Performance of Subbases for Concrete Pavements Under Repetitive Loading

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Laboratory data are reported on the performance of subbases for concrete pavements under the action of 500,000 repetitions of load. The type and gradation of subbase materials, and the placement conditions relative to density and moisture content, were evaluated.

Nine granular subbase materials ranging in gradation from an open-graded, free-draining material to a dense-graded, low-permeability material were tested. The materials were placed at densities ranging from approximately 80 percent to 110 percent of standard AASHO density, and at moisture contents ranging from 75 percent to 120 percent of AASHO optimum. The subbase thickness was 6 in. except for one material where the thickness ranged from 1 in. to 12 in. Four granular soil-cement subbases were tested.

The subbases were placed on a 2½ ft thick clay subgrade confined in a concrete box 4 ft by 6 ft by 3 ft deep. A 2-in. prestressed concrete slab, jointed at mid-length, was cast on the subbase and loads were applied over the joint at the rate of about 20 applications per minute. The loads were of sufficient magnitude to cause a pressure on the subgrade of about 7 psi. During the repetitive load operations, the moisture content of the subbase was increased from the placement moisture to a condition of saturation. The amount of densification that occurred, both in the subbase layer and in the composite subbase-subgrade foundation, was measured.

The data show that, for the materials investigated, an increase in the placement density from 90 to 108 percent of standard AASHO density reduced subbase densification by 80 percent, and an increase in density from 90 to 100 percent reduced densification by 45 percent. These results suggest that granular subbases should be compacted to at least 100 percent of AASHO standard density to preclude harmful densification under traffic.

Under the extremely severe conditions of these laboratory tests, the performance of certain dense-graded subbases was adversely affected by pumping, and the performance of open-graded, high-permeability material was adversely affected by intrusion of subgrade soil into the subbase. A 1-in. filter course of sand or of dense-graded crushed stone prevented the intrusion.

The densification of granular soil-cement subbases was practically zero, and the performance of the subbases was excellent.

●SUBBASES of granular materials are used under concrete pavements to fulfill three principal purposes: to provide protection against the attendant problems of frost action, to restrict volume change of certain subgrade soils, and to prevent pumping. In addition, when properly placed and compacted, subbases distribute the load to the subgrade and provide uniform and stable support for the pavement.

The use of subbases for prevention of pumping gained importance with the advent of more frequent and heavier wheel loads during the early 1940's. Pumping and the attendant loss of subgrade support, which in some cases led to structural failure of the pavement, became a widespread and serious problem. As a result, a committee to study pumping was appointed by the Highway Research Board in 1942, and in 1948 the final report of this committee was published (1). The report stated that subbases of granular materials placed over fine-grained subgrade soils would prevent pumping.

However, it was considered that more research was necessary to show the influence of subbase thickness and of subbase gradation and type in the prevention of pumping. Furthermore, field studies and observations have indicated two other principal areas of subbase design, beyond the function of inhibiting pumping, where additional research was required.

One of the areas is related to the strength of the pavement structure and suggests an investigation of the influence of various types and thicknesses of subbase materials on the load-carrying capacity of the pavement. The Portland Cement Association has in progress an investigation of this phase of subbase design, and data obtained from the first series of laboratory tests have been reported (2).

The second area concerns the densification of subbases under the action of repetitive loads, and it is with this phase of the problem that this report is concerned. Highway traffic operations tend to densify or consolidate the subbase material, resulting in a settlement of the pavement. If this settlement were uniform, little damage would occur, but usually more settlement occurs at transverse joints than elsewhere. Eventually the settlement may cause faulted joints and in severe cases a structural failure of the pavement slab. It is known that increasing the placement density of a material decreases the magnitude of further densification that may occur under repeated loadings, but little quantitative data are available on this subject.

The main purpose of this laboratory investigation was to determine the effects of subbase type, gradation, placement density, and placement moisture content on the densification of the subbase under repetitive loading. The ultimate aim of the project was to obtain experimental data which would aid in writing a specification controlling initial compaction of subbases to preclude harmful densification of the subbase in service. Supplemental information was obtained on the influence of thickness and physical characteristics of subbases in preventing pumping.

PLAN AND SCOPE OF PROGRAM

Nine granular subbases and 4 soil-cement subbases were tested. They were compacted on a clay subgrade soil which had been placed at AASHO standard density and optimum moisture in a 4- by 6- by 3-ft rigid container. For each test, a concrete slab was built on the subbase, and through this slab 500,000 loads were applied to the subbase-subgrade foundation. Water was added at various stages of the loading plan until the subbase was saturated. Measurements were made to determine the progressive densification of the subbase and of the subgrade. Measurements were also made of the pressure on the subgrade. Observations were made of the pumping phenomenon if it occured at various stages of the repetitive load program.

The principal variables of the program of tests on the granular subbases included (a) the initial in-place density of the subbase, ranging from about 80 to 110 percent of AASHO[1] standard; (b) initial in-place moisture content, ranging from 75 to 120 percent of AASHO optimum; (c) the type of subbase, principally sand and gravel and crushed limestone; and (d) the gradation of the subbase. Secondary variables included the thickness of the granular subbase layer and various combinations or blends of the subbase materials. The soil-cement subbases were tested only at AASHO standard density and optimum moisture content.

Supplementary tests were performed to aid in evaluating the performance of the granular subbases. These tests included minimum and maximum density, permeability, and triaxial compression.

MATERIALS

Subbases

The subbases included 5 basic materials selected to represent a range in gradation frequently used in current subbase construction plus 4 supplementary materials

[1] AASHO designation: T-99, The Compaction and Density of Soils.

which were made by changing the gradation of one of the basic materials by the addition or omission of fines. Table 1 gives a brief description of each material, together with the number which is used for identification throughout the text. Materials 1 through 5 are the basic materials, and 6 through 9 comprise the supplementary materials. Subbases of soil-cement were made of materials 1 through 4. A subbase thickness of 6 in. was used in testing all materials, and in addition, tests on material 1 included thicknesses of 1,2,4 and 12 in. The gradations of materials are shown in Figures 1a and 1b. With the exception of material 2 which had a PI of 2, the soil fraction of all the subbase materials was non-plastic.

TABLE 1

SUBBASE MATERIALS

Material	Description
1	Concrete sand with 6% silty loam added
2	Dense-graded sand and gravel
3	Open-graded sand and gravel
4	Dense-graded crushed limestone
5	Open-graded crushed limestone
6	Concrete sand
7	Concrete sand with 12% silty loam added
8	Concrete sand retained on No. 20 sieve
9	Concrete sand passing No. 20 sieve

To assure uniformity, a sufficient quantity of each material was obtained to complete all testing involving that material.

The AASHO moisture-density relationship was used for the control of the placement density in all tests, although for some of the materials the moisture-density curve was not clearly defined. To supplement this method of density control, tests of minimum and maximum density were performed, and the density relationships are also given in terms of relative density. The moisture-density relationships and minimum and maximum densities for each material are shown in Table 2

Triaxial compression tests were performed on each material when compacted to 100 percent of AASHO density at optimum moisture. The values for the angle of internal friction and cohesion are shown in Table 3.

A coefficient of permeability for each subbase material was determined at various densities with a constant head permeameter. These data are shown in Figure 2 as a function of the relative density.

Subgrade

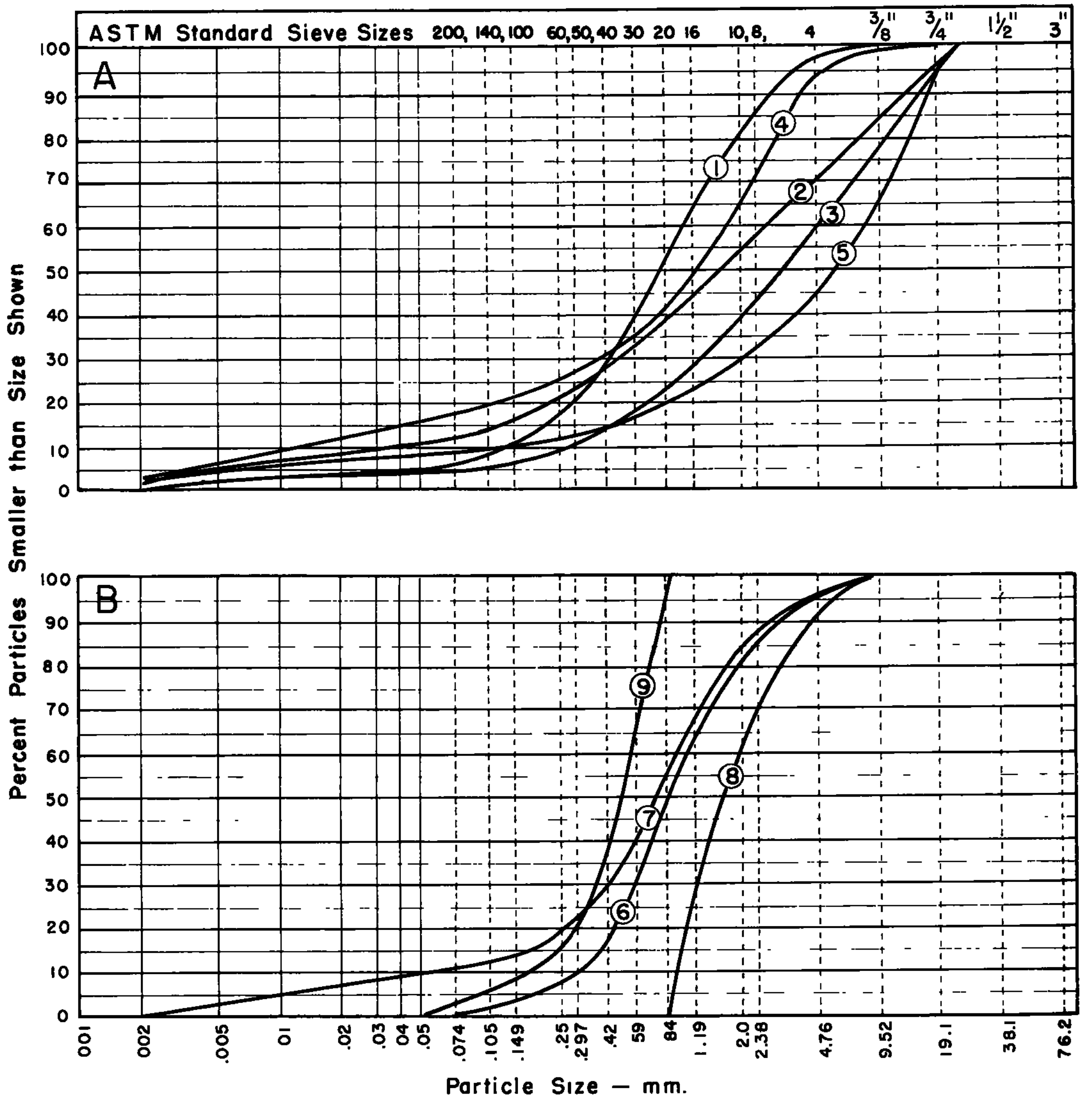
The subgrade material in all tests was a clay soil with the characteristics and gradation shown in Table 2.

TEST EQUIPMENT

The equipment (Figs. 3 through 6) consisted of a container which held the subgrade and subbase materials, a prestressed concrete slab which was loaded and transferred the load to the subbase, a repetitive load system, and instrumentation for measuring deflections, densification and pressures. Five of these test units were used in the investigation.

Soil Container

The soil container was a reinforced concrete box 4 ft wide by 6 ft long by 3 ft deep. The side walls of the box extended 4 in. higher than the end walls to retain a "shoulder surcharge." Unistruts were cast in the sides of the box to act as anchorage for a load



AASHO-ASTM SOIL SEPARATE CLASS

CLAY	SILT	SAND: FINE	SAND: COARSE	GRAVEL
- 0.005	0.005 — 0.074	0 074 - 0.42	0 42 - 2 0	2.0 — 76.2

Figure 1. Grain size accumulation curves.

frame used in performing plate bearing tests on the subgrade and on the subbase. Additional steel was cast in the concrete as anchorage for the repetitive load system.

