chemical the day before soil-cement construction. After adding the $CaCl_2$ some water may be required to dissolve it. The soil-$CaCl_2$ mixture should then be mixed to obtain uniform distribution.

If equipment is available, uniform application of $CaCl_2$ will be obtained by adding it in solution, either as part of the mixing water during soil-cement processing, or as part of the water used to prewet the soil the day before soil-cement construction.

It will be necessary to learn from field experience, which is now lacking, the most efficient and economical procedures to follow on construction. Experience with concrete and soil-cement paving construction indicates that adding calcium chloride in the field should present no particularly difficult or costly procedures.

The data in this report include the results of compression tests at various ages of a number of poorly reacting sandy soils containing various cement contents (without $CaCl_2$ admixture). It will be noted that the cement appears to be practically inactive for a considerable period of time after which it begins to harden the soil-cement specimens in a more normal manner, a cement phenomenon not generally known. This and other important observations can be made on cement hydration in poorly reacting sandy soils but since this paper is devoted primarily to determining successful treatment methods for soil-cement, they are not analyzed and discussed at this time. However, the cement and concrete technician will find considerable new and valuable information in the cement and raw soil data that will throw additional light on some of his special research and construction problems.

ACKNOWLEDGEMENT

The detail laboratory work for this research was performed by Ensign E. G. Robbins, C.E.C , U.S N.R , with the assistance of E. J. Deklotz and F. L. Goodman.

ROADWAY AND RUNWAY SOIL MECHANICS DATA

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SYNOPSIS

The data presented are a continuation of those reported in the soil-water-phenomena discussion at the Highway Research Board 1941 and 1942 meetings.

(1) *Method of Preparing Soil Specimens for Physical Tests:* Because too much time was required for making various moisture content tests with 1/30 cu. ft. cylinder specimens, experiments were made with small specimens molded in 20 cu cm. pat cups.

It appears that a consolidated specimen of cohesive clay soil has characteristics not very different in a general way from other building materials. No doubt moisture content fluctuations cause greater changes in a consolidated clay soil structure than in many of the other materials; but it seems that consolidated specimens of clay soil can be prepared and tested for structure durability and other properties in somewhat the same manner as the other materials.

(2) *Density and Strength of a Clay Soil When Consolidated and Saturated.* Experiments showed that the same type of soil compacted to different densities absorbed different amounts of water and ruptured under different loadings. When the soil with plastic index of 22 was consolidated to 72 lb. wet, the amount of water absorbed to become saturated was 46 per cent and the relative rupture load was 11, while the same soil consolidated to 97 lb wet absorbed 21 per cent water to become saturated and the relative rupture load was 129.

Data also showed the soil type made a difference in amount of water absorbed

and upon its load carrying capacity when specimens were saturated. The three test specimens with plasticities of 22, 26, and 57, when all were consolidated to approximately 125 lb., (dry) density, absorbed 21, 25, and 35 per cent moisture to become saturated and the relative rupture loads were then 129, 86, and 21.

(3) *Density, Moisture Content, and Strength of a Consolidated Clay Soil:* Data indicated the density to which the soil was compacted and the moisture content at time of loading had a great effect upon its load carrying capacity

When pat cup specimens were loaded to failure the rupture was surprisingly abrupt. At the time of rupture the indentations varied from approximately 0.025 in for the densest dry specimens to 0 05 in. for the non-dense saturated specimens.

The moisture content load carrying capacity graphs were not straight lines from the dry to saturated conditions. Direction of the graphs changed decidedly at approximately 14 per cent moisture

Check Tests made with soils of 22 and 26 plasticities molded in $\frac{1}{10}$-cu ft cylinders indicated the relative rupture loads of the pat cup specimens, if considered as compressive loads in lb. per sq in. were approximately three times the loads required to rupture the large cylinder specimens in a Southwark-Emery compression machine.

The dry cylinder specimen showed a deflection of approximately 0 05 in. while one with 10 per cent moisture showed a deflection of 0 10 in. when ruptured.

(4) *Moistures in Clay Soils Beneath Pavements:* It appeared that much could be accomplished toward increasing the load supporting powers of these soils under pavement if their moisture contents could be prevented from rising above approximately 20 per cent

During 1933–1936, moisture content samples were taken regularly from the soil beneath pavement on an 8-mile research project consisting of thirty-seven 1200 ft. test sections. On 22 sections the pavement was laid directly on natural clay soil; while on the other 15 sections various coverings or treatments of the top of soil substructures were employed immediately prior to laying pavement.

The study of maximum moistures in the clay soils beneath pavement during the four years showed the average ratio of maximum moisture content to plastic index of the untreated sections was 1 01 as compared with 0.83 on the treated sections

These experiments indicated that it will be practicable in some instances to reduce maximum moistures in soils beneath pavements to such an extent that the load supporting powers of the soils will be considerably increased above those of the saturated conditions

(5) *General Summary of Data Compiled to Date*

The data in this report are a continuation of those reported in the discussion of the soil-water-phenomena at the 1941 and 1942 meetings of the Highway Research Board.[1] In particular, these data concern, (1) the method of preparing clay soil specimens for physical tests, (2) the relation of density to strength of clay soil when consolidated and saturated; (3) relations of intermediate densities, moisture contents, and strengths of consolidated clay soils, (4) moistures in clay soils beneath pavement; and (5) general summary of data compiled to date

The investigations as originally planned were continued in 1943. The data compiled are rather voluminous and are briefed here to invite attention to items that appear to be most essential with regard to current practices.[2]

Reports of investigations previously submitted indicated that practical tests on a cohesive clay soil can be made and density-moisture content-strength graphs drawn which will enable highway and runway engineers to predetermine directly the relative load-supporting-power of clay soil, consolidated to different densities, when they contain different amounts of moisture Observations made

[1] H. C. Porter, "Soil Moisture Content and Density Data" *Proceedings,* Highway Research Board, Vol 21, p 466 and "Roadway and Runway Soil Mechanics Data," Vol 22, p. 469.

[2] Detailed data and comments on this research work are available in Texas Engineering Experiment Station Series 67 to 71-A, A and M College, College Station, Texas

during those experiments indicated that the clay soil was most stable when practically dry and least stable when saturated with water Additional experiments, therefore, were performed to determine (a) whether those phenomena could be substantiated, and (b) the relation between the moisture content and the load-supporting-power of the clay soil when consolidated to different densities The data obtained in these later experiments substantiated previous findings.

The main objective in this part of the work was to determine the load-supporting-power of a clay soil consolidated to different densities when it contained various amounts of moisture.

1. Method of Preparing Soil Specimens For Physical Tests

Too much time was required for varying the moisture contents of the originally prepared $\frac{1}{30}$ cu. ft cylinder soil specimens without causing objectionable structure rupture and disintegration. Experiments were made, therefore, with much smaller specimens molded in approximately 20 cu cm pat cups

In order to make the desired tests, three conditions were necessary in the specimens, as follows.

(1) Uniform density throughout the entire specimens,
(2) groups with each specimen of a group consolidated to the same density; and
(3) several groups consolidated to different densities—low, medium, and high.

Descriptions of the laboratory equipment used, and the methods of preparing and handling the test specimens in these investigations are described.

LABORATORY EQUIPMENT

Item	*No.*	*Description*
1	1[a]	Scales—to weigh accurately to one ten-thousandth of a gram
2	2[a]	Glass desiccators—8-in diameter by 6-in depth
3	2[a]	Porcelain bowls—5½-in top diameter by ½-in. depth
4	1[a]	Pyrex mercury cup—2½-in diameter by 1½-in depth, for measuring the volumes of the soil pats
5	1[a]	3-in square piece of flat glass, $\frac{1}{16}$ in thick with a $\frac{3}{32}$-in diameter hole in the center, and with three prongs inserted in the glass for pushing the soil pats down into the mercury to determine the volumes of the soil pats
6	1	3-in. square piece of flat glass—same as above described except with no prongs, for measuring the volumes of metal cups
7	1[a]	½-in diameter Pyrex 20-cu cm calibrated tube, graduated to $\frac{1}{10}$-c c , for measuring the volumes of mercury displaced by the soil pats and for measuring the mercury required for filling the pat cups
8	1[a]	Spatula with 4-in length by ¾-in width blade
9	1[a]	5-lb jug of mercury
10	1[a]	15-in square piece of chamois for cleaning mercury
11	2	12-in diameter sheets of filter paper
12	1[a]	Can of "Protopet White" No. 2 vaseline
13	12	Monel metal pat cups of approximately 20-cu cm volume, 4 44 cm inside diameter by 1 29 cm inside height with 1 hole 0 13 cm (0 05 in) in diameter in the bottom and 0 13 cm from inside edge of cup The hole in bottom of cup was drilled from inside to outside and the burr left on the outside. The insides of cups were smoothed and polished Numbers from 1 to 12 were stamped plainly on the outside of the cups for identification
14	3[a]	20-cu cm (approximately) monel metal pat cups, same as above described, except no holes in the bottoms, and numbered 13 to 15, inclusive
15	30	Flat bottomed all-wire-mesh kitchen strainers, 2¾-in diameter at bottom, 3-in diameter at top, by 2-in height, with handles removed
16	1	5 gal container of sawdust passing the ¼-in. and retained on the Standard No 20 sieve, which had been boiled and washed until the water the sawdust was boiled in for one hour was not colored One-half of this sawdust passed the Standard No 10 sieve
17	6[a]	15-in diameter porcelain pans—3-in or 4-in high with flat bottoms

[a] Same equipment as used for making standard liquid limit, shrinkage, etc tests

LABORATORY EQUIPMENT

Item	*No*	*Description*
18	3	7-in square tin pans—1½-in deep
19	1[a]	4-ft length by 2-ft width by 1-ft height humidor, the bottom of which was covered with a 1-in thick porous slab with the bottom of the slab set 2-in. above the bottom of the box The humidor was airtight when the lid was down
20	1[a]	10-in by 12-in. by 12-in "Circle B" electric oven.
21	2[a]	20-in by 12-in wire racks with 1½-in height sides and 2-in. length wire legs
22	2[a]	12-in by 8-in. wire racks with 1½-in height sides and 2-in. length wire legs
23	1[a]	3½-oz soft rubber syringe (No 819, Miller Rubber Div)
24	1[a]	6-in steel straightedge
25	15[a]	4-oz aluminum moisture content cans with corresponding numbers stamped on both can and lid
26	1[a]	Nest of screens consisting of one each of Standard No 40, No 20, No 10, and ¼ inch size, with one lid and bottom.
27	1	36-in piece heavy cotton toweling for moisture pad
28	1[a]	400 ML Pyrex beaker
29	1[a]	600 ML Pyrex beaker.
30	1	5 gal container of distilled water
31	1[a]	Mortar and rubber pestle
32	2	Small camel's hair brushes.

