)	Moisture, %
	1941			*1941*	
66	139 5	4.9	12	142 0	5 3
67	140 0	4 9	111	137 0	6.2
68	138 5	5.8	112	140 0	4 8
63	141 0	4.7	113	139 5	6 0
64	137 5	6 6	47	143 5	4 1
65	136 5	5 9	48	144 5	4 4
60	141 0	4 9	49	140 5	4 9
61	142 0	5 5	120	142 5	4 1
62	138 5	5 5	121	143 0	5 1
44	144 5	4 4	122	138 0	5 5
45	144 0	4 3	50	140 0	5 4
46	144 0	4 6	51	142 0	5 6
54	141 0	4 8	52	135 0	6 2
55	141 0	4 5	53	144 0	4 6
56	136 5	6 0			
123	139 5	5 2		*1942*	
124	136 5	5 3	1	143 5	4 2
125	135 0	6 5	2	144 5	4 2
7	141 0	4 9	3	140 5	5 7
8	142 5	5 4	4	143 5	4 6
9	134 0	6 6	5	142 0	5 5
108	142 0	5 0	6	143 0	5 3
109	141 0	5 0	105	136 0	5 8
110	143 5	5 0	106	138 5	5 2
10	144 5	4 5	107	138 5	5 7
11	140 5	6 0			

[a] Field tests made in 1943 after flood waters had subsided

the water reached the subbase and base Observations disclosed the following (1) the water reached the bottom of the subbase through saturation of the subgrade, (2) the water reached both the subbase and base from the sides through saturation of the soils on the shoulders, (3) no water reached the top of the base, from above, as evidenced by the fact that no softening of the base surface was found under any of the bituminous surfaces examined except at one location where the bituminous surface had blistered and ruptured.

Asphalt Wearing Surface

By the combined floating actions of air and water the asphaltic wearing surfaces tended to raise and separate from the base during the period of inundation. Instead of the asphaltic surfaces rising as a blanket, however, this action was confined to spots and caused the formation of a great number of boils. The gas bubbles issuing in a small stream from the boils were so numerous that they outlined the center line of all the runways. An analysis of the gas showed it to be a mixture of air and carbon dioxide, the latter no doubt being produced by decomposing organic matter in the old river deposits underlying the runways. We estimated that about 1500 of these boils appeared. Most of them formed along the center line of the runways, and some attained a diameter as great as 5 ft. and a height of 1 ft.

The thickness of the asphalt surface varies from 2 to 3 in. and consists of two layers. The lower course, constituting about three-fourths of the total thickness, is composed of a well-graded mixture of crushed limestone, sand, filler, and asphaltic cement The upper course is a standard sheet asphalt mixture containing nearly 12 per cent bitumen. The asphaltic cement used in both courses had a penetration of 150–200 at 77 F and a ductility of 100 at 41 F. The flexibility of this type of surface was demonstrated by the fact that only one boil broke and collapsed, damaging about 9 sq. yd In all other instances, the raised surfaces flattened out as the water receded and after the runways had been cleaned off no evidence could be found of the areas which had been raised and stretched.

CONCLUSIONS

1 The field subbase tests indicate that, as a whole, fine-grained soils compacted to relative densities of 95 per cent or higher do not absorb any more water, by capillarity, than is shown by the moisture-density curve on the wet side. The comparative poor showing made by the 1936 and 1937 work can be accounted for, we believe, by the fact that neither the contractor nor the inspection staff had had previous experience with compaction stabilization work It is quite possible that some of the locations now showing low density and high water contents were not properly compacted during construction

2. The tests made on the bases also show that these mixtures will resist the entrance of excess water when they are submitted to capillary absorption. The uniformity of the results on the work constructed in different years emphasizes the desirability of using controlled mixtures and a high degree of compaction.

3. The fact that densified water-soil and water-aggregate-soil mixtures do not take up more water than is required to saturate them shows that these soil masses do not swell during absorption.

TABLE 8
LOAD BEARING TESTS MADE IN APRIL IMMEDIATELY FOLLOWING THE FLOOD

Test No	Pounds per square inch at ¼ inch total deflection with the following plates: 72 sq in	216 sq in	432 sq in
1—CB		71	
QB	96	62	46
QS		65	38
EB		44	
2—CB		75	
QB	129	86	70
QS		87	58
EB		46	
3—CB		42	
QB	81	57	40
QS		50	37
EB		17	
4—CB		40	
QB	69	51	42
QS		43	31
EB		40	
5—CB		40	
QB	52	35	27
QS		47	29
EB		63	
6—CB		45	
QB	59	41	32
QS		45	37
EB		33	
7—CB		90	
QB	197	114	80
QS		108	
EB		74	
8—CB		83	
QB	78	51	43
QS		50	43
EB		33	
9—CB		81	
QB	100	57	46
QS		79	52
EB		54	

CB—at center of base, QB—at quarter point on base, QS—at quarter point on surface, EB—10 feet from edge on base.