To provide drainage of the subbase layer when desired, a 2-in. wide, 5-ft long, 7-in. high drain was installed along each side of the soil container at the level of the subbase. The drains, which were fabricated from steel, had a 7-in. open side facing the subbase. This side was covered with a No. 40-mesh sieve placed between two thin steel plates perforated with $^3/_{16}$-in. diameter holes spaced on $^5/_{16}$-in. centers. The drains were placed on a slight slope toward a controlled outlet at one end of the container. When a drain was closed, water could flow from the subbase and accumulate

TABLE 2

SUBBASE AND SUBGRADE CHARACTERISTICS

(a) Subbase

Material[a]	AASHO Moisture-Density Data: Optimum Moisture, %	AASHO Moisture-Density Data: Standard Dry Density, pcf	Relative Density Data: Minimum Density, pcf	Relative Density Data: Maximum Density, pcf
1	9.0	124	102	135
2	8.0	135	113	149
3	7.5	131	104	144
4	8.5	129	97	147
5	8.0	128	96	142
6	9.0	125	102	135
7	9.5	125	102	133
8	5.0	111	96	114
9	7.0	108	91	113

(b) Subgrade

		Particle Size	%
AASHO Optimum Moisture	20.4%	Sand (2.0-0.74mm)	20
AASHO std. Dry Density	105 pcf	Silt (.074-.005mm)	40
Liquid Limit	48	Clay (below .005)	40
Plasticity Index	24		

[a] All materials non-plastic, except No. 2 which has a PI of 2.

in the drain, when the drain was open, water could flow from the subbase into and out of the drain. Water could also be added to the subbase through the drain.

Concrete Slab

The concrete slab was 2 in. thick, 2 ft wide and 8 ft long; it was separated at mid-length by a ½-in. space to represent a joint in a pavement. The slab was pretensioned, and was cast in place on the subbase. Longitudinal tensioning consisted of 8 equally spaced ¼-in. diameter, 7 strand high strength cables located at the mid-depth of the slab and tensioned to 150,000 psi. The strands extended through the joint. This procedure produced a thin flexible slab capable of withstanding the repetitive loads without

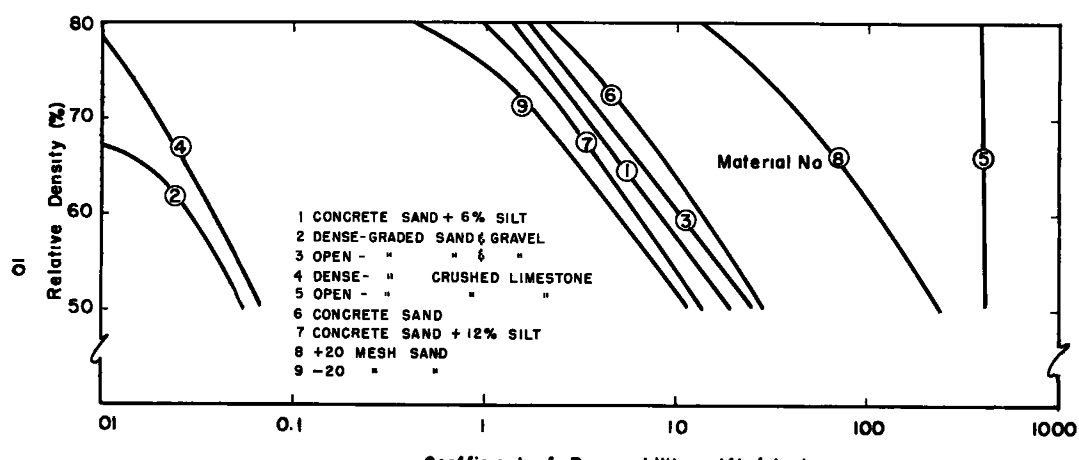


Figure 2. Variation of permeability with relative density.

Figure 3. View of soil container with clay subgrade, subbase drains, and soil pressure cell in place. A plate bearing test is being performed on the subgrade.

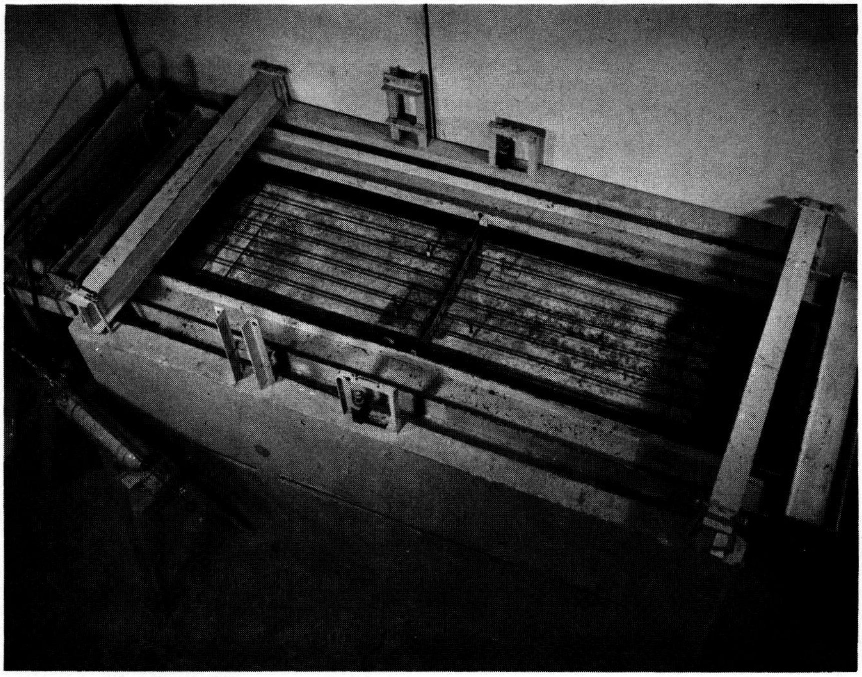


Figure 4. View after placement of subbase material showing prestress frame and wires prior to casting concrete slab. The center-joint dividing strip is in place.

failure. The subbase extended 1 ft on each side of the slab. This area was "shouldered" as described later.

Repetitive Load System

The mechanism for applying repetitive loads consisted of a steel I-beam with ballast weights (Fig. 6). The beam was hinged at one end and was alternately raised and dropped at the loaded end by a Westinghouse air brake. The reaction of the load beam was taken by a thrust rod located about one-fourth of the distance from the hinge to the ballast weights. The thrust rod transmitted the load to an 8-in. diameter steel plate resting on a rubber pad astride the joint in the concrete slab. The slab then transmitted the load to the subbase. The ballast weighed 975 lb, and produced a load of 4,000 lb on the plate which was of sufficient magnitude to transmit a pressure to the subgrade of about 7 psi. This pressure, according to other laboratory tests on full-scale pavements,

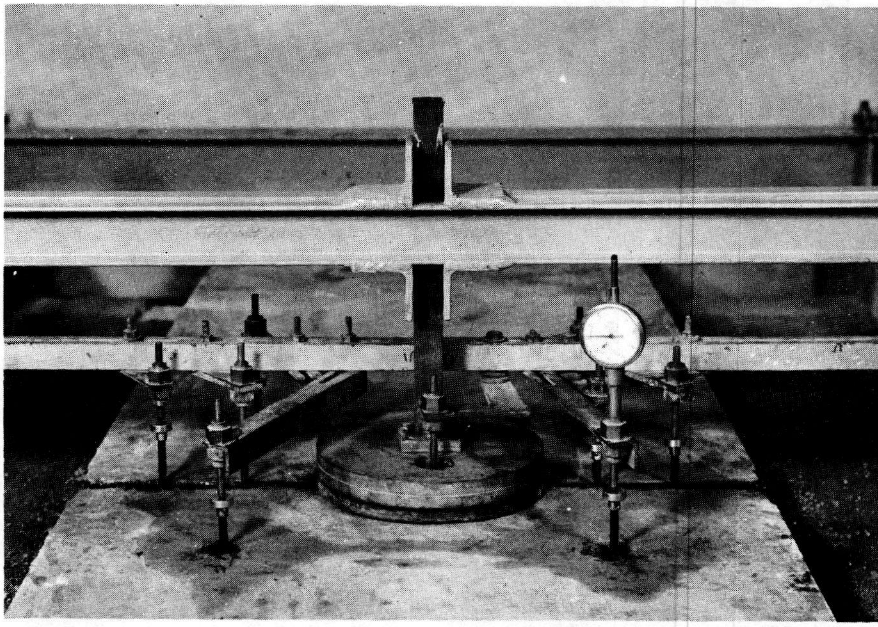


Figure 5. Load plate in position over the joint in the concrete slab. Reference rods and dial gage for obtaining deflection and densification data may be seen.

TABLE 3

TRIAXIAL TEST DATA

Material	Description	Angle of Internal Friction	Cohesion psi
1	Concrete sand plus 6% silt	34	1.0
2	Dense-graded sand and gravel	29	4.0
3	Open-graded sand and gravel	32	0.9
4	Dense-graded crushed limestone	41	5.2
5	Open-graded crushed limestone	42	0.0
6	Concrete sand	36	0.0
7	Concrete sand plus 12% silt	36	2.2
8	Concrete sand retained on No. 20	38	0.3
9	Concrete sand passing No. 20	38	2.2

is equal to or greater than the average pressure that may be expected on the subgrade under a concrete pavement in normal service. The load was applied at a rate of approximately 20 applications per minute. The number of repetitions was measured by a counter attached to the air brake, with the tripping arm fastened to the piston by a spring.

The rate and duration of the load was controlled by solenoid valves activated by an eletric timer. By instrumenting the thrust rod with SR-4 gages the trace shown in Figure 8 was obtained, which illustrates the characteristics of the load used in the test program.

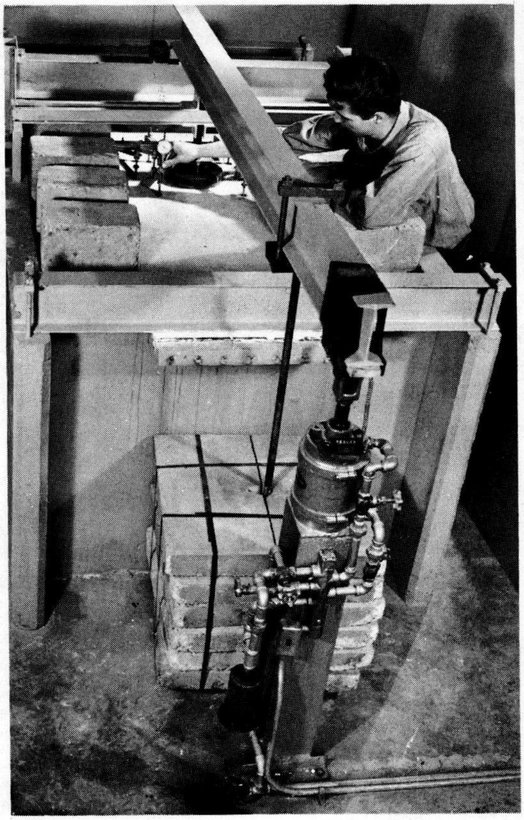


Figure 6. Assembled view of ballast weights, load mechanism and load beam with the shoulder surcharge blocks in position. A densification reading is being obtained on one of the reference rods.

Deflection, Densification and Pressure Devices

Deflection and densification data were obtained using ¼-in. steel reference rods attached to $^3/_{16}$-in. thick by 3-in. square steel plates. Four devices were installed with the base plates on top of the subgrade and four with the plates on top of the subbase. Two of each type were located at the joint, and two 6 in. away from the joint, (Figs. 5 and 7). Pipe sleeves were used around the rods to prevent them from adhering to the subbase or slab. Finally, one rod was attached to the top of the slab near the joint. The elevations of the top of the rods with respect to a fixed frame were determined with an Ames dial.

These reference rods permitted the following measurements:

1. Deflection of the slab during loading.
2. Decrease in thickness of the subbase layer (densification or consolidation).
3. Lowering of the elevation of the top of the subgrade because of densification (permanent deformation) or because of intrusion of the subgrade into the subbase. (Intrusion, if it occurred, could be observed at the completion of the test when a vertical excavation was made through the subbase into the top portion of the subgrade.)
4. Increasing deflection of the slab due to densification of the subbase and of the subgrade, and due to intrusion of the subgrade into the subbase.
5. Elastic deflection or deformation within the subbase and within the subgrade as distinguished from permanent deformation as measured in items 2 and 3.