PREPARATION OF SOIL SAMPLE

Immediately after the soil sample was received at the laboratory it was well mixed and then placed in pans and inundated with distilled water. After the soil had slaked, it was washed with distilled water into pans through a No. 40 sieve These pans were covered and placed on a shelf to allow the soil in suspension to precipitate. After precipitation the clear water was poured off the soil and the soil was placed where it dried at a temperature not exceeding 100 F Shortly before the soil had dried enough to become hard and difficult to break, it was pulverized by means of a rubber pestle, sufficiently to pass the No 40 sieve Next, the entire sample again was thoroughly mixed and was placed in a closed cupboard. Subsequently, as test specimens were desired from time to time, sufficient quantities of the soil were removed from the cupboard and dried to constant weight at 100 F.

PREPARATION OF PAT CUPS FOR MOLDING SPECIMENS

1 Fifteen pat cups were used for one set of specimens, 12 with a hole[3] in the bottom of each and three cups without the hole. After all cups were thoroughly cleaned, each was weighed to 0 001 g. and recorded. One thickness of filter paper cut to the exact size of the inside bottom of the cup then was fitted into each of the 12 cups with holes, and each cup with its filter paper was accurately weighed and recorded[4] The weights of the three cups without holes also were determined and recorded.

2 The volume of each cup with its filter paper was determined by filling it level full of mercury. The mercury was leveled with the glass plate without prongs, and was measured to 0.01 cu cm. in the graduated measuring tube. The volumes of the three pat cups without holes and filter paper also were determined in the same manner and recorded[5] All pat cups were accurately weighed before mercury was placed in them, and again directly after the mercury was emptied, in order to determine whether any of the mercury had adhered to the cup

3. The sides only of the 12 pat cups with holes and filter paper were covered with a thin

[3] The bottoms of pat cups for the first trial specimens molded had 20 uniformly distributed holes of the same size, but it appeared that the water was drawn into the specimens so rapidly that hair-lines or planes of weakness were formed throughout the specimens. For that reason the number of holes was reduced to one at the edge of the cup. This greatly reduced the appearance of hair-lines, but did not entirely eliminate them directly above the hole.

[4] In some instances the filter paper wrinkled while the specimen was being dried and caused its bottom surface to become rough and irregular, and it was found that a very small piece of filter paper over the hole with the remainder of bottom of cup covered with a thin film of vaseline made a better specimen for relative rupture load tests.

[5] In lieu of measuring the mercury volume in the graduated tube the volume that exactly filled the pat cup might have been determined by weighing the mercury and correcting for temperature

film of vaseline; and both sides and bottoms of the three cups without holes were covered with vaseline, to prevent sticking The weights of each of the 15 cups then were determined and recorded.

MOLDING SOIL SPECIMENS

Placing Soil in Pat Cups

1. Group A, B, and C specimens. Immediately after the pat cups were prepared as heretofore described, nine of them with the hole in the bottom of each were filled by placing the prepared minus 40-mesh soil in the cups with a spatula in increments of approximately 4 g. each. After all nine cups were filled until the soil overflowed the sides of the cups, each cup was raised 1 in. and dropped on the table twice, to eliminate large voids from the soil. The top of the dry soil in each cup was then struck off even with the top edge of its cup, with the steel straightedge (24). During these operations no soil was allowed to enter the holes in the bottoms of the cups. After all loose soil was removed from the outsides of the cups, each one containing the straightedged soil was weighed, recorded, and placed where the soil was not disturbed.

2 Group D Specimens:[6] Three more cups with one hole in the bottom of each, were filled immediately in the same manner as described for Groups A, B, and C specimens, except that instead of raising and dropping the cups heaped with soil on the table twice, the cups for the D specimens were raised and dropped repeatedly, until no more dry soil could be jarred into the cups. While the dry soil was being shaken down, more soil was added to keep it mounded above the top edges of cups. The tops of the dry soil were then straightedged. After removing all loose soil from the outsides of these three cups, each one containing the straightedged dry soil was weighed, recorded, and placed with the above described A. B, and C specimens

3. Group E Specimens. After the Group A, B, C, and D specimens were prepared, three more cups without holes were filled with wetted soil of the same type, to make the very dense E specimens. The soil was placed in these cups in accordance with the current standard requirements for making the shrinkage etc. determinations of the soil. A quantity of the minus 40-mesh soil was uniformly wetted with distilled water in a porcelain bowl until the soil was slightly above its liquid limit moisture content A thin layer of the wet soil was then placed in a pat cup and the cup bottom was pounded on the table-top until no more air bubbles would rise to the top of the wet layer of soil. This operation was repeated until each of the three E cups was over-flowing with wet soil. The tops of wet soil were then straightedged and the outsides of the cups cleaned. After the three cups with the straightedged soil were weighed and recorded, they were placed on the wire rack in the humidor to dry slowly.

Wetting Group A, B, C and D Specimens For Molding

1. The toweling was made into a thick pad and placed on the bottom of a 15-in. diameter pan. Distilled water was then poured into the pan until the pad was saturated and the free water was level with the top of the pad

2. The pat cups containing the Groups A, B, C, and D dry straightedged soil were placed on the water-saturated pad, as shown in Figure 1. The soil soon began absorbing water by capillarity through the holes in the bottoms of the cups. It was found that if the water was drawn into the soil very rapidly, hair-cracks formed therein, therefore, when hair-lines started to appear, the elevation of the water in the pan was lowered by means of the rubber bulb[7]

3. After the capillary water had spread over approximately three-fourths of the area and changed the color of the tops of the three A and the three B specimens from light to dark, they were transferred to the wire rack with the E specimens in the humidor.

4. After the Group A and B specimens had remained on the wire racks in the humidor for 4 hrs, the moisture on the outsides of the cups was removed and the weights of the cups with wetted soil were determined and recorded.

[6] There was so little difference in the densities of the Group C and the Group D specimens when dried to constant weight at 100 F that in some sets the Group D specimens were omitted.

[7] The rate of wetting the soil in the pat cups was controlled by raising and lowering the elevation of the free water in the cotton pad upon which the cups with holes were placed.

The Group A specimens were returned to the wire rack in the humidor; the Group B specimens were returned to the saturated pad in the pan with the Group C and D specimens.

5 The pan containing the Group B, C, and D specimens on the saturated pad was placed in the humidor, and allowed to remain there undisturbed for at least 24 hrs., until the specimen in each cup had become completely saturated. These nine cups with wetted soil were then transferred to the wire rack in the humidor with the Group A and Group E specimens.

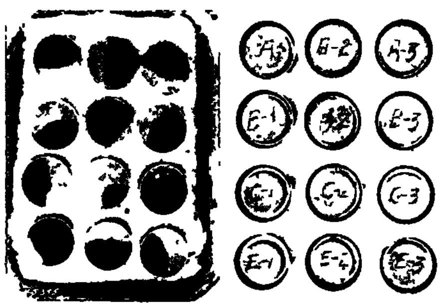

Figure 1. (Left) Dry Minus 4c-mesh Soil Absorbing Water from a Saturated Pad Through a Hole in the Bottom of the Pat-Cup. (Right) Test Specimens After Being Dried to Constant Weight at 100 F.

FIRST DRYING OF SPECIMENS AFTER BEING MOLDED WET

1 The set of 15 specimens was allowed to remain undistrubed on the wire rack in the closed humidor until each soil pat had dried to constant weight

2 The humidor lid was then raised a small amount each day[8] until it was completely open and all the soil pats had arrived at constant weight when exposed to the laboratory room atmosphere

3 By this time the pats had shrunk sufficiently to be removed from their cups[9] This was done and the filter paper and all loose soil were carefully removed from each specimen and placed in the respective pat cups to be dried and weighed for checking purposes

4. After each specimen was free of filter paper and loose soil, it was placed on an inverted aluminum can, which was marked with the proper group and specimen number for future identification All the soil pats, on their aluminum cans, were placed on the same shelf in a 100 F oven and dried to constant weight at that temperature Each pat cup that contained the filter paper and loose soil from its respective soil pat was placed in the oven at 100 F and also dried to constant weight at that temperature

5. When the soil pats arrived at constant weight at 100 F they were removed one at a time from the oven, accurately weighed to 0 001 g., and their volumes determined by mercury displacement[10] The volume of the overflow mercury was measured in the 20-cu cm. graduated tube read to 0 01 cu cm. The test specimens were then placed on their respective aluminum cans in a place of safe keeping where the natural temperature and humidity of the air in the laboratory room prevailed

6 At the same time the weights and volumes of the test specimens were determined, the weight of each monel metal pat cup with the filter paper and lost soil also was determined and recorded for purposes of checking

FIRST WETTING OF SPECIMENS AFTER BEING MOLDED WET AND DRIED

1. After the weights and volumes of the 100 F oven-dry soil specimens had been determined and recorded, all the specimens were transferred to a wire rack in the laboratory room atmosphere and remained there until they arrived at constant weight. The rack with the specimens was then transferred to the humidor, and allowed to remain there until all the specimens arrived at constant weight.

