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ROUNDED CUT SLOPES ON A CONNECTICUT HIGHWAY

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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A STUDY OF SAND-CLAY-GRAVEL MATERIALS FOR BASE-COURSE CONSTRUCTION

BY THE DIVISION OF TESTS, BUREAU OF PUBLIC ROADS

Reported by **C. A. CARPENTER**, Associate Civil Engineer, and **E. A. WILLIS**, Associate Highway Engineer

THE RESULTS of an investigation of sand-clay materials for base-course construction were reported in the November 1938 issue of PUBLIC ROADS. A similar investigation of sand-clay-gravel materials for base courses has recently been concluded and the results of these tests are presented in this report.

Insofar as possible, the same general procedure was followed in making this study as was used in investigating the sand-clay materials. Two series, or a total of 11 mixtures, were prepared using water-worn Potomac River gravel, Potomac River sand, pulverized silica, and a red-clay soil from the same local source as that previously used.

The purpose of the study was to determine the effect of variations in plasticity index and aggregate grading on the stability and general serviceability of sand-clay-gravel materials when used as base courses for bituminous wearing surfaces. Such characteristics of the base-course mixtures as were known to have a direct bearing on their stability were investigated in conjunction with traffic tests in the circular track. These factors included compactibility, resistance to infiltration of water, and resistance to softening and loss of stability when exposed to the action of capillary water in conjunction with traffic.

To enable determination of the effect of variations in plasticity index, the five mixtures of series 1 were so designed that the fractions passing the No. 10 sieve were essentially the same as the five sand-clay materials used in series 1 of the previous tests. The plasticity indexes of the fractions passing the No. 40 sieve ranged from 0 to 16. The material retained on the No. 10 sieve was intended to have the same grading for all five mixtures, but mechanical analyses of samples from the track sections showed that there were minor variations in grading from section to section.

In order to determine the effect of variations in grading, the six mixtures of series 2 were designed to have a wide range of gradings and, with the exception of section 1, plasticity indexes of approximately 8. Section 1 was designed to have a plasticity index of 0.

The gradings and soil constants of the 11 materials used in the sand-clay-gravel studies are shown in table 1.

As in the studies of sand-clay mixtures, the indoor circular track was used to evaluate the serviceability of the various mixtures when used as base courses for a bituminous surface treatment and subjected to traffic under severe moisture conditions.

MIXTURES TESTED IN CIRCULAR TRACK

For the traffic tests on the materials of series 1, the track was divided into five, 7.5-foot sections, one for each of the five test mixtures, so that the traffic test could be made simultaneously on all five. The materials of series 2 were also tested as a group comprising six, 6.3-foot test sections. All the test sections were approximately 6 inches in depth when compacted and were laid over a porous, crushed-stone sub-base through which water introduced from below could pass. They were covered, after compaction, with a thin bituminous surface treatment, the purpose of which was to afford protection from the abrasive action of the test traffic and thus confine the test to a determination of the single factor of stability, or resistance to internal movement under traffic with the water table at various elevations in the base course.

The materials for each section of series 1 were prepared for laying by first thoroughly mixing the constituent aggregate fractions together dry and then adding sufficient water to bring the moisture content of the mortar portion, or material passing the No. 10 sieve, to its optimum moisture content as previously determined by Proctor tests on the sand-clay fractions. Because of this use of the fine fractions only as a basis for determining the moisture contents for consolidation, the mixtures proved to be somewhat deficient in moisture for maximum compaction in the track.

In order that there should be no such deficiency of moisture in series 2, it was necessary to devise a method

TABLE 1.—*Gradings and soil constants of sand-clay-gravel base-course materials*

	Series 1					Series 2					
	Section 1	Section 2	Section 3	Section 4	Section 5	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
Grading:	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Passing 1-inch sieve	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing ¾-inch sieve	93.4	93.2	89.2	93.8	90.3	88.1	98.5	79.4	97.5	87.1	93.9
Passing ⅜-inch sieve	81.3	76.7	74.0	82.8	73.2	70.6	89.3	58.9	90.2	70.7	83.3
Passing No. 4 sieve	68.2	62.5	61.6	67.3	60.8	58.5	83.9	41.9	82.5	56.4	75.6
Passing No. 10 sieve	53.5	47.9	47.9	50.3	47.0	42.3	65.0	31.9	41.9	38.0	66.1
Passing No. 20 sieve	44.2	40.3	40.3	43.9	39.5	35.5	58.4	27.3	37.0	32.5	57.2
Passing No. 40 sieve	34.0	31.0	31.0	34.4	30.3	25.9	48.5	19.8	30.5	24.0	41.4
Passing No. 100 sieve	20.7	18.1	18.9	19.9	18.8	2.6	26.0	14.4	22.9	16.9	28.5
Passing No. 200 sieve	16.9	15.1	16.0	16.7	16.1	1.2	24.6	12.4	22.1	16.2	27.5
Passing 0.005 mm	5.1	6.4	7.8	8.7	10.5	0	10.9	4.9	8.0	5.8	10.3
Passing 0.001 mm	2.0	3.0	5.0	6.0	9.0	0	7.0	3.0	5.0	4.0	7.0
Dust ratio [1]	50	49	52	49	53	5	51	63	72	67	66
Tests on material passing No. 40 sieve:											
Liquid limit	15	20	24	26	31	15	24	24	23	22	23
Plasticity index	0	5	9	11	16	0	9	8	7	6	7