To determine the pressure on the subgrade, a Carlson stress meter was installed in each box. The cell was located 6 in. from the joint and was bedded in mortar with the face of the cell level with the top of the subgrade. All cells were calibrated in place.

TEST PROCEDURE

The clay subgrade soil was prepared by crushing the dried material to pass a No. 4 sieve. Water required to bring the soil to optimum moisture content was added and the material was compacted to standard AASHO density in the test box to a depth of 30 in. The soil was compacted in 6-in. layers with a mechanical impact hammer. In-place density tests were made using the sand-cone method. After the density tests,

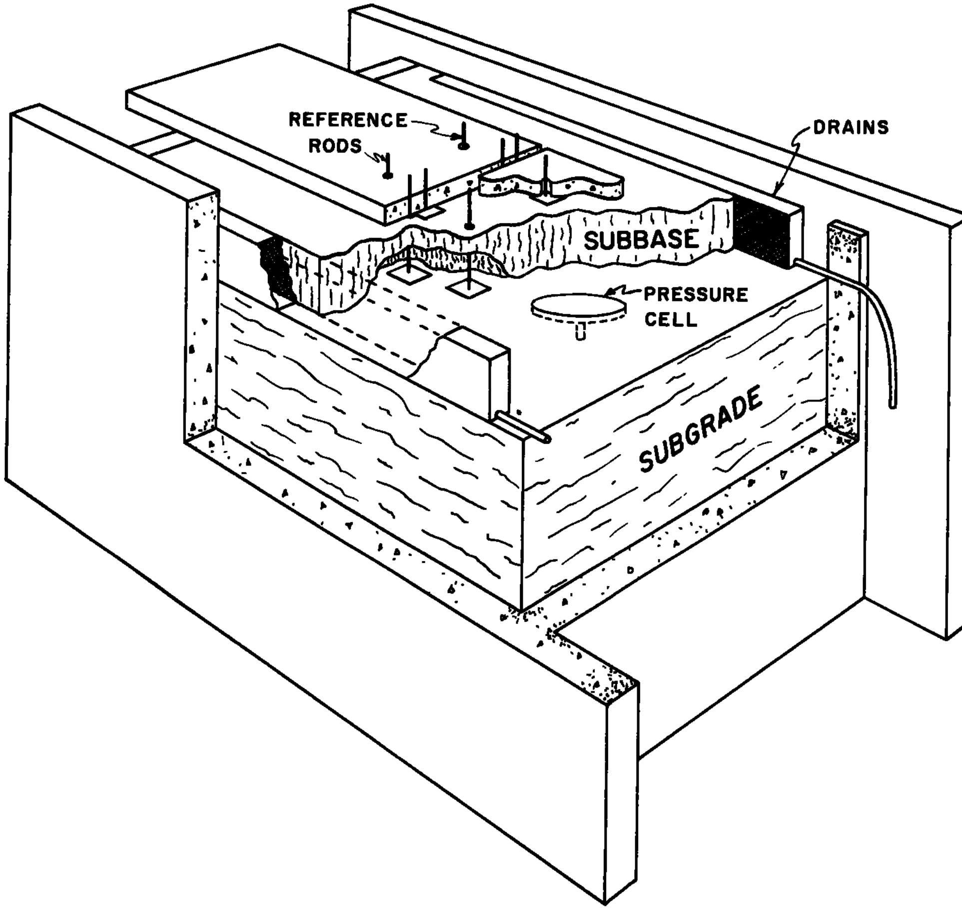
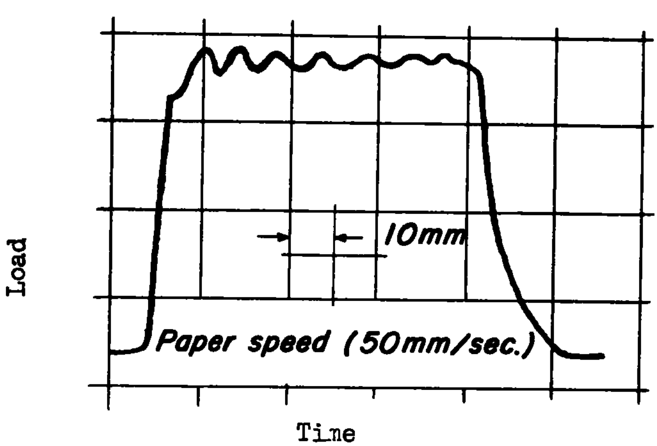


Figure 7. Location of reference rods, pressure cell, and side drains.



Operation	Time (sec.)
Load applied	*0.10*
Load on	*1.38*
Load released	*0.42*
At rest	*1.00*
One cycle	*2.90*

Figure 8. Load characteristics.

the subgrade was leveled, and the pressure cell was installed and calibrated. Plate bearing tests were then made using a 12-in. diameter plate. These tests were repeated at the completion of densification test to determine whether the subgrade "strength" had changed during the repetitive loadings (Table 5).

TABLE 4

PLAN OF SUBBASE PLACEMENT CONDITIONS

Standard AASHO Density, %	Moisture Content
80	AASHO Standard Optimum
90	AASHO Standard Optimum
100	AASHO Standard Optimum
100	2% below AASHO Standard Optimum
100	2% above AASHO Standard Optimum
110	AASHO Modified Optimum[a]
100 (soil-cement)	AASHO Standard Optimum

[a] Optimum moisture determined by AASHO Modified Moisture-Density Test.

The design water for subbase placement was mixed with the material in a concrete mixer, and the subbase was then placed at one of several different densities and moisture contents as outlined in Table 4. The material was compacted with a hand tamper to obtain designed densities in the lower range and with a pan vibrator to obtain densities in the higher range. To check compaction control, in-place density determinations were made using the sand-cone method on all materials except the open-graded crushed limestone (material 5) where a 70-30 mixture of plaster of paris and portland cement was used to obtain a cast of the hole. Next, a plate bearing test was made on the subbase with the plate centered over the pressure cell in the subgrade. This procedure provided data relating the influence of density and type of material to the magnitude of pressure transmitted to the subgrade. Reference rods to measure subgrade densification (permanent deformation) were installed on top of the subgrade in the holes made when determining the subbase density. The installation of the reference rods on top of the subbase completed the operation.

The prestress frame was then set in place, and spacer plates for forming the joint were installed. Cables were tensioned, and the slab was cast. After the slab had cured, the tension in the cables was released, and the prestress frame was removed. Then the loading aparatus was assembled, and initial dial readings obtained. A shoulder surcharge load of 0.7 psi was then placed on the subbase along each edge of the slab. This load was sufficient to retain the subbase material in place without upward shearing movement during the loading operations. The loading apparatus was then set in operation.

To determine the influence of placement density and moisture content on densification, each of the five basic subbase materials was tested under conditions conforming as nearly as practical to the plan shown in Table 4. Materials 6 through 9 and the four soil-cement subbases were tested only at 100 percent of standard dry density and at optimum moisture. The actual density and moisture content of the subbases as placed are shown in Table 5.

The repetitive load test was completed in four stages. During the last three stages water was added to the subbase to simulate extreme conditions of subbase moisture which might be attained in service.

Stage 1—Subbase at Placement Condition

During this stage 150,000 loads were applied to the subbase as placed to determine the amount and rate of densification of the various subbase materials at moisture conditions near the standard or modified optimum and at densities of approximately 80, 90, 100, and 110 percent of standard AASHO density. The drain outlets were open. Depending on the moisture content and permeability of the subbase, some moisture was discharged from the drains.

Stage 2—Subbase Being Wetted

In this stage 150,000 loads were applied to determine the densification characteristics of subbases as the moisture content was increased to saturation. Water was added to the subbase through the joint in the pavement twice daily in a quantity, calculated from the void ratio, sufficient to saturate the subbase during this test stage. The drain outlets were closed but limited drainage from the subbase into the drains could occur.

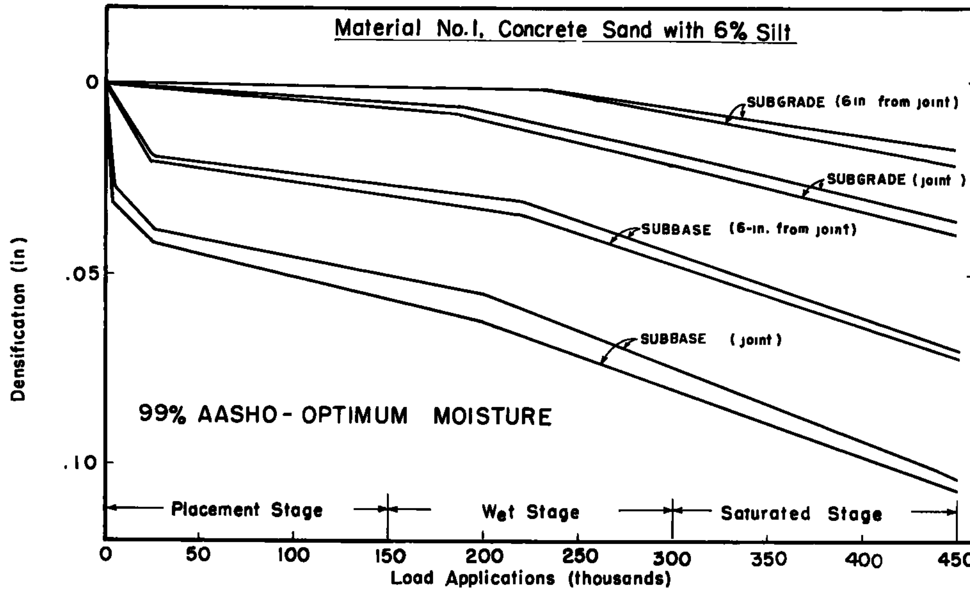


Figure 9. Representative densification data.

Stage 3—Subbase Saturated with No Pumping

In this stage 150,000 loads were applied to determine the densification of a saturated subbase. The drain outlets were kept closed and water was added though the drains to fill them approximately two-thirds full. If during the loading cycles, pumping of the subbase developed, the loading was temporarily stopped until the moisture had disseminated so that a continuation of loading did not result in pumping.

Stage 4—Subbase Saturated with Pumping Permitted

This final stage consisted of 50,000 load repetitions to distinguish between pumping and non-pumping subbases under severe moisture conditions. The drain outlets were kept closed, but the drains were completely filled with water and a visual record was obtained of any pumping which occurred during the loading cycles.

TEST RESULTS

Measurements were made of the permanent deformations associated with decrease in the thickness of the subbase layer and with the lowering of the elevation of the top of the subgrade accompanying an increase in density due to the repeated load applications. For convenience this decrease in thickness of the subbase and the permanent deformation of the subgrade are referred to as densification. This method of reporting was satisfactory in all tests but one in which intrusion of the subgrade into the subbase occurred and as a result, lowering of the elevation of the top of the subgrade was due to a combination of densification and intrusion.