2 Next, the specimens were removed one at a time from the humidor and immediately packed in sawdust with a moisture content of 25 per cent,[11] each in the center of a wire

[8] While the humidor lid was being raised gradually, the soil pats were closely observed and if they showed any tendency toward cracking, the lid was lowered or closed until the moisture throughout the specimen apparently had equalized

[9] See Figure 1-right for illustration of specimens when dry the first time after being molded wet.

[10] Every time a soil specimen was submerged in mercury it was accurately weighed immediately before and after contact with the mercury, in order to be sure no mercury adhered to the specimen

[11] The sawdust packing with 25, 50 and 75 per cent moisture contents passed the No, 10

strainer as illustrated in Figure 2. Care was exercised that the sawdust was packed against the edges of the specimens as well as against the tops and bottom, but not tight enough to break them. Immediately after packing the specimens in sawdust the strainer containers were placed on the wire rack in the humidor and allowed to remain there for 24 hr.

3. At the end of every 24-hr. period the specimens were re-packed in sawdust with a moisture content 25 per cent greater than that from which they had just been removed, and so on, until the specimens had remained for 24

Figure 2. Soil specimens packed in damp sawdust for slowly raising the moisture content of the specimens.

hr. in sawdust with a moisture content of 150 per cent.[12]

4. After the specimens had remained in the 150 per cent moisture content sawdust for 24 hr., the elevation of the distilled water was raised to the top of the porous slab in the bottom of the humidor, and the strainers with specimens in sawdust were transferred from the wire rack to the porous slab. They were allowed to remain on the saturated slab for 24 hr. The water then was raised to $\frac{1}{8}$-in. above the top of slab for 24 hrs., and then raised to approximately $\frac{3}{4}$-in. for the same period. The specimens then were considered saturated.

5. Next, the specimens were removed one at a time from the strainer containers and all sawdust was removed carefully from the test specimens with a camel's hair brush.[13] Each saturated specimen was weighed,[14] its volume determined and recorded, and the specimen was placed on an aluminum can on the wire rack in the closed humidor. The aluminum can first was covered with a thin film of vaseline to prevent the wet soil from sticking to it.

SECOND DRYING OF SOIL SPECIMENS AFTER BEING MOLDED WET

1. The specimens were allowed to remain in the closed humidor until they arrived at constant weight. Then the lid of the humidor was gradually raised from day to day until it finally was wide open.[15] After the specimens arrived at constant weight with the lid open they were transferred to the closed oven, and the temperature of the oven was raised slowly to 100F. and constantly kept at that tempera-

and was retained on the No. 20 sieve when dry. The sawdust used with the 100 per cent and greater moisture contents passed the $\frac{1}{4}$-in. screen and was retained on the No. 10 sieve when dry. Distilled water was used for wetting the sawdust.

[12] The highly expansive SIII soil specimens were carried through 200 per cent moisture content sawdust packing.

[13] For illustration of specimens when saturated with water, see Figure 2 of Part II, "Density and Moisture Content of Clay Soil When Saturated," Engineering Experiment Station Series No. 68, College Station, Texas.

[14] When the soil specimens were removed from the saturated sawdust they had a film of free water on their surfaces. Before weighing, the film of free water was allowed to evaporate and immediately upon the disappearance of the last trace of free water, the specimens were weighed. This procedure was adopted in order to treat all specimens alike.

[15] The humidor was kept in a closed room free from air currents. Usually the air in the room was at natural relative humidity and temperature. From the time of the beginning of raising the humidor lid, until the specimens arrived at constant weight in the 100 F. oven, the test specimens were kept under close observation and when any tendency toward warping or cracking appeared, the drying was stopped until it was thought the moisture in the specimens had equalized.

ture until the test specimens again arrived at constant weight.

2. Figures 1, 2, and 3 of Part V, "Density and Intermediate Moisture Contents of Clay Soil,"[16] give an idea of the rates at which the specimens lost their moisture. There were indications that these specimens could have been dried faster without damage to them.

3. When the specimens all had arrived at constant weight in the 100 F. oven, their weights to thousandths of a gram and their corresponding volumes measured to hundredths of a cubic centimeter were recorded.

SUBSEQUENT WETTINGS AND DRYINGS OF SPECIMENS

1. The operations described under "First Wetting of Specimens after Being Molded Wet and Dried" and "Second Drying of Specimens After Being Molded Wet" were repeated for as many cycles of wetting and drying as has been shown in the foregoing parts of these data.

GENERAL REMARKS

1. In order to make these test practicable, the period of time required for each operation must be reduced as much as is possible without injury to the specimens. The rate at which the soil pats can be wetted and dried depends to a great extent upon the lineal shrinkage or volumetric change of the soil. It was found however, that these specimens could not be dried as rapidly the first time after being molded wet as they could the second time. The principle of mechanics involved in the rupture of the soil structure caused by wetting and drying too rapidly is similar to the cracking of glass because of too rapid non-uniform change of temperature therein. The laboratory operator will have to determine by experience the rate at which clay soils of different types can be wetted and dried without breakage or disintegration of the test specimens.

2. It was noted in Figures 42 to 72 of Part I, "Permanency of Clay Soil Densification[17] that the wet density and the dry density of a specimen was not exactly the same in each cycle of wetting and drying, and also it was noted in Figures 3 to 7 of Part II, "Density and Total Moisture Content of Clay Soils"[18] that the moisture contents of the specimens when saturated in the different cycles were not exactly the same. In Part I it was stated that the tests were performed in a standard soils laboratory room in which there was some natural variation in the relative humidity and temperature from time to time. If exact data are desired, the heretofore described tests should be made in a room where the relative humidity, temperature, and air pressure is kept constant.

2. Relation of Density to Strength of Clay Soils When Consolidated and Saturated

Foregoing experiments indicated that the denser the clay soil was consolidated the smaller was the percentage of water it absorbed to become saturated and that the specimens that absorbed the least percentages of water required the greatest load to rupture them. Tests were made that substantiated those phenomena It also was determined that there was a direct relation between the density and the strength of the clay soil specimens when saturated.

When the prepared specimens were saturated, as described under (1) "Method of Preparing Clay Soil Specimens For Physical Tests," they were removed from the wet sawdust packing one at a time, placed in the machine shown in Figures 3 and 4, and slowly loaded until their structures were ruptured to a certain established extent.

Usually the first break of a full size specimen divided it into two or more pieces, as shown in Figure 5, and each piece was large enough to be tested separately. In the graphs shown in Figure 6 the average saturated rupture loads of the SI, SII, and SIII soils were plotted as abscissa, with the saturated densities plotted as ordinates.

The relatives strengths of the different density specimens of a set when saturated was desired more than the actual shear strength, or the compressive strength, or the resistance to

[16] Engineering Experiment Station Series No. 70, A. and M. College, College Station, Texas.

[17] Engineering Experiment Station Series No 67, A and M. College, College Station, Texas.

[18] Engineering Experiment Station Series No. 68, A and M. College, College Station, Texas.

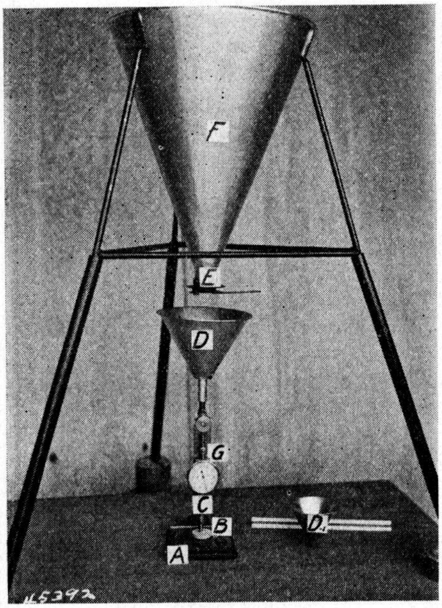

Figure 3. Front view of apparatus used for loading and rupturing the test specimens

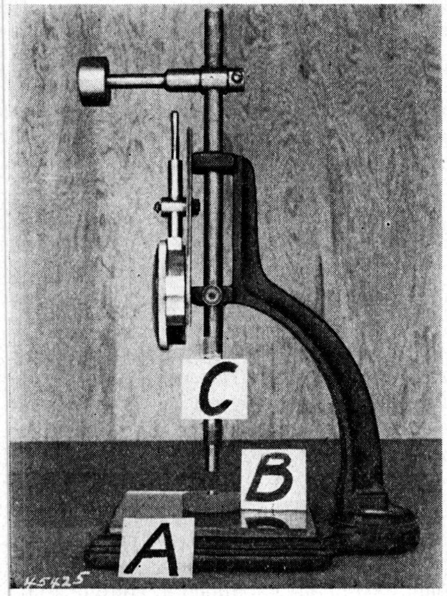

Figure 4. Side view of Figure 3

penetration, punching, or mashing.[19] Consequently the words "relative rupture load" were used instead of the foregoing terms, any one of which alone might be misleading. The load was applied until each test specimen, or part thereof was ruptured to the same extent, as nearly as could be determined with the eye. Although the loads applied were figured in pounds per square inch of contact between the $\frac{1}{20}$-sq. in. plunger and the soil specimen. the loads shown in the graphs should be considered as relative only for the present.