4. Since the water holding capacity of soil-water mixtures can be controlled and since the strength of these mixtures varies inversely as their water contents, any desired structural property can be imparted to these mixtures within reason by the proper degree of compaction.

LOAD BEARING TESTS

After the soils investigation had been completed some load bearing tests were made for a twofold purpose. First, to ascertain if any loss of strength had occurred and secondly, to evaluate the load carrying capacity of the runways Nine locations were selected to represent different years, subgrade conditions, and types of subbase and base. At each location tests were made at the quarter point on both the asphalt surface and the top of the base. Tests were also made on the base only at the center line and at a point near one edge.

TABLE 9
LOAD BEARING TESTS MADE IN AUGUST, FOUR MONTHS AFTER THE FLOOD

Test No	Pounds per square inch at ¼ inch total deflection with the following plates: 216 sq in	432 sq in	Test No	Pounds per square inch at ¼ inch total deflection with the following plates: 216 sq in	432 sq in.
0	85 8	66 5	4	56 7	46 5
			4A	56.3	45 7
1	59 0	39 6			
1A	74 4	50 1	5	54 0	37.5
1B	68 4	48 6			
			6	53.0	39 4
2	91 5	64 1	6A	58.9	45 7
2A	73 8	57 0			
2B	64 8	48 2	8	78.0	54 5
3	59 2	47 8	9	96 5	65.1
3A	91 2	62 5	9A	90.6	60 9

All tests made at the quarter point on base

TABLE 10
APRIL LOAD BEARING TESTS ON BASE CALCULATED TO 280 SQ IN CONTACT AREA

Test No	Pounds per square inch at ¼ inch total deflection	Test No	Pounds per square inch at ¼ inch total deflection
1—QB	57	6—QB	37
2—QB	79	7—QB	105
3—QB	46	8—QB	48
4—QB	47	9—QB	53
5—QB	32		

TABLE 11
AUGUST LOAD BEARING TESTS ON BASE CALCULATED TO 280 & 545 SQ IN CONTACT AREAS

Test No	Pounds per square inch at ¼ inch total deflection on the following areas: 280 sq in	545 sq in	Test No	Pounds per square inch at ¼ inch total deflection on the following areas: 280 sq in	545 sq in
0	77	61	4	52	44
			4A	51	43
1	50	34			
1A	63	43	5	46	33
1B	59	43			
			6	47	36
2	78	56	6A	52	42
2A	66	52			
2B	57	44	8	67	48
3	54	45	9	82	56
3A	77	54	9A	76	53

At the quarter points three rigid circular steel plates, having areas of 72, 216 and 432 sq. in.,