Densification measurements were made periodically at eight locations in each test. The measurements were obtained from the reference rods located on the subbase and on the subgrade, either at the joint or 6 in. from the joint. A complete set of data for illustration is shown in Figure 9. These data are for material number 1 placed at 99 percent of standard AASHO density and at optimum moisture. Good agreement is noted in densification measurements on each pair of reference rods located on either the subbase or the subgrade. The measurements obtained 6 in. from the joint were of secondary significance. When considered for all the tests, they showed that as the subbase placement density was increased, the difference between the densification

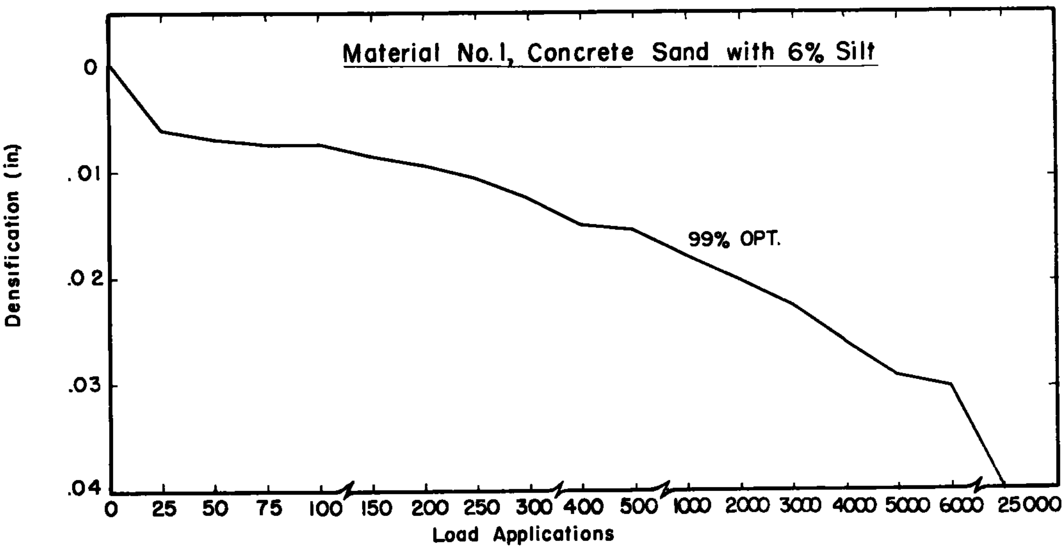


Figure 10. Subbase densification first 25,000 load applications.

at the joint and at 6 in. from the joint became smaller. On the average, the densification 6 in. from the joint varied from 50 to 95 percent of the densification at the joint as the placement density was increased from 80 to 110 percent of standard AASHO density. Only the average densification data measured at the joint are considered in the remainder of the figures.

Replicate tests conducted on each of the subbase materials placed at 100 percent of AASHO density and optimum moisture showed the the greatest discrepancy in the magnitude of densification for any replication was 14 percent.

PERFORMANCE OF GRANULAR SUBBASES

Data indicating the influence of the variables on the densification in the 6-in. subbase layer are shown in Figures 10 through 19. The lettering on each curve defines the placement density as a percent of the standard density, and the initial moisture content as optimum or on the dry or the wet side of optimum as outlined in Table 4. The placement density in pounds per cubic foot, moisture content in percent, and modulus of soil reaction in pounds per cubic inch are shown for each test in Table 5.

The influence of the variables on densification is discussed by considering the performance of the various subbase materials during the four stages of loading.

Placement Stage

During the first 150,000 load applications (placement stage) the drains were open and no water was added to the materials; however, water could flow from the materials into the drains. Densification during this stage varied from an almost negligible amount (0.025 in.) to more than 0.25 in. The variable which was most significant was the placement density, although moisture content and gradation were also significant.

About 60 percent of the densification occurred during the first few thousand applications of load. This rapid rate of densification is illustrated in Figure 10 by an expanded plot of the early portion of loading for the data of Figure 9. By comparing Figures 9 and 10 it may be seen that about 10 percent of the densification obtained after 150,000 load applications had occurred after only 25 load applications, and about 50 percent had occurred after 6,000 load applications.

Generally, about 80 percent of the densification that occurred during the placement stage was obtained after 25,000 load applications. This was observed with all of the materials and for all of the conditions of placement density and placement moisture. The magnitude of densification during this period varied from 0.022 in. to 0.18 in.

TABLE 5

SUMMARY OF PLACEMENT DATA

Initial Subbase Moist. and Density		Subbase Init. % Standard AASHO Den.	Subbase Relative Density Initial	Subbase k (12-in. plate)		Initial Subgrade Moist. and Density		Subgrade k (12-in plate)	
W.[a]	Den.[b]			Init.	Final	W.	Den.	Init.	Final
				Material 1					
8.6	103.0	83	46	175	490	20.5	106.0	310	255
8.6	116.4	94	51	320	420	21.8	110.0	350	340
8.3	122.4	99	68	365	485	22.9	103.0	340	285
12.0	123.8	100	72	290	418	20.2	110.0	355	365
6.5	122.7	99	68	340	500	20.5	106.5	394	410
7.3	133.6	108	97	504	510	18.9	109.8	305	305
8.3[c]	120.0	97	62	332	516	21.6	106.0	300	306
8.0[d]	123.2	100	72	271	455	19.0	108.0	260	297
				Material 2					
7.3	104.1	79	-	87	278	19.4	106.0	339	308
7.8	120.9	90	27	299	394	22.3	103.5	305	278
7.8	136.9	102	72	420	673	20.0	103.6	365	353
9.9	136.3	101	70	406	696	21.0	106.7	339	411
6.1	133.9	100	65	390	520	22.8	107.4	285	305
5.2	143.6	107	88	418	522	23.2	104.0	278	288
				Material 3					
7.2	105.1	80	34	18	-	19.2	102.6	291	309
7.4	117.7	90	40	217	430	21.5	109.4	388	364
7.0	132.7	101	78	290	338	21.4	102.7	408	500
9.6	133.7	102	80	370	408	20.3	106.5	400	455
5.7	128.7	98	69	404	503	20.6	103.1	296	308
6.0	143.0	109	98	508	700	22.2	108.3	364	388
				Material 4					
9.0	105.9	82	25	280	432	21.2	106.0	348	312
8.7	115.4	90	47	300	427	19.5	101.4	425	384
8.8	127.9	99	71	424	464	20.2	105.2	309	341
10.8	129.0	100	73	437	682	19.5	105.0	344	325
7.2	129.4	100	73	390	666	20.8	109.7	306	319
6.2	139.5	108	90	475	850	19.6	103.9	387	336
				Material 5					
8.2	104.0	81	24	232	357	19.5	104.9	279	245
8.6	113.2	88	47	383	529	20.0	107.9	328	304
8.3	128.2	100	78	386	650	21.0	101.0	393	414
11.0	129.7	101	80	312	465	22.1	100.2	381	377
6.1	130.4	102	81	464	394	23.6	105.0	307	312
7.8	140.1	109	97	531	610	22.0	102.9	305	280
				Material 6					
7.8	121.0	97	71	334	482	18.8	110.5	280	257
				Material 7					
9.1	126.5	101	83	420	510	18.0	113.0	305	279
				Material 8					
6.8	106.8	97	65	348	371	19.2	106.9	366	383
				Material 9					
6.8	109.5	101	85	383	460	19.6	112.3	274	279

[a] Moisture content, percent by dry weight of material
[b] Density, pounds per cubic foot, dry.
[c] 12-in. thickness
[d] 4-in. thickness.

To facilitate comparing the materials at the various placement conditions, densifications at the end of 25,000 load applications and at the completion of the placement stage (150,000 applications) are given in Table 6. The benefit of increased subbase placement density in reducing the magnitude of densification under repetitive loading may be observed in this table. For example, based on the average densification data for the basic subbase materials, an increase in placement density from 80 percent to 90 percent of standard reduced the densification by 63 percent; the increase from 90 to 100 percent resulted in a reduction of 41 percent; and, the increase from 100 to 110 percent resulted in a reduction of 20 percent.

If a densification of about 0.05 in. for this test condition is arbitrarily selected as a basis for designating superior performance, it is found that materials 1 through 5 and material 7 meet this criterion when compacted to 100 percent or more of AASHO standard density at optimum moisture. Densifications greater than 0.05 in. were shown by materials 6, 9 and 8, increasing in that order. However, after the rapid rate of densification during the first 25,000 load applications, each of the materials showed only slight additional densification (0.01 to 0.03 in.) during the remaining 125,000 load applications, and each could be considered as showing satisfactory performance at the completion of the first stage. This conforms to the concept that satisfactory subbase performance can be obtained with most properly compacted granular materials provided the moisture content can be maintained near the optimum.

The effect of drier placement (2 percent less than optimum) as determined for materials 1 through 5 at 100 percent density varied with the type of material, but in general the densification was about the same as when the subbase was placed at optimum.

TABLE 6

DENSIFICATION (INCHES) OF 6-IN. SUBBASES AT END OF 25,000 AND 150,000 APPLICATIONS

	Placement Conditions											
Approximate Density (% Standard)	80		90		100		100		100		110	
Moisture	opt.		opt.		opt.		opt. -2%		opt. +2%		mod. opt.	
Load Applications (thousands)	0 to 25	0 to 150	0 to 25	0 to 150	0 to 25	0 to 150	0 to 25	0 to 150	0 to 25	0 to 150	0 to 25	0 to 150
1 Concrete Sand, plus 6% silt	0.180	0.215	0.043	0.053	0.040	0.050	0.030	0.045	0.075	0.090	0.022	0.032
2 Dense Graded Sand and Gravel	0.257	0.280	0.073	0.085	0.033	0.050	0.045	0.045	0.048	0.060	0.027	0.043
3 Open Graded Sand and Gravel	0.140	0.147	0.067	0.067	0.025	0.032	0.030	0.040	0.060	0.070	0.020	0.027
4 Dense Graded Crushed Limestone	0.045[a]	0.060[a]	0.032	0.075	0.032	0.042	0.035	0.042	0.050	0.060	0.025	0.036
5 Open Graded Crushed Limestone	0.105	0.125	0.047	0.075	0.025	0.030	0.030	0.060	0.053	0.100	0.017	0.027
Average Densification (Basic Materials 1-5)	0.170	0.194	0.052	0.071	0.031	0.041	0.034	0.046	0.057	0.072	0.022	0.033
6 Concrete Sand	-	-	-	-	0.055	0.080	-	-	-	-	-	-
7 Concrete Sand plus 12% Silt	-	-	-	-	0.030	0.030	-	-	-	-	-	-
8 Concrete Sand, retained on No. 20 sieve	-	-	-	-	0.062	0.100	-	-	-	-	-	-
9 Concrete Sand passing No. 20 sieve	-	-	-	-	0.062	0.085	-	-	-	-	-	-

[a] Anomaly in data, not included in average.

An increase in placement moisture to 2 percent above optimum showed an adverse effect in all cases, and for this condition the densification of all materials exceeded the 0.05 in. criterion. The effect of the increased placement moisture was more pronounced for materials 1, 3 and 5, which were open-graded, than for the dense-graded materials 2 and 4. This appears reasonable, as water could drain from the open-graded materials, thus permitting additional densification under repetitive loading. The dense-graded materials could not drain as rapidly, and densification was thus delayed. This may explain why a placement moisture increase with the open-graded materials was in some cases more adverse than was a 10 percent reduction in placement density.

The above discussion pertains only to the placement stage of the testing, when no moisture was added to the subbase. For the majority of service conditions water would be available to the subbase, and the discussion of the test data in the later stages is considered more pertinent to the problem of subbase densification than the placement stage data.

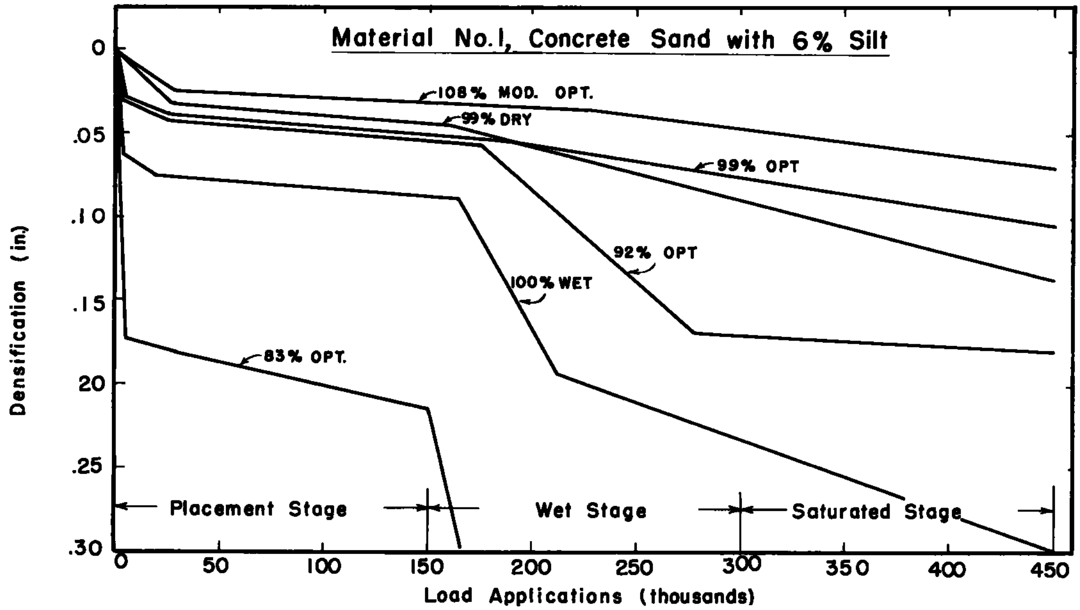


Figure 11. Influence of placement conditions on subbase densification.