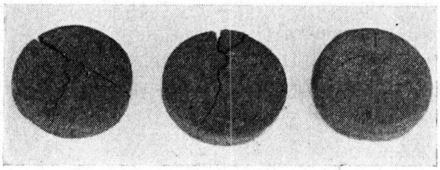

Figure 5. First break in each of test specimens

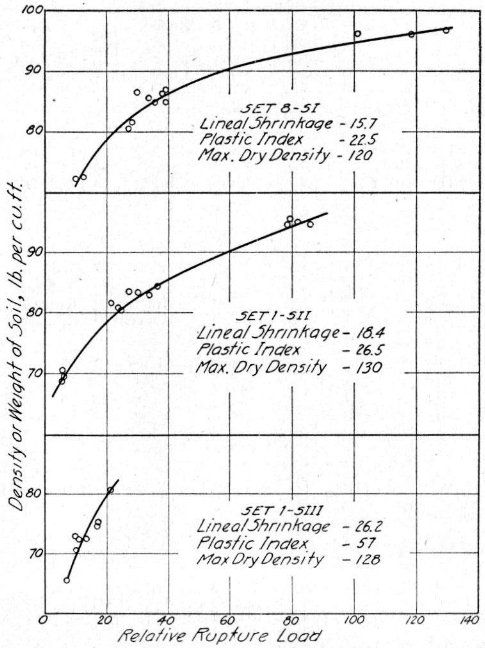

Figure 6. Relative Rupture Load

In performing these experiments it first was thought that the point of rupture of the soil structure would have to be determined by rate of penetration of the plunger, but it was found that failure occurred rather abruptly and the load which caused the structural rupture could be determined fairly accurately. It also was observed that the amounts of indentation at the time of structure rupture varied from ap-

[19] The objectives in these experiments were to determine trends or fundamental principles rather than to determine accurate values.

proximately 0.025 in for the dense dry pat cup specimens to 0 05 in. for the non-dense saturated specimens, as measured by the extensometer.

DISCUSSION

The relations of the densities to the load supporting powers of the three clay soils when consolidated and saturated are as given in Table 1.

The data also indicated that the load supporting power of the clay soils depended to a great extent on the type of the soil, when it was consolidated to a given density (between 120 and 130 lb. per cu ft. dry in this instance) and

TABLE 1

Soil Type	Minimum		Maximum		Difference in	
	Dry Density	Relative Rupture Load	Dry Density	Relative Rupture Load	Dry Densities	Relative Rupture Load
	lb per cu ft		*lb per cu ft*		*lb per cu ft*	
SI	91	11	120	129	29	118
SII	86	6	130	86	44	80
SIII	102	7	128	21	26	14

TABLE 2

Soil Type	Plastic Index	Dry Density	Saturated Moisture Content	Relative Rupture Load
		lb per cu ft	*Per Cent*	
SI	22 5	120	21	129
SII	26 5	130	25	86
SIII	57 0	128	35	21

slowly wetted to saturation, as shown in Table 2.

3. Relation of Density, Moisture Content and Strength of Consolidated Clay Soils

For making tests pertaining to the relations of density, moisture content, and strength of consolidated clay soils, four sets of specimens with approximately 55 specimens in each set were prepared[20] for that particular purpose. All specimens in each set were made as near the same density and size as practicable but the densities of the different sets of each of the two types (SI and SII) of soil were different. Each set was divided into groups of approximately four specimens each, and a cycle of slow wetting to saturation and re-drying to constant weight at 100 F was started. When the specimens arrived at different approximate moisture contents in this cycle, a group of four at a time was taken from the set and slowly loaded until failure occurred, somewhat as follows.

While being wetted

Group 1—at 0 0 per cent
" 2— " 10 0 " "
" 3— " 15 0 " "
" 4— " 20 0 " "
" 5— " 25 0 " "
" 6— " 30 0 " "
" 7— " Saturation

While being dried

Group 8—at 30.0 per cent
" 9— " 25.0 " "
" 10— " 20 0 " "
" 11— " 15.0 " "
" 12— " 10.0 " "
" 13— " 0.0 " "

All specimens with a relative rupture load less than 500 were broken in the machine shown in Figures 3 and 4, all with more than 500 were broken in the machine shown Figure 7

It was thought that there might be some difference in the load supporting power of the clay soil (at a certain moisture content) while being wetted as compared with its load supporting power while being dried In order to gain information in this regard, after the saturated group was tested the remaining specimens of the set were slowly dried, and when they arrived at the various desired moisture contents (approximately 25, 20, 15, 10, and 0) the different groups were loaded to failure.

The solid lines in Figures 8 and 9 show the relative rupture loads at different moisture contents when the consolidated specimens were being wetted and expanded in volume; and the broken line in each of those figures shows the relative rupture load at different moisture contents when the specimens were being dried and were shrinking in volume Parallel experiments made with SII soil substantiated these SI soil data but for brevity they have been omitted.

[20] See Section 1 "Method of Preparing Clay Soil Specimens For Physical Tests" for details.

DISCUSSION

Attention is invited to general statements regarding the density-moisture content-strength data compiled while the moisture content was slowly rising (shown graphically in Figures 8 and 9) given in Table 3.

CHECK TESTS WITH LARGE CYLINDER SPECIMENS

The relative rupture loads of 4865 for the SI soil, as shown in Figure 9 (and 4519 for the SII soil) appeared high if those figures were considered as expressing the rupture load in pounds per square inch It so happened that the $\frac{1}{30}$ cu ft. cylinder specimens of these same soils prepared[21] in the District 15 laboratory had been carefully preserved They were in the same condition as when air dried to constant weight after being removed from the mold It was decided, therefore, to test these larger cylindrical specimens for their load supporting power when containing different amounts of moisture and compare that data with those shown in Figure 9. The densities of the specimens when dried to constant weight at 100 F. were computed. One specimen each of the SI and SII soil specimens was loaded until rupture of the soil structure occurred Pictures together with data prepared during those operations, are shown in Figures 10 to 15, inclusive.

Figure 7. Machine used for slowly loading soil test specimens that required more than 500 lb. relative load to rupture them.

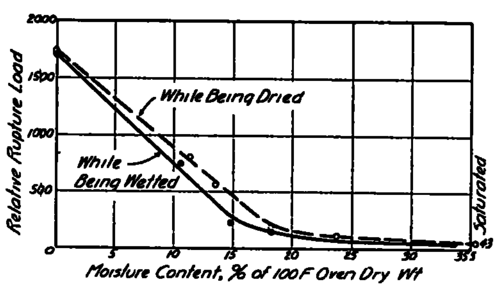

Figure 8

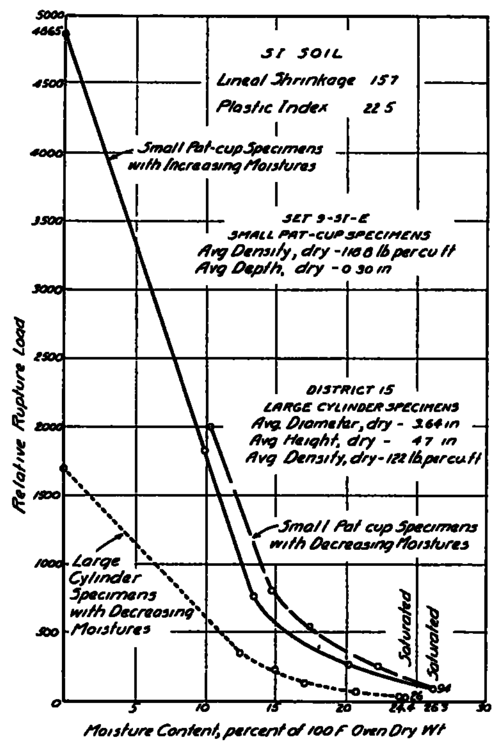

Figure 9

While the large cylinder specimens were being tested, three very interesting observations were made regarding the behavior of the soil structure under load. (1) When the specimen failed under the first loading there was no indication of an explosion, in fact there was very little change in its outside appearance, as shown by comparing Figures 11 and 13 (2) At the time of failure the vertical deformation of the cylinder specimen was approximately 0 05 in (3) Immediately after the SI specimen failed under the total load of 17,150 lb ,

[21] For detailed description of specimens see Part I, "Permanency of Clay Soil Densification," Texas Engineering Experiment Station Series No 67, A and M College, College Station, Texas

the load was entirely removed and then gradually re-applied. Under the second slow application the pointer on the loading machine stopped moving at the total load of 10,350 lb.

TABLE 3

1. The density to which the clay soil was consolidated had a great effect upon its load supporting power:

Type of Soil	Difference in Oven-dry Densities	Difference in Relative Load Supporting Power at		
		Oven-Dry	14 Per Cent	Saturation
	lb per cu.ft.			
SI	119–101=18	4865–1708=3157	700–360=340[a]	94–43=51[a]
SII	126–108=18	4519–1973=2546	500–160=340	79–28=51

2. From the 100 F. oven-dry to the saturated condition of the test specimens there was considerable decrease in the load supporting power of the consolidated clay soil. The following tabulation gives an idea of those differences.

Soil Type	Density	Loss in relative load supporting power, from the zero moisture to the saturated condition
	lb per cu.ft.	
SI	101	1708–43 = 1665
SI	119	4865–94 = 4771
SII	108	1973–28 = 1945
SII	126	4519–79 = 4440

3. The decrease in load supporting power with the increase in moisture content was at a much greater rate between the zero and the approximately 14 per cent than it was between the 14 per cent and saturation.