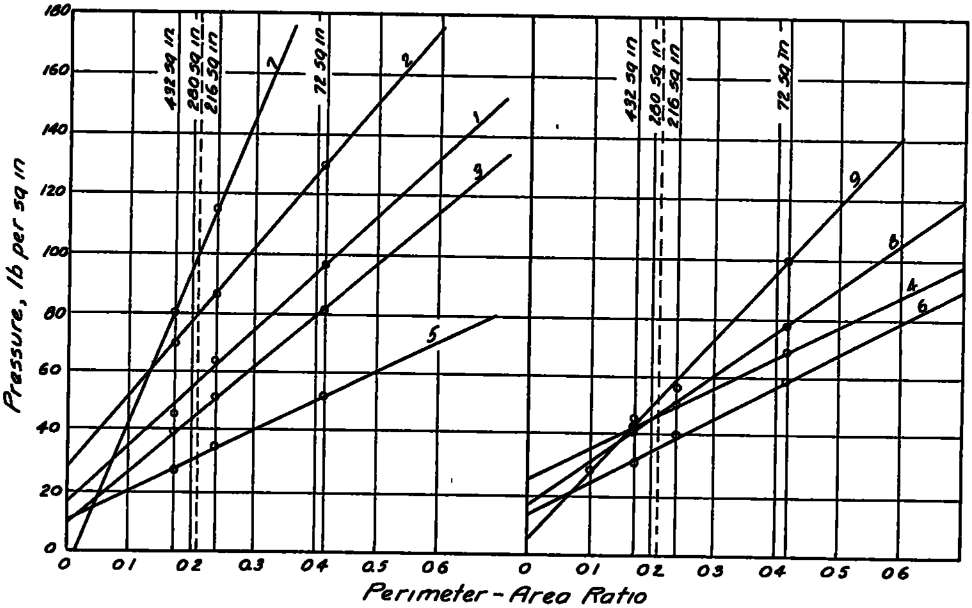

Figure 1

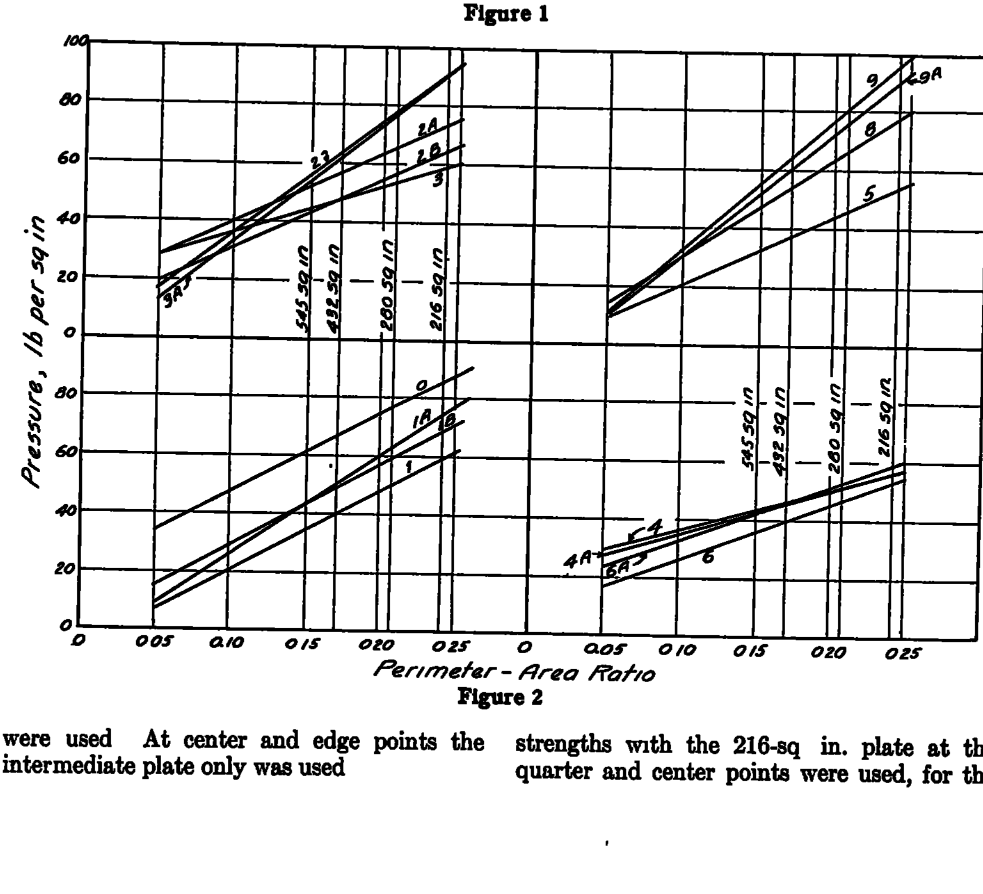

Figure 2

were used At center and edge points the intermediate plate only was used

The results of all tests are shown in Table 8. In estimating the strength loss, the base strengths with the 216-sq in. plate at the quarter and center points were used, for the reason that similar tests had been made in the summer of 1942 The 1942 tests ranged from about 60 to 90 lb. per sq. in. Of the tests made after the flood this year, only 55 per cent had strengths of about 60 lb. or more. The remaining 45 per cent had strengths of from 40 to 50 lb. This shows that a substantial number of locations lost from 17 to 33 per cent of their former strength. It should be observed that on the average the strengths on the surface were the same as on the base beneath.

Subgrade observations lead us to believe that the loss was due mostly to saturation of the natural deposits. To confirm our belief, we repeated the load bearing tests the latter part of August, 1943. Meanwhile the water table had been lowered to points 5 to 10 ft. below the surface and the runways had received three thorough rollings, with multiwheeled pneumatic tired equipment Seventeen locations were tested with two plates. The results are shown in Table 9.

A summary of these tests shows that 13 (or 77 per cent) of the locations had strengths of about 60 lb or more with a 216-sq in. plate while the other 23 per cent showed strengths of about 55 lb These tests indicate that the runways have regained practically all of their former strength.