Wet Stage

During the wet stage, 150,000 applications of load were applied to determine the densification characteristics of subbases as the moisture content was gradually increased to saturation. Water was added to the subbase twice daily in a quantity calculated to saturate the subbase by the end of the wet stage.

The magnitude of densification that occurred during the wet stage and the total densification at the completion of the wet stage are given in Table 7. This table does not include data for the subbases placed at 80 percent of standard density, as in several cases the densification became so large that the slabs broke and the tests were discontinued.

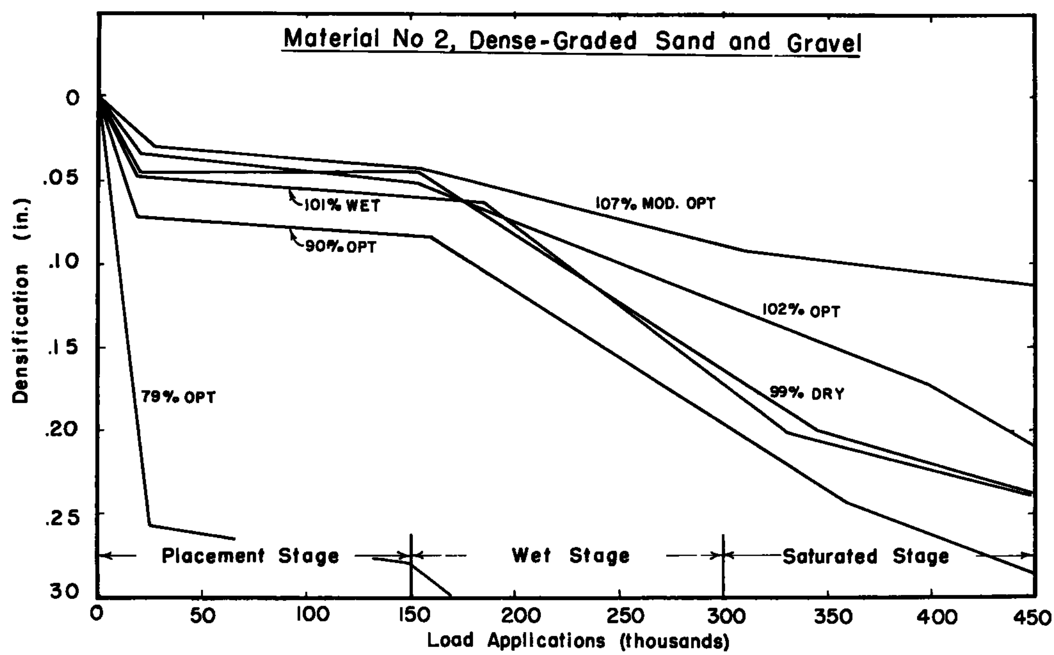


Figure 12. Influence of placement conditions on subbase densification.

The addition of water increased the rate and magnitude of densification for each material at all of the placement conditions. The increase in densification and the time required after the water was added for the detrimental effects to become apparent (as indicated by the first change in the rate of densification after 150,000 load applications) were functions of the test variables. As in the placement stage of loading, the most

TABLE 7

DENSIFICATION (INCHES) OF 6-IN. SUBBASES DURING WET STAGE AND AT END OF 300,000 APPLICATIONS

	Placement Conditions									
Approximate Density (% Standard)	90		100		100		100		110	
Moisture	opt.		opt.		opt. -2%		opt. +2%		mod. opt.	
Load Applications (thousands)	150 to 300	0 to 300	150 to 300	0 to 300	150 to 300	0 to 300	150 to 300	0 to 300	150 to 300	0 to 300
1 Concrete Sand plus 6% silt	0.119	0.172	0.025	0.075	0.045	0.090	0.145	0.235	0.010	0.042
2 Dense Graded Sand and Gravel	0.112	0.197	0.075	0.125	0.117	0.162	0.112	0.172	0.047	0.090
3 Open Graded Sand and Gravel	0.093	0.160	0.043	0.075	0.040	0.080	0.100	0.170	0.018	0.045
4 Dense Graded Crushed Limestone	0.092	0.167	0.010	0.052	0.029	0.071	0.045	0.105	0.011	0.047
5 Open Graded Crushed Limestone	0.034	0.109	0.030	0.060	0.020	0.080	0.025	0.125	0.013	0.040
Average Densification (Basic Materials 1-5)	0.090	0.161	0.037	0.077	0.050	0.097	0.085	0.161	0.021	0.056
6 Concrete Sand	-	-	0.015	0.095	-	-	-	-	-	-
7 Concrete Sand plus 12% silt	-	-	0.021	0.051	-	-	-	-	-	-
8 Concrete Sand retained on No. 20 sieve.	-	-	0.035	0.135	-	-	-	-	-	-
9 Concrete Sand passing No. 20 sieve	-	-	0.015	0.100	-	-	-	-	-	-

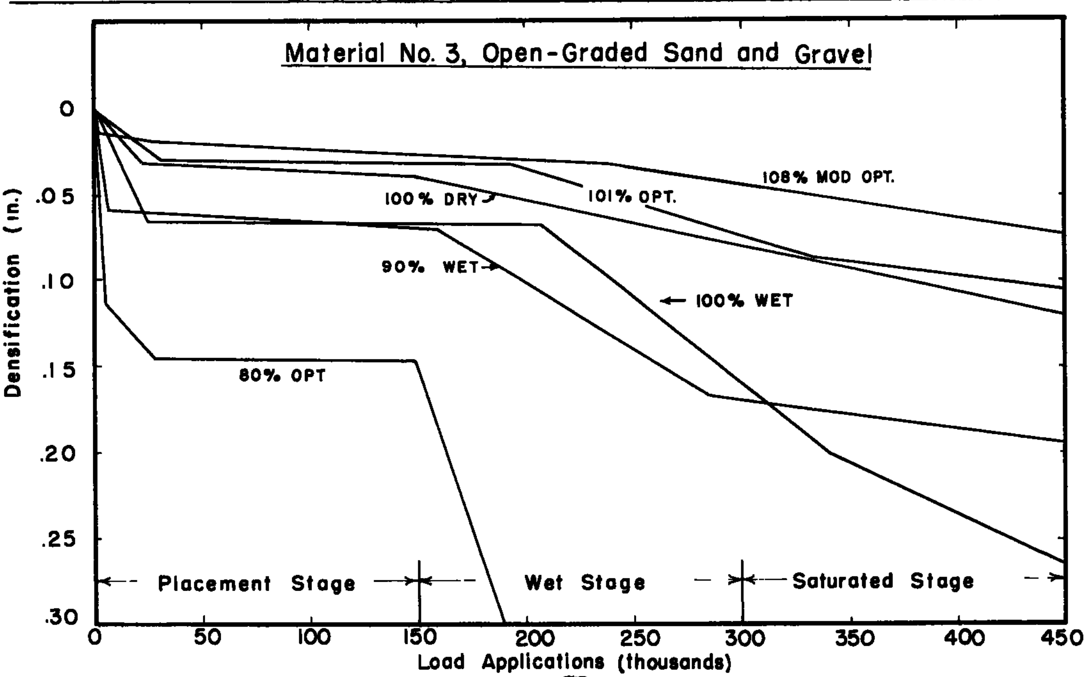


Figure 13. Influence of placement conditions on subbase densifiction.

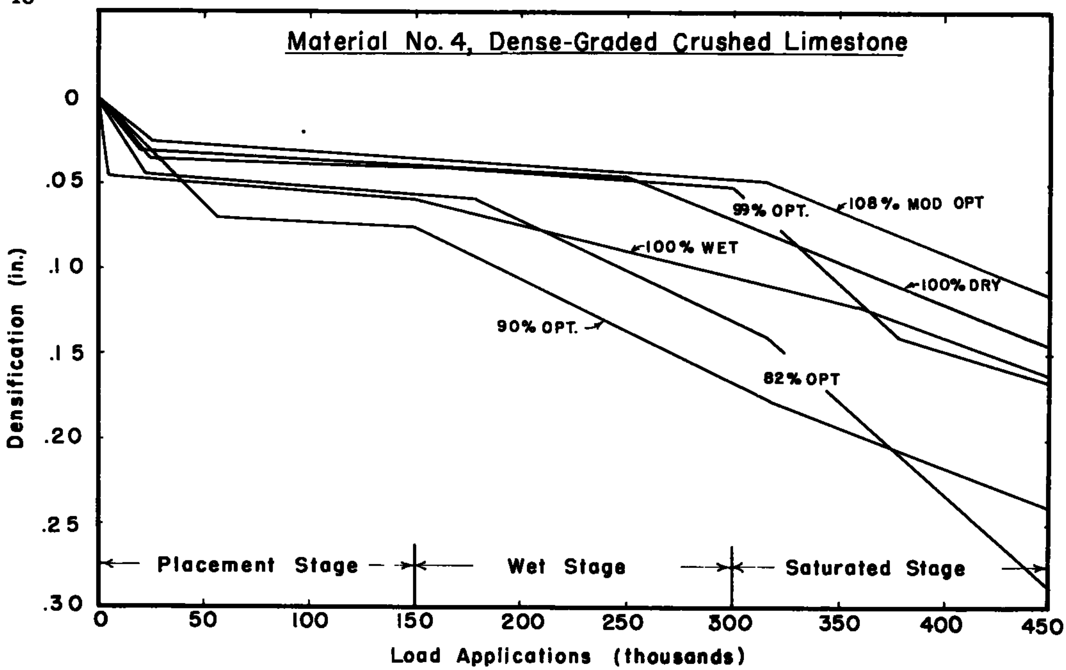


Figure 14. Influence of placement conditions on subbase densification.

significant variable in the wet stage was the placement density, although placement moisture and gradation of the subbase were also significant.

The data show that materials compacted at the higher placement densities were the least influenced and were the last to show the effects of the added water. For example, at a placement density of about 110 percent of standard, the average densification during the wet stage was 0.021 in., whereas at a placement density of 90 percent of standard the average densification was 0.090 in. Furthermore (as can be determined from Figs. 11 to 15) the average number of load repetitions at which the effects of the added water first became apparent was 240,000 for the materials placed at 110 percent density and 170,000 for the materials placed at 90 percent density.

In this stage the materials placed wet of optimum continued to show a greater densification than the materials placed at optimum or dry of optimum. Generally, the materials placed dry of optimum showed the adverse influence of the added water before the materials placed at optimum. Furthermore, the densification of the materials placed dry of optimum was greater than that of the materials at optimum.

Of the five basic subbase materials, dense-graded material 2 (Fig. 12) was the first to show the adverse influence of the added water (average 162,000 load applications) and showed a greater densification in this stage than any of the other materials. In contrast, dense-graded material 4 was not influenced by the addition of water in this stage. This material showed only slight densification and the rate of densification did not change between 25,000 and 300,000 load applications. A possible explanation for the difference in behavior between the two dense-graded materials may be found in the type of soil binder. The binder of material 2 was a plastic clay which could be influenced rapidly by the added water; whereas the binder of material 4 was a non-plastic limestone dust which would not be influenced so rapidly. The rate of densification of the open-graded materials during the wet stage was variable, but tended to increase when the materials were compacted at densities below standard and at moisture contents above optimum.

In considering the sandy soils of varied gradation, good performance (Fig. 16) was achieved during the wet stage with all materials except material 8.