Soil Type	Density	Loss in relative load supporting power from	
		0 to 14%	14% to Saturation
	lb per cu.ft.		
SI	101	1350	325
SI	119	4165	606
SII	108	1850	110
SII	126	4130	310

4. In each set of test specimens more load was required to rupture the specimen at a certain moisture content when the specimens were drying out and shrinking than was required (for the same moisture content) when the moisture in the specimen was slowly increasing and the soil was increasing in volume. This indicated that the minimum rupture load of a consolidated clay soil at a certain moisture content should be made while the soil is being wetted slowly and expanded rather than when it is losing its moisture and shrinking.

[a] The occurrence of the same differential in these two columns may be coincidences.

When that load was removed there was still no appreciable change in the appearance of the specimen from that shown in Figure 13. Load was gradually applied to the soil cylinder

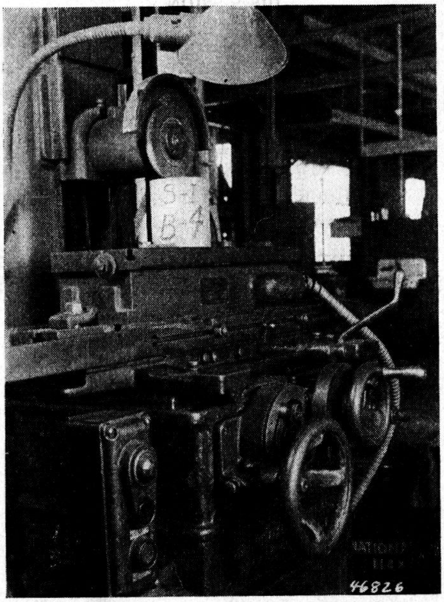

Figure 10. The SI-B-4 soil specimen in the magnetic surface grinder where the ends of the test specimens were made smooth and parallel to each other.

Figure 11. District 15 soil specimen before it was loaded to failure in the machine shown in Figure 16. The specimen had been dried to constant weight at 100 F., the ends ground smooth and parallel and the volume computed. The average diameter was 3.585 in., height 3.973 in., and the density was 124.6 lb. per cu. ft. The rupture load was 1700 lb. per sq. in. and the deformation at the time of rupture was 0.056 in.

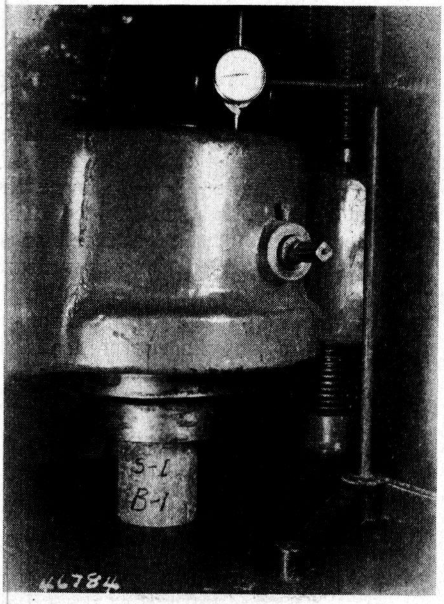

Figure 12. Showing the soil cylinder immediately after it failed under a compressive load 1700 lb. per sq. in. The extensometer dial measured the vertical deformation (0.056 in.) at rupture.

Figure 14. Close-up of specimen shown in Figure 13 after the testing machine pointer stopped at 6,475 lb. and machine continued to run. The loose outside broken pieces of soil then were scratched down.

Figure 13. Close-up of specimen immediately after rupture at 17,150 lb. Platen of testing machine raised for this picture. Load then slowly re-applied until pointer stopped at 10,350 lb. Platen again was raised but no change in appearance of specimen could be seen. Load again was slowly applied until pointer stopped at 6,475 lb. No difference in appearance of specimen at that time.

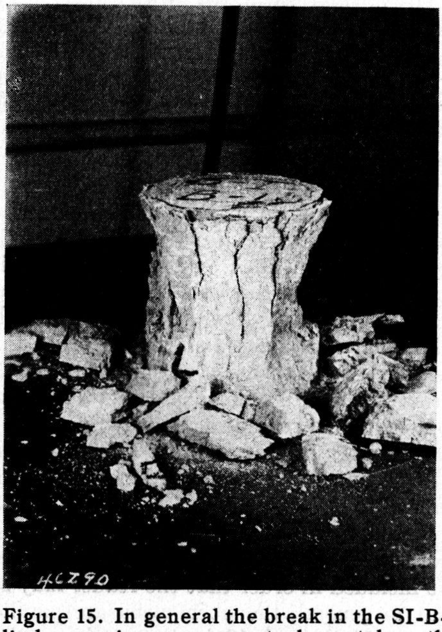

Figure 15. In general the break in the SI-B-1 cylinder specimen appears to have taken the hourglass form.

again and this time the machine pointer stopped at the total load of 6475 lb. Still there was very little change in the appearance.

It was difficult to tell by visual inspection when the structures of the unconfined cylinder specimens were first ruptured. Perhaps it is much more difficult to tell when the structure of a confined specimen ruptures by visually inspecting the top of the soil and measuring the amount of its deformation or indentation.

Without removing the load again, the specimen was crushed to the condition shown in Figure 14. The broken outside pieces then were scratched down with a pencil point and the picture shown in Figure 15 was made. The pattern made by the ruptured soil structure appears similar to those of other materials broken in compression.

Additional Experiments
With Large Cylinder Specimens

Density and load-supporting-power tests also were made with $\frac{1}{30}$ cu. ft. specimens set up in pairs, each pair having a different density. One specimen of each pair was used to determine the compressive strength of the consolidated soil with the molding moisture, and the companion was used to determine the compressive strength of the consolidated soil when it was saturated with water. Immediately after being molded, all of these specimens were removed from the mold. The first of a pair was placed directly in the compression machine, shown in Figure 16, and loaded to failure. The companion specimen, after removal from its mold, was packed in sawdust with ascending amounts of moisture until the specimen arrived at the saturated condition. Then it also was placed in the compression machine and loaded until its structure ruptured. This companion specimen was removed from its mold before the additional wetting was started in order that its volumetric expansion would not break the structure of the specimen. Also, its moisture content was increased very slowly by means of the sawdust packing in order to prevent disintegration of the structure before load was applied to it.

Pictures of the *two extreme conditions* of moisture content—oven-dry and saturation—are included in order that the reader may see that in general, the phenomena are parallel. Figures 16 through 19 for the specimen when saturated corresponds to Figures 11 through 15 showing the SI-B-1 specimen when dry. The test specimens for these additional experiments were consolidated in the 4-in. diameter by 4.59-in. height split mold with a 2-in. diameter $5\frac{1}{2}$-lb. hammer dropped 12 in.[22] At the time rupture of the test specimen occurred, its vertical deformation was measured by the extensometer shown in Figure 16. For convenience in making comparisons of density, moisture contents, rupture loads, deformations, and rebounds, a brief of those data are given in Table 4.

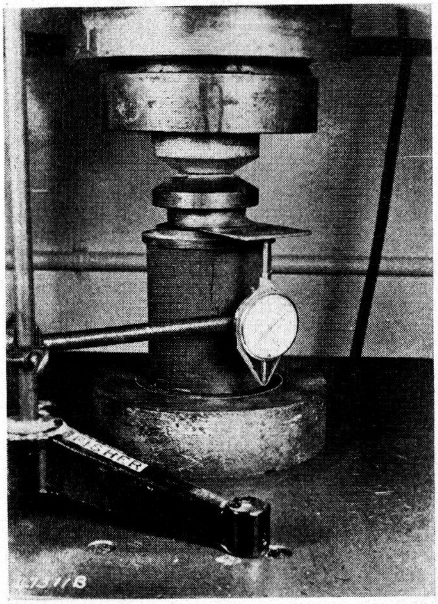

Figure 16. Saturated test specimen with 96 lb. per cu. ft. density, immediately after its structure was ruptured and the rupture-load had been removed. The load required to rupture the specimen was 34 lb. per sq. in.; the vertical deformation at time of rupture as 0.09 in., and the vertical rebound when the load was removed was 0.04 in.

Attention is invited to the following general observations regarding the data in Table 4.

1. When the light consolidated 1-M and the

[22] It should be noted that specimens 1-M and 1-W are the only ones that had the optimum load predetermined for obtaining maximum density with the molding moisture used. The compaction loads applied to the other eight test specimens were arbitrarily chosen to make specimens of different densities when molded.

densely consolidated 5-M specimens were removed from their molds the difference in their densities was approximately 13 lb. per cu. ft.; the difference in their moisture contents was 8 per cent; and the difference in their rupture-loads was 79 lb. per sq. in.

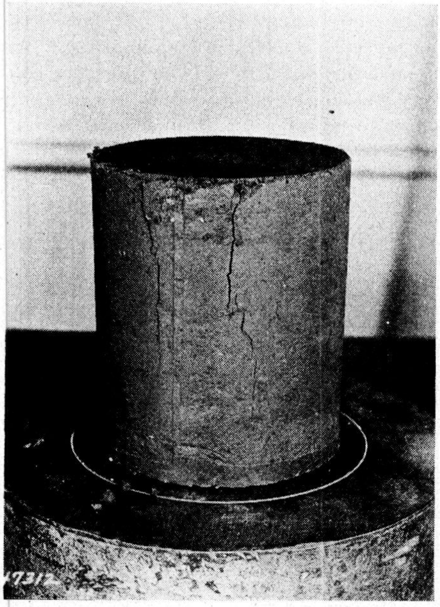

Figure 17. Close-up of the specimen shown in Figure 16 after its structure was ruptured and the load removed. Without moving the specimen, load then was slowly re-applied until the machine pointer stopped moving upward at 335 lb. (26 lb. per sq. in.) and then began to fall back. The vertical deformation during this loading was 0.08 in.; and when the load was removed the vertical rebound was 0.05 in. At that time the appearance of the specimen had changed very little from that shown in this figure. Load again was applied the third time until the pointer stopped its upward movement at 250 lb. (21 lb. per sq. in.). The vertical deformation during the third loading was 0.09 in.; and when that load was removed the vertical rebound was 0.05 in. After load was applied the third time, the outward appearance of the specimen was not greatly changed from that shown in this figure.