To evaluate the load carrying capacity of the runways we first constructed perimeter-area ratio curves from the values obtained with the plates used Figure 1 shows the curves for the April investigations. From these curves we prepared Table 10, which shows the load bearing value of all the locations at the quarter points with a 280-sq in. plate. This plate represents the DC3, or mainliner, commercial plane. It will be observed that 7 out of 9 (or 78 per cent) of the spots tested had strengths of over 45 lb. per sq. in., the minimum strength required for the DC3 plane, whose tires carry 45 lb air pressure.

The curves on Figure 2 were constructed from the data in Table 9. The values shown in Table 11 were taken from Figure 2 and show the calculated load bearing values of the locations tested with the 280-sq. in. plate as well as the 545-sq. in plate. The latter plate represents the contact area of the B24 tire, which is inflated to about 45 lb. These figures show that all locations tested had strengths of 46 lb. or more with the 280-sq. in. bearing plate. Furthermore, 14 out of 17 (or 82 per cent) of the locations tested showed strengths of 42 lb. or higher with the 545-sq in. bearing plate.

As a result of the April tests we recommended that the runways be limited to 15,000-lb wheel loads After the August tests we recommended that 25,000-lb wheel loads be allowed Our recommendations were followed in both cases It is three months now since the B17 and B24 have been using the runways. The runways are in perfect condition

In connection with this load bearing value analysis, it should be mentioned that originally the Omaha Municipal Airport runways were designed to carry a maximum wheel load of 15,000-lb When the B17 and B24 were built they were allowed to use the runways to a limited degree, until it was ascertained that the runways could handle them The restrictions were then removed and these heavy planes used them at will until the flood came.

DISCUSSION ON BEHAVIOR OF DENSIFIED SOIL-WATER MIXTURES

Mr. O J. Porter, *California Division of Highways:* Do you conclude that all fine grain soils will not swell?

Mr. Campen All the fine grain soils that we used.

Mr Porter· You would restrict it to the fine grain soils in the Omaha airport?

Mr. Campen: That is correct. I said we used fine grain soils having PI. 13 to 29, which is quite a variety in itself.

Mr. Porter: Did the swelling of the soil after the flooding have anything to do with the 33-per cent reduction in strength and did subsequent traffic consolidate the soil to increase its strength again?

Mr. Campen: As was said in the report, we came to the conclusion that the loss of load bearing value was due to the saturation of the subgrade below the compacted layer

Mr. Roy M Young, *Civil Aeronautics Administration:* Those of us connected with the

Kansas City office of the Civil Aeronautics Administration were very much concerned about the effects of the flood at the Omaha airport and followed with much interest the tests that were made. I want to compliment Mr. Campen on his ability to not only make the tests but to induce the city council of Omaha to allow him to make the test. I wish it could be more generally done. We need all kinds of such investigations.

I want to stress one point that seems material to me. Mr. Campen hinted at it when he said that he found a line of bubbles I think the clue to the lack of saturation of both the subgrade and the base is in those bubbles. There was considerable air trapped under the impervious hot mix top forming an air pocket which prevented the rapid percolation of the water under the runway. If we keep this entrapped air in mind, then we can see why the bearing tests show that there was softer material along the edge. The runways all tested better in the center than they did along the edge. While the material acted a good deal like Mr. Campen says,—and I am pretty well sold on his idea of densified soil-bound mixtures,—I nevertheless believe you can't draw too strong a conclusion from the fact that the airport runways were inundated for the period that the flood lasted.

Mr. Campen. I think Mr. Young's point is well taken but it needs further elaboration. It is true that, if the soil layers had not been covered with a tight bituminous blanket, they could have been saturated more quickly The bituminous wearing surface no doubt did retard the saturation of the compacted subbase and base layers but saturation did take place as can be determined by making a volumetric analyses of the samples taken. Perhaps I should have mentioned in the original paper that most of the boils opened enough to release the entrapped gas or air.

It should be pointed out that the entrance of water into compacted soil mixtures may produce two effects. The entering water may simply displace the air or in addition it may produce swelling. The former is normal in our opinion and its strength reducing effects are limited by the amount of displaceable air. We have steadily maintained that the water holding capacity of a soil mixture can be restricted by proper selection and compaction. If swelling occurs during absorption additional water holding capacity is created and by this process practically all the strength can be destroyed.

A close analysis of the data in this paper will show that most of the samples examined weigh as much per cubic foot, dry weight, as when they were laid. This shows that they did not swell while taking up all the water they could hold.