In general, the increase in the rate of densification during the wet stage of loading was greater than that during the "placement stage" and provided a more distinct separation between the materials with respect to performance at the various placement

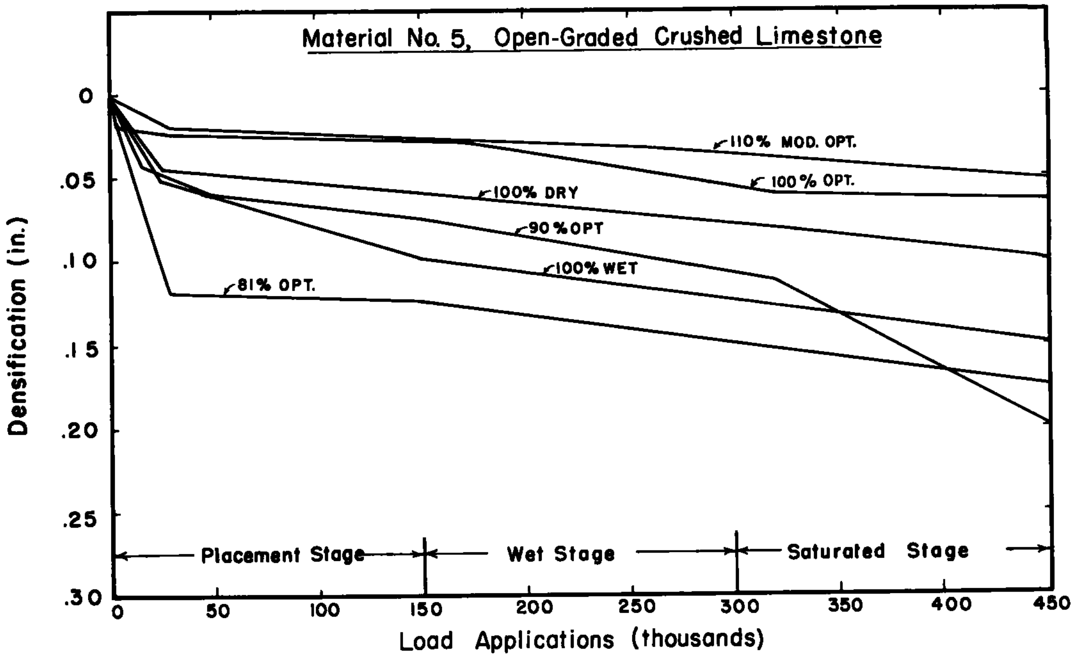


Figure 15. Influence of placement conditions on subbase densification.

conditions. In the saturation stage the separation is further amplified, and the influence of the type or gradation of the material is of greater significance at the completion of the saturation stage.

Saturation Stage

In this stage 150,000 loads were applied to determine the performance of the saturated subbases. Water was added to the drains to fill them approximately two-thirds full. This provided a water reservoir which maintained the subbase in a saturated

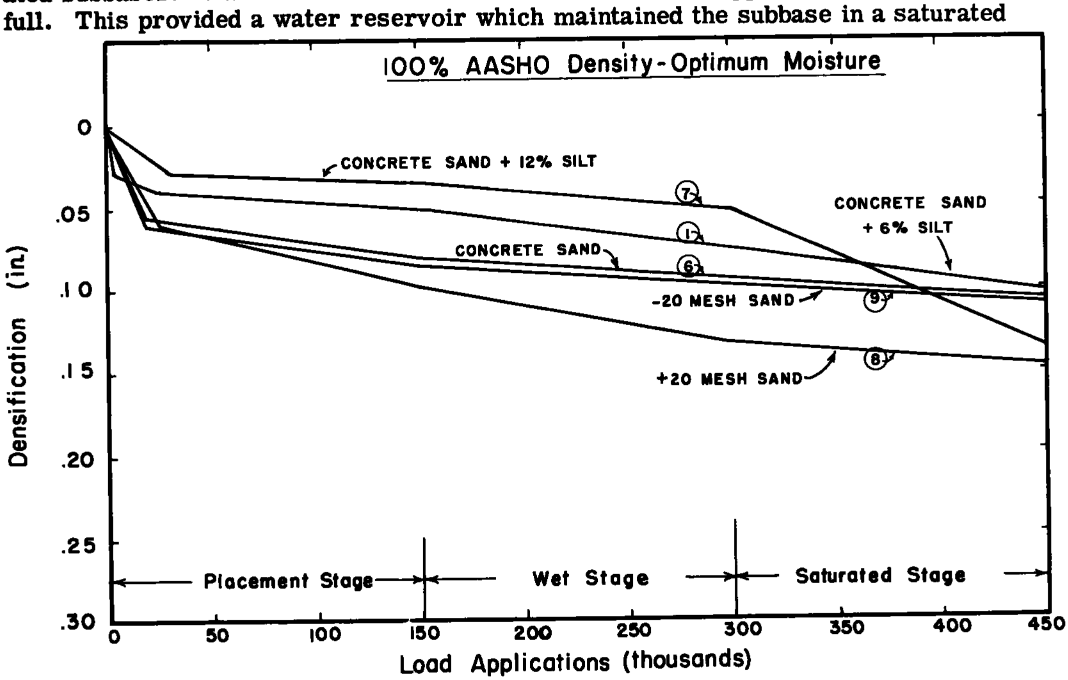


Figure 16. Influence of gradation on subbase densification.

TABLE 8

DENSIFICATION (INCHES) OF 6-IN. SUBBASES DURING SATURATED STAGE AND AT END OF 450,000 APPLICATIONS

	Placement Conditions									
Approximate Density (% Standard)	90		100		100		100		110	
Moisture	opt.		opt.		opt. -2%		opt. +2%		mod. opt.	
Load Applications (thousands)	300 to 450	0 to 450	300 to 450	0 to 450	300 to 450	0 to 450	300 to 450	0 to 450	300 to 450	0 to 450
1 Concrete Sand plus 6% silt	0.008	0.180	0.030	0.105	0.045	0.135	0.065	0.300	0.028	0.070
2 Dense Graded Sand and Gravel	0.078	0.275	0.085	0.210	0.075	0.237	0.068	0.240	0 023	0.113
3 Open Graded Sand and Gravel	0.105	0.265	0.031	0.106	0.040	0.120	0.025	0.195	0.028	0.073
4 Dense Graded Crushed Limestone	0.073	0.240	0.111	0.163	0.069	0.140	0.052	0.157	0.063	0.110
5 Open Graded Crushed Limestone	0.081	0.200	0.005	0.065	0.020	0.100	0.025	0.150	0.013	0.053
Average Densification (Basic Materials 1-5)	0.068	0.232	0.052	0.129	0.050	0.146	0.047	0.208	0 031	0.084
6 Concrete Sand	-	-	0.015	0.110	-	-	-	-	-	-
7 Concrete Sand plus 12% silt	-	-	0.084	0.135	-	-	-	-	-	-
8 Concrete Sand retained on No. 20 sieve	-	-	0.015	0.150	-	-	-	-	-	-
9 Concrete Sand passing No. 20 sieve	-	-	0.015	0.115	-	-	-	-	-	-

state. If pumping developed in this stage (this occurred to a limited degree only with materials 2 and 4), the loading was temporarily stopped until the moisture had disseminated so that a continuation of loading did not result in pumping. Densification during this stage varied from about 0.01 in. to more than 0.10 in. The placement density was still the most significant variable although the type of material was also of considerable significance.

The densifications that occurred during the saturation stage and the total densification at the completion of the saturation stage are given in Table 8. These data show that for this stage the increase in placement density from 90 to 100 percent of standard resulted in a 56 percent reduction in the magnitude of densification. This is about the same percentage of reduction in densification that occurred for similar density increases in the placement and wet stages of loading.

The influence of placement moisture on the magnitude of densification that occurred during the saturation stage was not as significant as it was during the placement and wet stages. This is not surprising as the effects of variation in placement moisture have been equalized by the stage of saturation.

The influence of the type or gradation of the material on the densification during the saturation stage was most apparent with materials 4 and 7. These materials, which had not shown the adverse influence of the added water during the wet stage, showed a rapid increase in the rate of densification during the saturation stage. In contrast, the other materials continued to show about the same rate of densification that had been observed in the wet stage. Slight pumping developed with dense-graded materials 2 and 4 late in the saturation stage, and it was necessary to suspend loading operations to allow time for the moisture to disseminate. However, no pumping was observed with any of the open-graded materials.

In Figure 17a the densification is shown for each of the basic subbase materials placed at approximately 100 percent of standard density and optimum moisture. A comparison of Figures 16 and 17a shows that at the end of 450,000 applications of load the smallest magnitude of subbase densification occurred with open-graded material 5, and the greatest densification occurred with dense-graded materials 2 and 4. In

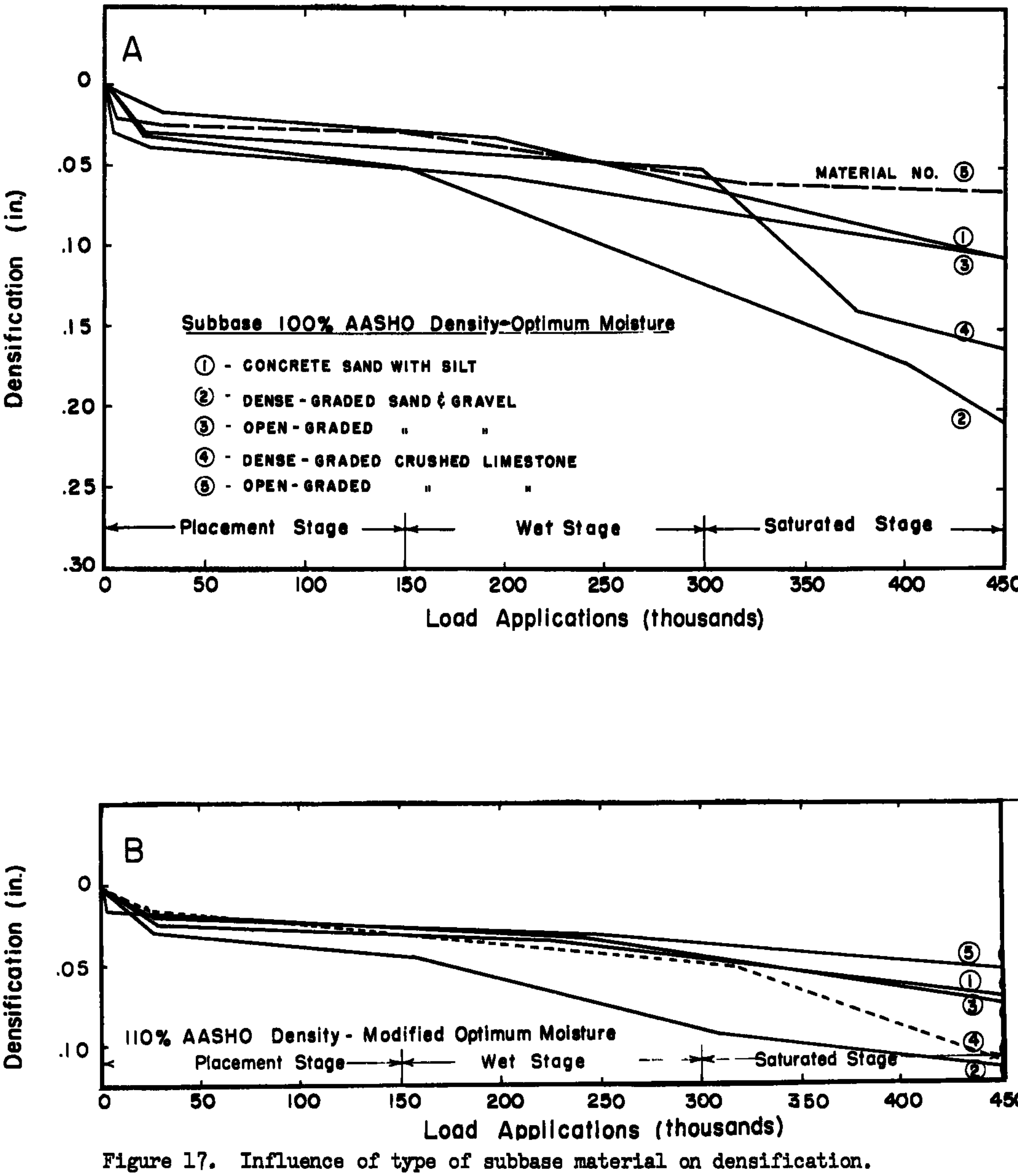
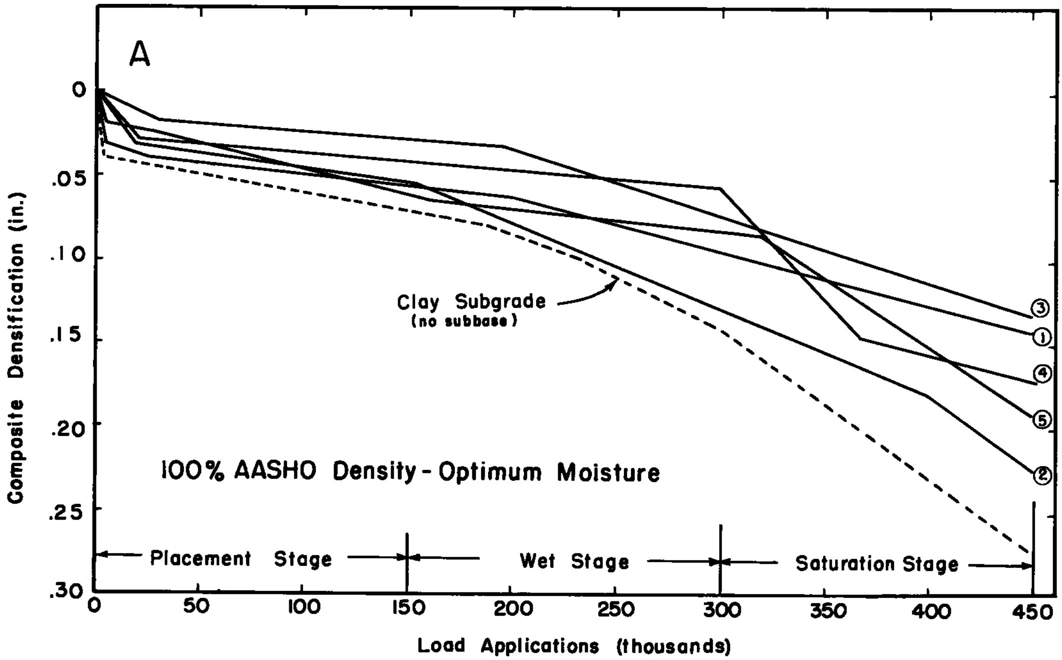