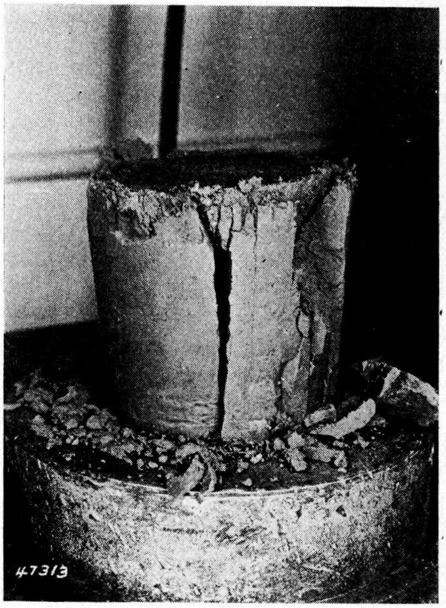

Figure 18. Load was reapplied to the specimen the fourth time, and continued until the specimen was partially crushed, as shown here. The outside broken pieces of soil then were flicked off, as shown in Figure 19, in order that the form of the break might be seen.

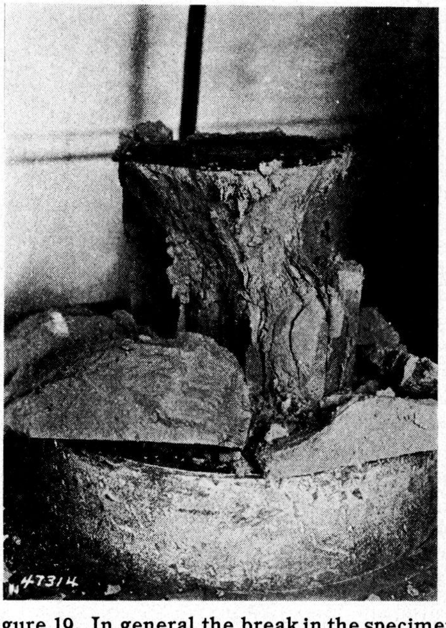

Figure 19. In general the break in the specimen took the hourglass form, as shown here.

2. On the other hand when the 1-W and the 5-W specimens were wetted to saturation the difference in their densities was approximately 12 lb. per cu. ft.; the difference in their moisture contents was 10 per cent; and the difference in their rupture-loads was only 26 lb. per sq. in.

3. The difference in the rupture loads of the densely consolidated No. 5 specimens when removed from the mold and when saturated with water was 69 lb. per sq. in.—the gain of 6 per cent in moisture content caused a loss of 67 per cent in load-supporting-power

4. Particular attention is invited to the maximum vertical deformations of these test specimens at the time of rupture, as shown in Column 10 The maximum was 0 3 in , the minimum was 0 05 , and the average was 0 13 in. The maximum vertical rebound of the specimen when the rupture load was removed was 0.06 in , the minimum was 0 01 in., and the average rebound was 0.03 in. These data indicate that if considerable settlement occurs in a roadway or runway, one of three conditions probably prevailed. (a) the soil was never consolidated into an integral structure, (b) the integral structure later was broken and disintegrated, or (c) the natural foundation settled.

5. As previously stated, the load applied (475 hammer blows) in consolidating the No. 5 test specimens may not have been the optimum load for obtaining maximum density when the moisture content of the SI soil was 18 4 per cent. The absorption of the additional 6 per cent moisture to become saturated and loss of 69 lb per sq. in. in load supporting power of the No. 5 specimens appears excessive Perhaps that is due to a lack of the proper relation of moisture content to consolidation load used in the molding of the specimen It may be there is an optimum load and also an optimum moisture content which will make a specimen that will absorb a minimum amount of moisture to become saturated and have the maximum load-supporting-power. If a clay soil could be consolidated to such a density with such moisture content that the soil structure would absorb no more water to become saturated, in one way it appears that that condition would be ideal for roadway and runway construction.

The proper method of consolidating the clay soil in order that it will absorb the least amount of water to become saturated and carry the greatest load without rupture when saturated (or when it reaches the maximum subsequent moisture content) is now being investigated.

TABLE 4
ADDITIONAL EXPERIMENTS WITH LARGE CYLINDER SPECIMENS

Specimen No	No Rammer Blows Applied	When Removed From Mold		Period of Raising Moisture	When Specimen Ruptured					Rebound When load was removed
		Moisture Content	Density		Moisture Content	Density	Volumetric Change	Load Applied in	Vertical Deformation	
		%	lb per cu ft	days[a]	%	lb per cu ft	%	lb per sq in	in	in
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1-M	75	26 7	90 1	0	26 7	90 1	0 0	24	0 30	0 06
1-W	75	26 3	87 8	39	34 0	83 7	4 9	8	0 06	0 03
2-M	475	13 9	95 8	0	13 9	95 8	0 0	99	0 07	0 02
2-W	475	14 4	95 6	41	33 0	84 4	13 3	9	0 06	0 02
3-M	175	20 2	97 8	0	20 2	97 8	0 0	82	0 21	0 01
3-W	175	21 4	97.7	53	27 8	93 0	5 1	16	0 14	0 05
4-M	340	19 5	101 6	0	19 5	101 6	0 0	108	0 22	0 06
4-W	340	19 5	102.5	41	25 4	97.7	5 0	27	0 08	0.04
5-M	475	18 4	103 3	0	18 4	103 3	0 0	103	0 18	
5-W	475	18 4	101.5	40	24 0	95 6	6 2	34	0 09	0.04

[a] Perhaps the specimens could have been wetted faster without structure disintegration Experiments now are being made for detailed information regarding speeds with which different size specimens of different type clay soils can be wetted and dried without damage to the soil structure

MOISTURES IN CLAY SOILS BENEATH PAVEMENTS

The foregoing data showed that the existing moisture content of the two (SI and SII) consolidated clay soil specimens had a great effect on the load supporting power of the soil. It appeared that the minimum rupture load of the densely consolidated soils would be increased considerably above that of the saturated specimens if the moisture content could be held continuously below approximately 20 per cent. The question then arose as to whether it would be practicable to design and construct roadways and runways in such manner that subsequent moistures in the soil substructures could be controlled to that extent.

Tests made in one county in March and in November 1934 showed subsoil moisture content fluctuations of 25 per cent (from 45 to 20) at the 2-ft. depth and 14 per cent (38 to 24) at the 12-ft. depth. These tests were made, however, at the right-of-way line where the soil was not covered, and there was an unusual drought during the summer and fall of that year [23]

In 1933 investigations made at different depths below the natural ground surface near the Guadalupe County Research Project showed the moistures down to the 3-ft. depths were considerably less in a "laid-by" corn field than they were in the same type clay soil only 15 ft. away where cotton was growing and the top soil was kept mulched by frequent plowing. The average moisture content in the corn field was 5 per cent less than in the cotton field.[24]

Data taken during the four years following construction of an approximately 8-mile paving project in 1933 indicated that it would be practicable to appreciably control maximum moisture contents in soils beneath pavement There were 37 1200-ft test sections on that project The pavement was laid directly on the natural clay soil on 22 of the test sections, while on the other 15 various treatments and coverings of the clay soil were employed immediately before the pavement was laid.[25] The maximum moistures of soil specimens taken from beneath the pavement on this research project are shown graphically in Figure 20.[26]

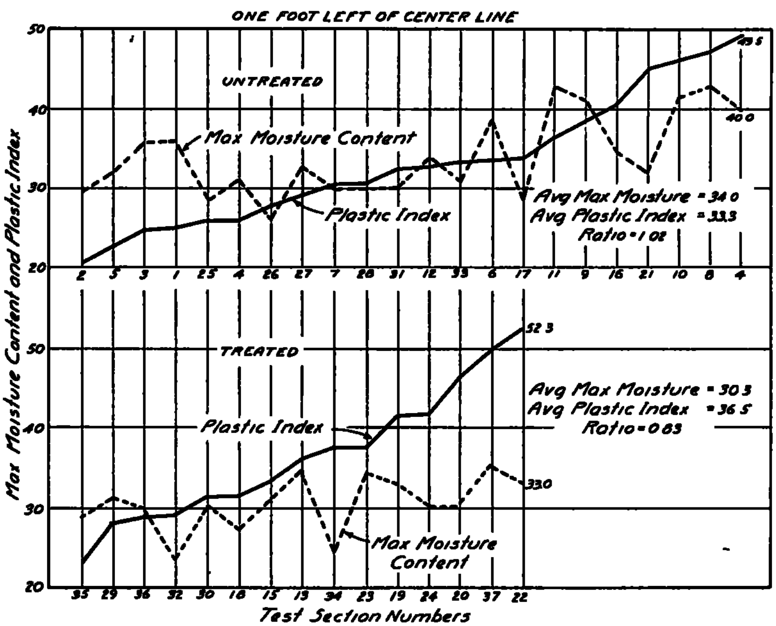

Figure 20

[23] For detailed data see *Proceedings*, International Conference on Soil Mechanics and Foundation Engineering, Volume II, p 259, June, 1936, or *Proceedings*, Highway Research Board, Vol. 18, Part 2, p. 345, 1938.