Figure 17. Influence of type of subbase material on densification.

general, the magnitude of densification of the subbase materials was related to the permeability and percentage of material passing the 200 sieve. As the permeability decreased and the percentage of minus 200 increased, the magnitude of subbase densification increased. However, as shown in Figure 17b an increase in the placement density of materials 2 and 4 from 100 to 110 percent of standard reduced the densification to about the same magnitude as that of the open-graded materials placed at 100 percent of standard.

Pumping Stage

During the pumping stage the drains were completely filled with water and 50,000 load applications were applied to the saturated subbase. No densification measurements were obtained and if pumping developed it was allowed to proceed without stopping the load operations.



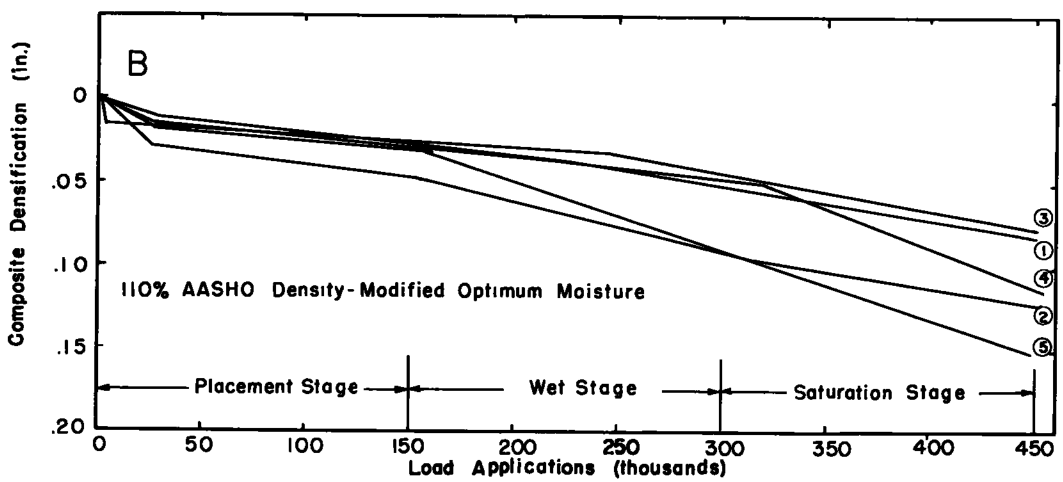


Figure 18. Influence of type of subbase material on composite densification.

No pumping was observed with the subbase materials numbers 1, 3, 5, 6, 8 and 9. In these materials the percentage of minus 200 ranged from 0 to 8 percent and the permeability ranged from 500 ft per day to 3 ft per day. This is significant in view of the pumping that occurred with materials 2 and 4, with the permeabilities of about 0.01 ft per day and 0.03 ft per day, and minus 200 contents of 12 and 17 percent, respectively. The pumping that occurred with material 4 was less severe than the pumping with material 2. Perhaps this was due to the non-plasticity of the soil binder in material 4. Slight indication of pumping of material 7 was observed, although this material had a permeability of about 5 ft per day; however, the minus 200 was 12 percent. The pumping of materials 2 and 4 under adverse conditions was objectionable and emphasized that for conditions of heavy saturation and frequent heavy loads, considerable care is necessary in selecting the type of subbase to prevent pumping and minimize densification. The data showed that no pumping occurred when the subbase material contained less than about 10 percent minus 200 and that densification was the least for well-graded materials having high permeability. However, the gradation must not be so coarse that intrusion of the subgrade may occur. This will be obvious in the discussion to follow on composite subbase-subgrade densification.

Composite Subbase-Subgrade Densification and Performance

Figure 18a shows the densification of the composite subbase-subgrade foundation for each of the basic subbase materials placed at approximately 100 percent of standard density and at optimum moisture, and also data indicating the "densification" of a clay subgrade when a slab was cast directly on the soil (no subbase). Pumping, beyond control, developed in this test soon after the addition of water in the "wet stage" and continued throughout the test. Thus, in this case most of the so-called densification actually consisted of loss of soil due to pumping. A comparison of the test data in Figure 18a with the data on subbase densification in Figure 17a shows that the subgrade densification or permanent deformation under subbase materials 4, 2, 1 and 3 ranged from 0.01 in. to about 0.04 in. This indicates that with these subbase materials which had permeabilities ranging from about 0.01 ft per day to 9 ft per day, there was little or no softening of the subgrade. This was further confirmed by the almost elastic behavior of the subgrade after the first several thousand load applications. However, with material 5, which had a permeability of 500 ft per day, the subgrade softened during the wet and saturation stages and there was severe intrusion of the subgrade into the subbase, This was readily apparent when the sample was removed after test. Principally as a result of this intrusion, the elevation of the top of the subgrade under subbase material 5 lowered 0.13 in. This resulted in a total settlement or measured "composite densification" of 0.2 in., which is greater than the composite densification of dense-graded material 4, but less than that of material 2. Further evidence of the adverse effect of the subgrade intrusion on the over-all performance of material 5 may be seen in Figure 18b for subbases compacted at 110 percent AASHO density.

One method of preventing intrusion of the subgrade and the eventual development of

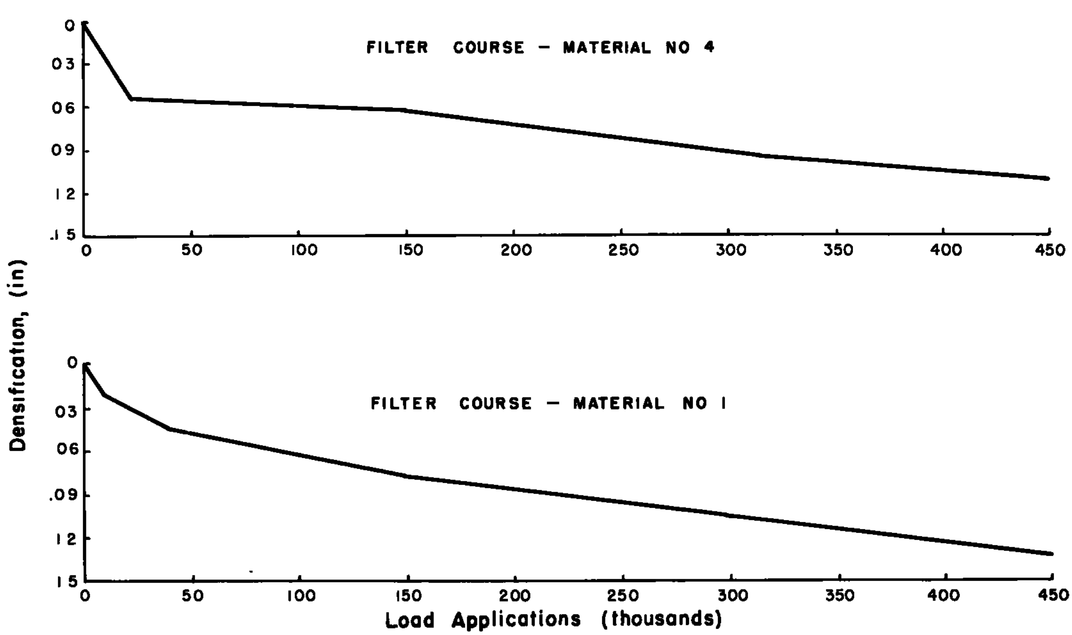


Figure 19. Composite densification of material No. 5 with filter course.

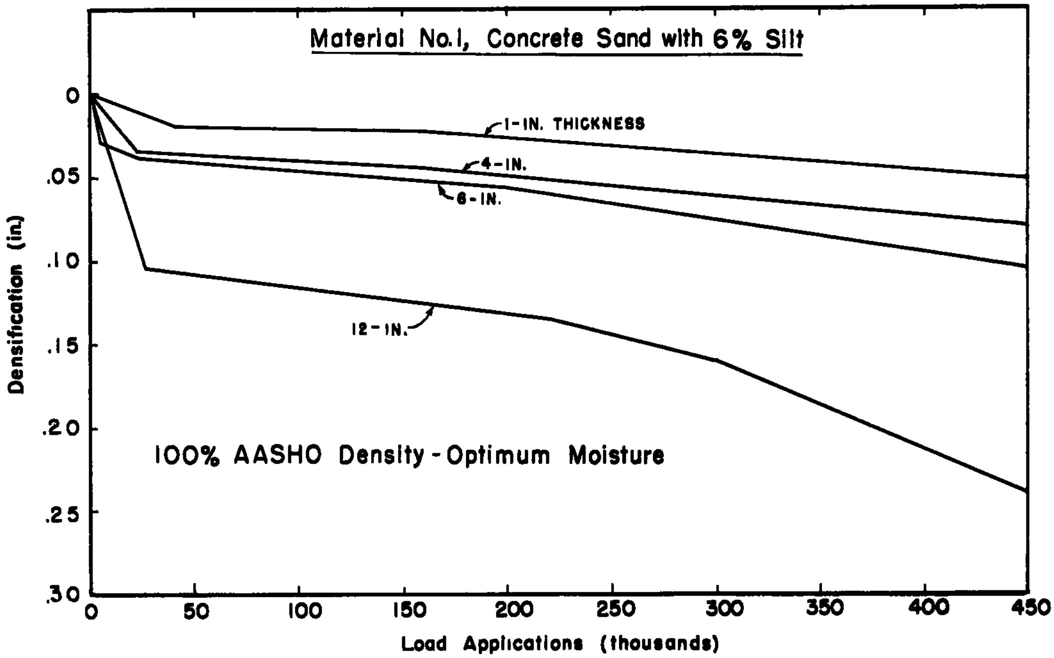


Figure 20. Influence of subbase thickness on densification.

subgrade pumping through the open-graded subbase is to place a filter course between the subgrade and the open-graded subbase. Several criteria have been proposed for the gradation of filter courses. The Corps of Engineers, U.S. Army (3) has established one criterion which states that satisfactory performance may be obtained if the particle sizes of the filter and protected material have the following relationship:

$$\frac{D_{15} \text{ filter material}}{D_{85} \text{ protected material}} \leq 5$$

where

D = particle size, such that

15 percent of filter particles are smaller than D_{15}

85 percent of soil particles are smaller than D_{85}

Materials 1 and 4 were selected for use as a filter course because they met the gradation requirements and furthermore represented both a pumping and non-pumping type of subbase. The use of a 1-in. layer of these materials under a 5-in. layer of material 5 completely prevented subgrade intrusion. This is shown in Figure 19 where composite densification is 0.13 in. or less. This compares favorably with the composite densification for any of the other subbase-subgrade combinations shown in Figure 18a.

Influence of Subbase Thickness on Densification and Pumping

The influence of the thickness of the subbase layer on the magnitude of subbase densification is shown in Figure 20. The data show that the magnitude of densification increased with an increase in the thickness of the subbase layer. With the exception of the 1-in. thickness, the magnitude of densification was approximately proportional to the thickness of the layer.

It is significant that even a 1-in. thickness of subbase material 1 prevented pumping. However, with only 1 in. of subbase the magnitude of subgrade densification or permanent deformation was about 0.12 in. The 4-in. subbase reduced the subgrade densification to about 0.04 in., and a 12-in. subbase reduced the amount to 0.03 in. The smallest magnitude of composite subbase-subgrade densification was obtained with the 4-in. subbase. Thus, with some subbase materials it would appear unwarranted and even undesirable to construct a subbase with a thickness greater than that required to minimize the composite subbase subgrade densification and to prevent pumping. It is apparent that to fulfill these objectives the subbase material should be graded as a filter course that would prevent infiltration of the subgrade into the subbase.

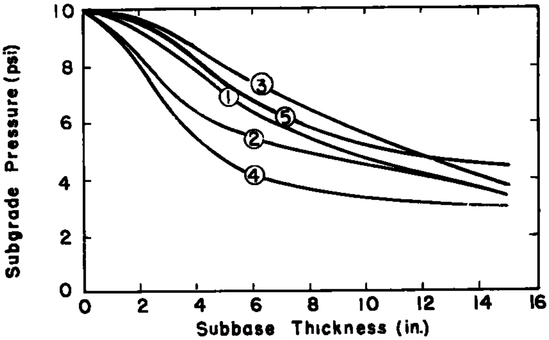


Figure 21. Pressure transmitted to subgrade through various types and thicknesses of subbase. (10 psi load on 12-in. dia. plate)

SOIL-CEMENT SUBBASES

Considerable use is not being made of granular soil-cement subbases to prevent pumping and to increase the bearing value of the pavement foundation. Cement was added to materials 1, 2, 3, and 4 to determine to what extent the cement would improve their general performance and reduce densification. The soil-cement subbases, 6 in. thick, were placed at AASHO standard density and optimum moisture. A summary of the test data after 450,000 load repetitions is shown in Table 9. In this table the term "composite densification" is again used to indicate a lowering of the elevation of the top of the subbase. The very small changes in the elevation of the soil-cement are attributed to permanent deformation in the subgrade, rather than to densification of the soil cement.

TABLE 9

DENSIFICATION OF SOIL-CEMENT SUBBASES

Type Material	Cement by Wt (%)	Composite Densification (in.) With Cement	Composite Densification (in.) Without Cement
1 Concrete sand + 6% silt	4.0	0.005	0.14
2 Dense-graded gravel	5.3	0.01	0.22
3 Open-graded sand and gravel	4.0	0.005	0.13
4 Dense-graded limestone	5.3	0.04	0.17

After 500,000 load applications for each soil-cement material the concrete slab was lifted from the subbase to destroy any bond that might exist between the two materials. In each case, there were areas where the cement subbase adhered to the slab. The unbonded slab was then replaced on the subbase, a continuous flow of water was fed onto the subbase, and the loading was continued. As many as 500,000 additional load applications (making a total of 1,000,000 repetitions) were applied without an appreciable increase in the magnitude of densification and without the occurrence of pumping. It was of particular significance that the addition of cement to materials 2 and 4 prevented the pumping exhibited by these materials in the subbase densification tests.

SUBGRADE SOIL PRESSURE

In addition to the 12-in. diameter plate bearing tests made on the subbases before and after repetitive loading (Table 5), supplementary plate tests were made on samples of the subbases compacted to thicknesses ranging from 2 in. to 15 in. These tests

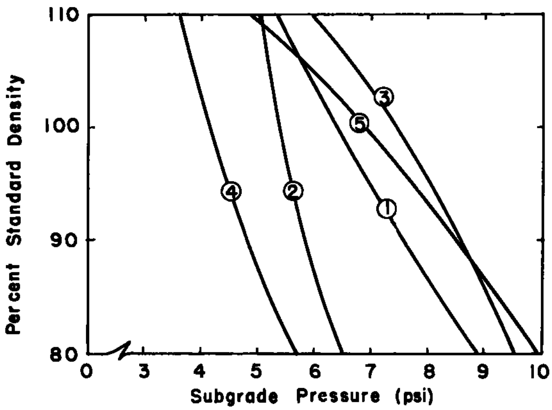


Figure 22. Influence of subbase density on pressure transmitted through various types of subbase materials. (6-in. subbase layer - 10 psi on 12-in. dia. plate.)

were conducted with the 12-in. plate centered over the subgrade pressure cell. This procedure permitted the development of data on the transmission of pressure through various subbase materials to the subgrade. The data shown in Figures 21 and 22 were obtained by applying 10 psi to the plate on the subbase, and reading the pressure indicated by the subgrade pressure cell. The data indicate that the magnitude of subgrade pressure is related to the cohesion of the subbase material (Fig. 22 and Table 3). Materials 2 and 4, with cohesive strengths of 4.0 to 5.2 psi, transmitted only about two-thirds of the pressure transmitted by materials 1, 3 and 5, with cohesive strengths of 1.0 psi or less.

Figure 22 shows that a decrease in the density of the subbase increased the pressure transmitted to the subgrade. This increase in subgrade pressure varied from about 23 to 50 percent. The larger increase occurred with material 1, 3 and 5 which had low cohesion. Materials 2 and 4, which had some cohesion, were able to maintain more integrity at lower densities and thus showed the smaller increases in subgrade pressure.

The subgrade pressures created by the repetitive loading of the slab exhibited the same trends of pressure transmission as determined from the plate loading tests. The magnitude of subgrade pressure varied from 5 to 10 psi for the 6-in. granular subbases, to about 0.5 psi for the granular soil-cement subbases of the same thickness, showing the improved load-distributing characteristics developed by the addition of cement.

SUMMARY

This program was conducted to investigate the influence of placement density and moisture content on the performance of various types of subbases under repetitive loading. The three factors which primarily determine the severity of the test conditions and thus the performance of the subbases are: the number and frequency of load applications, magnitude of load, and degree of subbase saturation. In these tests an adverse combination of these three factors was used to accelerate the program. The test conditions of frequent applications of a heavy load to a saturated subbase were more severe than existing or probable future field service conditions. It is well known that with less severe service conditions, satisfactory subbase performance is obtained with materials which contain more minus 200 fraction than the limiting 10 percent indicated by these tests. Therefore, the data and the conclusions do not necessarily justify changing subbase designs which have proved satisfactory under extremely severe conditions.

Subject to modification in accordance with the above comments, the following conclusions appear warranted.

Placement Conditions

A positive relationship was established between the subbase placement conditions and the magnitude of subbase densification under repeated loading which showed that an increase in placement density decreased the magnitude of densification. The average densification of the subbase materials compacted at 90, 100 and 110 percent of AASHO density was 0.232 in., 0.129 in., and 0.045 in., respectively. Thus, the densification was decreased about 80 percent by increasing the placement density from 90 to 110 percent of AASHO density. Furthermore, the larger portion of this decrease in densification occurred as a result of increasing the density from 90 to 100 percent. These data indicate the necessity of specifying a compaction requirement of at least 100 percent of AASHO density if densification under traffic is to be small. It is significant that the test densities of 100 and 110 percent of AASHO were obtained with a sled-type vibratory compactor.

The materials generally showed less densification and better performance when they were placed at optimum moisture than when they were placed at 2 percent on the dry side or at 2 percent on the wet side of optimum. Furthermore, the performance of the materials was better in all cases when they were placed on the dry side of optimum than when they were placed on the wet side of optimum.

Type and Gradation of Subbase Material

In general, the densification of the subbases was related to the permeability of the materials. The open-graded, high-permeability subbase materials showed less densification than the dense-graded, low-permeability subbase materials. However, in the case of material 5 (open-graded limestone), intrusion of the subgrade soil into the subbase affected its performance adversely, and considerable slab settlement (plotted as composite densification in Fig. 18) occurred. A 1-in. thick filter course of dense-graded limestone completely prevented the intrusion, and this combination showed the best performance of any of the materials.

The use of any of the subbase materials tested prevented pumping of the clay subgrade, although in time subgrade soil undoubtedly would have been pumped through the material 5 without a filter course. Even a 1-in. thickness of dense-graded limestone or of concrete sand with 6 percent silty soil prevented subgrade pumping. There was no pumping of the subbase, when the subbase material contained less than about 10 percent material passing a 200 mesh sieve. Subbase pumping occurred late in the saturation stage with two dense-graded, coarse granular subbases; one was a silty sand and gravel which contained 12 percent minus 200, and the other was a crushed limestone which contained 17 percent minus 200. Some indication of pumping was observed with a subbase of sand containing 12 percent minus 200. The performance of the three other predominantly sand subbases was very good.

The addition of cement to four granular subbase materials reduced the densification of these materials to an insignificant amount and eliminated pumping from two of them which had shown pumping without the added cement.

Pressures transmitted through the 6-in. thick subbases to the subgrade were from 5 to 10 psi for the granular materials and 0.5 psi for the soil-cement subbases.

Principal Findings

1. Compaction of granular subbases to at least 100 percent of AASHO standard density was found necessary to assure that only minor densification would occur under repeated loading.
2. Total densification increased as the thickness of subbase increased. Therefore, particular attention must be directed to compaction of thick subbases to preclude serious densification under traffic.
3. Open-graded, high-permeability subbases showed less densification than dense-graded, low-permeability subbases.
4. Subgrade intrusion into coarse-graded subbases was prevented by a 1-in. filter course of dense-graded material.
5. Under severe conditions of test, some dense-graded subbases pumped. Pumping did not occur when the subbases contained less than about 10 percent passing a 200-mesh sieve.
6. Granular soil-cement subbases did not pump; they showed little or no densification, and, as compared to granular subbases, they reduced greatly the pressure transmitted to the subgrade.

ACKNOWLEDGMENTS

The initial planning of this project was undertaken by L. D. Childs. Recognition is also given to Ray Boldt and R. D. Ward for their careful attention to conducting the tests. The entire program was under the direction of E. F. Felt, Manager, Transportation Development Section, and Douglas McHenry, Director of Development.

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Appendix

DETERMINATION OF MAXIMUM AND MINIMUM DENSITY

Maximum density was determined by a vibration method. A 5-lb saturated sample was placed in a 1/10-cu ft cylindrical container. The bottom of the container, which was perforated, was covered by a 40-mesh screen and a filter cloth which permitted drainage of the specimen without loss of soil fines. A surcharge weight of 3 psi was placed on the specimen and the container was bolted to a wooden platform. The assembly was vibrated 30 minutes at a frequency of 60 cycles per second and an amplitude of about 0.1 in. The final volume and moisture content were determined, and the unit weight was computed.

Minimum density was determined by a gravity method. A funnel was filled with 12 lb of air-dry soil and discharge into a 1/10-cu ft cylindrical container until it overflowed. The funnel, having a 2-in. by 2-in. tube initially resting on the bottom of the container, was raised spirally permitting the soil to fall in place approximately 1 in. below the point of discharge. Excess material was removed by screeding without jarring the container or compressing its contents. Unit weight was computed from the amount of soil contained in the mold.