[24] For detailed data see "Compilation of Data on the Guadalupe County Research Project," Part I, p 216, October, 1934, or *Proceedings*, Highway Research Board, Vol. 18, Part 2, p 353, 1938.

[25] See "Identification Sheet," page 11, Part I, "Compilation of Data on the Guadalupe County Research Project," Texas Highway Department, Austin, Texas

[26] In studying these data it should be borne in mind that this project was not designed

Because the type of soil affects the amount of water it will absorb at a certain density, the type must be taken into account The plastic index is generally used to identify the soil type, therefore in Figure 20 the plastic indexes are plotted with the solid line in the order of the increasing plasticities of the soil on each test section. The maximum moisture contents are shown with a broken line in the same graph. From those data the observations in Table 5 and 6 are made

In the treated test sections shown in the lower part of Figure 20, the maximum moisture content graphs did not follow very closely the general directions of the plastic index graph. Table 6 gives detailed observations regarding those dates.

The average maximum moisture content for all tests on the untreated sections was 43.1, as compared with 36.7 for the treated sections—a difference of 6 4 per cent, even though the

primarily for this investigation Foregoing data show the density of a clay soil governs to a large extent the amount of water it will absorb No soil density data were taken on this project It was assumed in this study that the soil density on all test sections was relatively the same

TABLE 5
UNTREATED SECTIONS

Figure No	Minimum		Maximum		Average	
	Plastic Index	Moisture Content	Plastic Index	Moisture Content	Plastic Index	Moisture Content
		%		%		%
20-a[a]	20 3	26 0	46 4	41 7	33 2	34 0
20-b	20 3	26 0	49 5	43 0	33 3	34 0
20-c[a]	20 3	26 0	46 4	44 5	33 9	34 1
Average	20 3	26 0	47 4	43 1	33 5	34 0

[a] Graphs of data taken at 5 ft left and at 5 ft right of center line were omitted for brevity

TABLE 6
TREATED SECTIONS

Figure No	Minimum		Maximum		Average	
	Plastic Index	Moisture Content	Plastic Index	Moisture Content	Plastic Index	Moisture Content
		%		%		%
20-a[a]	25 8	23 0	60 4	38 0	37 6	30 2
20-b	23 0	23 5	52 3	35 0	36 5	30 3
20-c[a]	24 9	23 0	49 6	37 0	35 0	30 5
Average	24 6	23 2	54 1	36 7	36 4	30 3

[a] Graphs of data taken at 5 ft left and at 5 ft right of center line were omitted for brevity

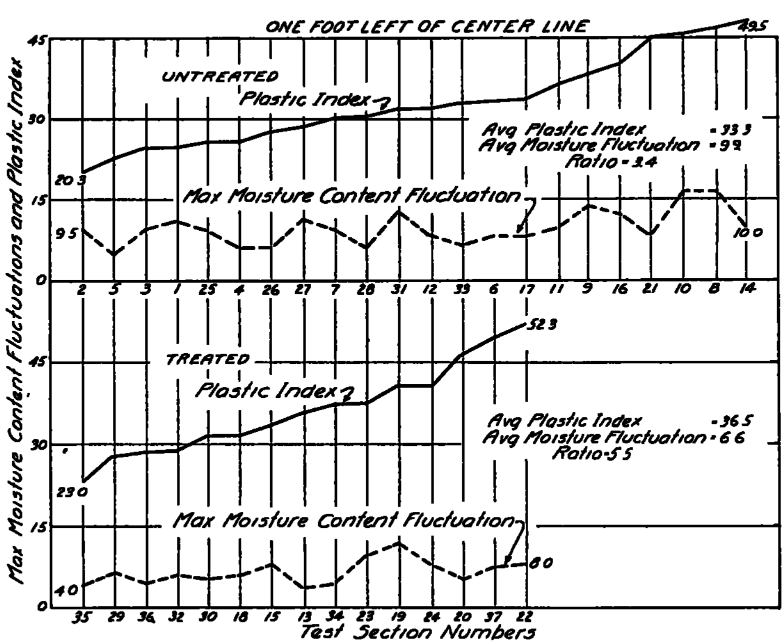

Figure 21

average plastic index (54 1) of the treated sections was 6 7 higher than that of the untreated sections (47 4)

The average maximum moisture contents were 34.0 for the untreated and 30 3 for the treated sections, while the corresponding average plastic indexes were 33 5 and 36 4. This made a ratio of 1.01 for the untreated and 0.83 for the treated sections.

It also has been shown previously that rapid moisture content fluctuations in clay soil substructures cause rupture and disintegration; therefore a study of the Guadalupe County data was made for information regarding this phenomenon. At the same time the graphs shown in Figure 20 were made, graphs also were plotted of the differences in the maximum and minimum moisture contents with the plastic indexes of the soils on the test sections, as shown in Figure 21

For reasons previously given, these moisture content variations can be compared in a general way only. The ratio of the average plastic index to the moisture content fluctuation is 3 4 for the untreated sections as compared with the ratio of 5 5 for the treated section, as shown in Figure 21. It appears that different treatments can be used that will appreciably reduce the moisture fluctuations in clay soils beneath the pavements. The maximum moisture content fluctuation on Test Section 34 was only 5 per cent during the approximately three years that observations were made

CONCLUSIONS

These data indicate that·

1. Investigations with small pat-cup test specimens will reveal much information pertaining to the characteristics of soils at different densities and containing various moistures

2 The denser the clay soil was consolidated the smaller was the percentage of water it absorbed to become saturated and the greater was the load required to rupture the specimen when saturated

3 The load supporting power of a clay soil when consolidated to a given dry density and slowly wetted to saturation depended to a great extent on the type of the soil The load required to rupture the clay soil with plastic index of 22 5 was approximately 1.6 times that required to rupture the soil with a plastic index of 26 5, and 6 times the load required to rupture the soil with the plastic index of 57, when all three soils were consolidated to practically the same density.

4 The load supporting power of the clay soil at any and all moisture contents, from the dry to the saturated, also was greatly affected by the density to which the soil was consolidated.

5 The graph of the plotted data did not make a straight line when the moisture content of the consolidated clay soil specimen was raised slowly from the oven-dry to the saturated condition and the strengths of the specimens were determined from time to time at the different moisture contents. At the approximately 14 per cent moisture there was a decided change in the graph. As the moisture gradually rose above that point the ratio of decrease in load supporting power to increase in moisture content grew smaller and smaller

6. The deflection of the pat-cup specimens when rupture occurred was approximately 0 025 in for the dense dry specimens and 0 05 in for the non-dense saturated specimens. (Check tests made with the approximately $\frac{1}{30}$-cu ft cylinder specimens showed the unit load required to rupture the small pat-cup specimens when oven-dry was approximately three times the unit load required to rupture the large clyinder specimens The check-tests also showed the vertical deformation of the dry large cylinder specimens was 0 05 in. when rupture occurred.)

7. The minimum rupture load of a clay soil at a certain moisture content must be determined while the soil specimen is slowly being wetted and expanded in volume.

8. For the densely consolidated test specimens a decrease in moisture content of 1 per cent caused an appreciable increase in load supporting power; and the closer the moisture content approached the critical point (approximately 14 per cent) the greater was the increase in strength with each 1 per cent decrease in moisture.

9 It will be practical in many instances to design and construct roadways and runways so that the maximum subsequent moisture content of the clay soil substructure will be reduced and its load supporting power materially increased from that of the saturated condition

10 These data indicate that it also will be practicable to control moisture content fluctu-

ations to such an extent that they will not cause rupture or disintegration of the soil substructure.

GENERAL SUMMARY OF DATA COMPILED TO DATE

From the experiments and studies made to date the following general observations are made:

1 All materials used in roadway and runway substructures should be consolidated to the most economical densities with relation to the costs of construction and maintenance of safe and comfortable riding surfaces.

2. Where other conditions are the same, the load supporting power of sand generally is greatest when it is saturated with gravity water (similar to beach sand directly after being submerged by tide water) and least when the sand is dry.[27] On the other hand the load supporting power of a consolidated clay soil structure is least when it is saturated with water and greatest when practically dry. Therefore, when soils are being considered for construction of the substructure, their types first must be determined—whether sand, silt, or clay.

3. Cohesive clay soils only have been experimented with and studied in these investigations and it appears that some general conclusions can be made relative thereto, as follows;

(a) Because the moisture content as well as the density of a consolidated clay soil substructure governs its load supporting power to a great extent, a practical and accurate method should be employed for predetermining the rupture load of a consolidated and integral soil structure with various moistures.

(b) Laboratory tests should be satisfactorily correlated with conditions in the field.

(c) It is difficult to determine just when rupture occurs in a consolidated laboratory specimen under load by visually examining its exposed surface. Observations made during these experiments showed that the amount of vertical deformation at the time of rupture was not uniform. With the pat-cup specimens the deformation varied in the same direction as the moisture content, but not so with the large cylinder test specimens. It appears, therefore, that it is not feasible to establish a certain amount of vertical deformation as a definite criterion for the amount of load imposed when rupture occurs, regardless of the type of soil, its density, and its moisture content.

(d) Practicable and reliable tests of the load supporting power of the clay soils after they are in place also should be made before pavement is laid, but those tests (made with only the moisture content that exists immediately prior to the placing of pavement) often do not give enough definite information regarding the minimum rupture load with moistures that will prevail thereafter.

(e) Usually the ideal procedure would be to determine the load supporting power of the consolidated clay soil structure when it contains its maximum subsequent percentage of moisture and then design the pavement to fit that condition.

(f) It is important that the pavement be designed to distribute the live load in such manner that the consolidated soil structure will not be ruptured.

(g) A great deal of detailed work now is being performed on converting loose dirt into consolidated soil substructures for receiving roadway and runway pavements, and these substructures have definite characteristics, one of which is compressive strength. Even though the clay soil substructure is built with definite load supporting characteristics, that structure at some later time might be ruptured either by rapid moisture content fluctuations[28] or overloading. If the structure is ruptured, regardless of the cause, it will not continuously give the desired service.

4. When a clay soil substructure is designed and built in accordance with the best known principles of soil mechanics, it then should be treated as a structure with characteristics that

[27] Sands when in the quick condition are an exception.

[28] Page 36–38 of Part I, Texas Engineering Experiment Station Series No 67, Figures 36, 37, 38, and 39, definitely showed that the structure of the SI soil consolidated with the optimum moisture of 28 per cent disintegrated when it was suddenly submerged in water. This very important phenomenon also was illustrated in Figures 76 through 84 of Part I.

must be respected if desired results are to be obtained A consolidated, integral, cohesive, clay soil mass has constant properties, similar, in a general way, to designs of other materials such as wax, rubber, wood, concrete, glass, and steel It should be borne in mind, however, that all materials have distinctive features or peculiarities different from each other and when tests are made on consolidated soil structures, certain qualities thereof must be known, taken into consideration, and respected.

5 Some apparently constant characteristics of consolidated cohesive soil specimens (approximately 1 5 in. in diameter, 0.4 in in thickness and made of two different clays, SI and SII,) were found to be as follows

(a) Rapid non-uniform moisture content fluctuations ruptured and disintegrated the structures of the consolidated clay soil specimens. On the other hand, *slow and uniform* moisture content fluctuations did not rupture or disintegrate the soil structure even though the specimens were finally wetted to saturation and inundated.[29]

(b) When the consolidated soil specimens were slowly carried through several cycles of wetting to saturation and drying to constant weight at 100 F., the density of the soil with a given moisture content was the same in each cycle; also the percentage of water required to saturate the soil in each cycle was constant.[30]

(c) The total fluctuations in densities of the test specimens, (measured in pounds per cubic foot) between the dry and the saturated conditions were greatest in the densest specimens and smallest in the least dense specimens [31]

(d) The data compiled on the relation between the density and the total volumetric change between the dry and the saturated conditions of the test specimens did not make the same picture when all were plotted Generally, there was not a great deal of difference between the total volumetric change in the non-dense and in the dense specimens.[32]

(e) Density and intermediate moisture content graphs showed critical points near the 5 and 20 per cent moistures.[33]

(f) The ratio between density change and volumetric change was very nearly constant at all points from the dry to the saturated conditions of the specimens regardless of the density to which the soil was compacted.[34]

(g) Graphs of intermediate moistures plotted as ordinates and intermediate volumetric changes as abscissas, showed a critical point to be near the 20 per cent moisture content, above which the behaviors of the specimens consolidated to various densities were different; but at that critical point the graphs of a set (drying from saturation) converged From the point of convergence down to the dry condition the graphs of the different density specimens of a set were very close together.[35]

(h) The denser the clay soil was consolidated the smaller was the percentage of water it absorbed to become saturated and the greater was the load required to rupture the specimens when saturated [36]

(i) The load supporting power of the clay soil when consolidated to a given density and slowly wetted to saturation depended to a great extent upon the type of soil The load required to rupture the SI soil with a plastic index of 22.5 was approximately 1 6 times that required to rupture the SII soil with a plastic index of 26.5 and six times the load required to rupture the SIII soil specimens with a plastic index of 57.[37]

(j) The load supporting power also was greatly affected by the density to which the soil was consolidated at any and all moisture contents from the dry to the saturated conditions

[29] Part I, Engineering Experiment Station Series No 67, A. and M College, College Station, Texas.

[30] Part II, Engineering Experiment Station Series No 68.

[31] Part III, Engineering Experiment Station Series No 69.

[32] Part IV, Engineering Experiment Station Series No. 69

[33] Part V, Engineering Experiment Station Series No 70

[34] Part VI, Engineering Experiment Station Series No 70

[35] Part VII, Engineering Experiment Station Series No 70

[36] Part IX, Engineering Experiment Station Series No 71

[37] Part IX, Engineering Experiment Station Series No. 71.

(k) The graph of the moisture content load supporting power data from the dry to the saturated condition did not make a straight line At the approximately 14 per cent moisture there was a decided change in the slope of the graph.

(l) The vertical deflection of the pat-cup specimens when rupture occurred was approximately 0 025 in for the dense dry specimens and 0 05 in for the non-dense saturated specimens (The vertical deformations of the "Check Test" and the "Additional Experiment" large cylinder specimens varied from 0 05 to 0 30 in, and those variations were irregular and not parallel to the moisture content variations, as was the case with the small pat-cup specimens)

(m) For the densely consolidated test specimens a decrease in moisture content of 1 per cent caused an appreciable increase in load supporting power; and when drying from the saturated condition, the closer the moisture content approached approximately 14 per cent the greater was the increase in strength with each 1 per cent of decrease in moisture.

(n) The minimum rupture load of a clay soil at the moisture content other than saturation should be determined while the soil structure is being wetted slowly and expanding in volume, rather than when it is drying and shrinking in volume

6. Two of the most important objectives to be attained in the construction and maintenance of clay soil substructures are (a) that the clay soil be prepared in the form of a uniformly consolidated, integral, cohesive structure at the time pavement is laid thereon,[38] and (b) that the clay soil be kept in that condition continuously thereafter.

The preparation of the clay soil substructure (in such manner that it will carry, maximum traffic loads continuously without rupturing) is sufficiently important to be reiterated These experiments show that the denser the soil is consolidated the greater is its rupture load; and, that the density to which the soil can be consolidated depends upon its type, its moisture content, and the amount of energy exerted in compacting it For a certain clay soil, the greater the compacting force used (weight of roller and number of trips, for instance) the smaller is the optimum moisture content for obtaining the maximum density, and vice versa. When a clay soil with a certain moisture content is compacted to a maximum density, any further loading is apt to cause or tend to cause disintegration of the soil structure Often, excavated clay soil contains a high percentage of moisture appreciable reduction of which is impractical If that soil must be used, its high moisture will then govern the amount of compaction-loading that will produce the greatest density or load-supporting-power in the soil substructure, and the compaction-loading to obtain maximum density will have to be fitted to the existing moisture content. That "optimum load" should be predetermined by experiment, in the laboratory, perhaps. Pavement then should be designed to carry, with the proper factor of safety, the difference between the rupture load of the prepared soil substructure and the maximum live or traffic load plus weight of superstructure.

If, after the clay soil is properly consolidated, it is allowed to remain uncovered and exposed to the elements, its top—at least—is likely to dry rapidly and crack. If it then is suddenly wetted by rain, the soil will disintegrate and later it often is difficult to tell by visual inspection alone whether the soil is in the form of a consolidated integral structure or a mass of disintegrated, poorly connected, soil particles Where precautions are not taken, therefore, the soil is likely to be in a disintegrated state when pavement is laid thereon and subsequently cause defects to develop in the riding surface. The wetted and consolidated clay soil substructure generally should be covered the day it is finished; this specification would be parallel to that of requiring outside lumber of a new house to be painted the same day it is put up [39]

[38] The detrimental effects caused by exposed clay soil shoulders have been discussed in detail in "Proceedings of the International Conference on Soil Mechanics and Foundation Engineering," June, 1936, Vol II, p 256, and "Proceedings of the Eighteenth Annual Meeting of the Highway Research Board," 1938, Part II, p 352.

[39] In many instances where clay soils are in a disintegrated condition when pavement is laid thereon, they continuously remain in that state, have a great affinity for water, and become plastic and often liquid during rainy weather. When those clay soils are in the

It also is important that provision be made to prevent disintegration of the consolidated soil structure after pavement is laid. In addition to loss of load-supporting-power, accompanying volumetric change or bulking of the soil is likely to cause irregularities to develop in the riding surface.

7. Much valuable information regarding the rupture loads of a clay soil consolidated to different densities and with various moisture contents up to saturation can be determined directly by consolidating the clay soil to desired densities in a cylinder, removing the specimen from its mold, and either testing the specimen for its rupture load with the molding moisture or changing it slowly to some other desired moisture content before loading to rupture.

8. Compiled data regarding moistures in clay soils beneath pavements indicate that in many instances it will be practicable to design and construct roadways and runways so that the maximum subsequent moisture content of the clay soil substructure will be permanently reduced and its load supporting power materially increased from that of the saturated condition.[40]

9. Data of Part (4) "Moistures in Clay Soils Beneath Pavements," also show that the maximum moisture content fluctuation of some of the test sections on the Guadalupe County Research Project, during the three or more years of testing, were only 5 per cent. This indicates that in many instances it will be practicable to prevent moisture content fluctuations in clay soil substructures from becoming sufficiently rapid to rupture the soil structure.

plastic or liquid state they will support very little load without flowing or tending to flow. When confined, though, they often will support considerable load without appreciable movement, in the same way that water in a cylinder will support great loads on a piston if the piston is tight enough to prevent the water from passing it Now that considerable effort, money, and time is being expended to create a soil structure in roadways and runways, that investment should be properly protected

[40] See Part (4) "Moistures in Clay Soils Beneath Pavements" Even though no systematic method of consolidation was employed on the Guadalupe County Research Project, the maximum moisture content on some of the treated sections was less than 25 per cent If the soil had been consolidated to a high state of densification perhaps the maximum amount of water absorbed would have been considerably less than 20 per cent.