[1] Dust ratio $=100\left[\frac{\text{percentage passing No. 200 sieve}}{\text{percentage passing No. 40 sieve}}\right]$.

that would take into account the coarse aggregate fraction. Since it was considered impractical to make the Proctor tests on materials containing 1-inch maximum-size stone, the moisture contents for the sections in series 2 were determined by vibratory compaction tests made on the dry aggregates, the volume of water used being that computed to be just sufficient to fill the voids in the vibrator-compacted aggregate. These moisture contents proved to be essentially correct for constructing the test sections since they did not render the material too wet to handle and yet were high enough to allow some drying during compaction operations without lowering the moisture content below the optimum.

The designed moisture contents and the actual moisture contents of samples from the uncompacted test sections immediately after laying are given in table 2. The required amounts of water were added to the aggregate mixtures on the basis of their air-dried weight whereas the actual moisture contents after laying were determined by oven drying. This accounts for the apparent increases shown for the more plastic sections of series 1 and the sections of series 2 having the higher soil-mortar contents.

TABLE 2.—*Designed moisture contents and actual moisture contents of track sections*

	Moisture content [1]		
	Designed by Proctor test	Designed to fill voids	Immediately after laying
SERIES 1	*Percent*	*Percent*	*Percent*
Section 1	4.5		4.3
2	4.8		4.4
3	4.9		4.9
4	5.4		5.5
5	5.5		6.5
SERIES 2			
Section 1		10.0	10.7
2		7.4	8.4
3		5.9	6.2
4		6.6	6.9
5		6.0	5.6
6		6.5	7.2

[1] Based on dry weight.

The procedure for preparing the materials and constructing the test sections was as follows:

1. The moistened sand-clay-gravel materials were thoroughly mixed to distribute the water uniformly and were then placed in the track in two approximately equal layers, each layer being compacted with pneumatic-tired traffic uniformly distributed over the surface.
2. Compaction was continued on the top layer until no perceptible subsidence could be produced in any section by additional wheel-trips. This required 30,000 wheel-trips for series 1[1] and 42,000 wheel-trips for series 2.
3. The sections were sprinkled with water to soften the surface slightly and were trimmed smooth with a blade.
4. After drying for a few days the surface was primed with light tar.
5. As soon as the prime had been absorbed and had cured sufficiently to be fairly dry, a ¾-inch surface treatment consisting of 0.4 gallon per square yard of hot-application bituminous material and 50 pounds of cover stone was constructed.
6. The surface treatment was consolidated by applying distributed traffic.

ADDITIONAL COMPACTION NECESSARY FOR THREE SECTIONS OF SERIES 1

Consolidation of the base and surface treatment appeared to be completed in series 1 after a total of 50,000 wheel-trips, and water was then admitted to the subbase and maintained at a height of ½ inch above the bottom of the base course being tested. After only 300 wheel-trips of distributed test traffic, sections 2, 3, and 4 began to move and displace so badly that traffic had to be discontinued. The loss of stability resulting from the introduction of water was accompanied by marked subsidence over the entire area of these three sections. Section 1, which was nonplastic, also showed marked subsidence although it remained highly stable. Tests showed that with the exception of section 5, which had a decrease in moisture of 1.5 percent, the materials had absorbed from 3 to 3.6 percent of moisture in addition to that contained at the time they were laid (see table 3). This absorption of moisture, together with the subsidence of the surface, definitely indicated that the moisture contents used for construction in sections 1, 2, 3, and 4 were too low to permit maximum compaction.

In an attempt to complete the compaction without reworking the materials in the weak sections, 7,700 wheel-trips of additional distributed traffic were applied. This additional traffic resulted in the complete failure of the surface treatments on sections 2, 3, and 4.

TABLE 3.—*Moisture contents of the track sections at various stages of the investigation*

Series 1	Moisture content expressed as a percentage of the dry weight of the aggregate				
	When laid	At 50,300 wheel-trips	At 58,000 wheel-trips	At 75,000 wheel-trips	At 425,000 wheel-trips
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Section 1	4.3	7.3			5.3
2	4.4	8.0	6.7	4.6	4.9
3	4.9	8.4	6.8	4.7	5.1
4	5.5	8.9	7.0	5.9	5.5
5	6.5	5.0			6.6

Series 2	Moisture content expressed as a percentage of the dry weight of the aggregate		
	When laid	At 145,000 wheel-trips	At 330,000 wheel-trips
	Percent	*Percent*	*Percent*
Section 1	10.7	6.2	6.9
2	8.4	6.6	6.9
3	6.2	3.9	4.0
4	6.9	4.9	4.9
5	5.6	4.5	4.1
6	7.2	5.8	6.2

Samples for moisture content and density determinations were taken and the surface treatment was removed to facilitate drying in conjunction with subsequent compacting operations. At this time the moisture contents of these three sections were approximately 2 percent higher than when they were originally constructed (see table 3). The condition of sections 2, 3, and 4 just prior to removal of the surface treatment is well illustrated by the photograph of section 3 shown in figure 1.

After removal of the surface treatment from sections 2, 3, and 4, 17,000 wheel-trips of additional compacting

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[1] Introduction of water and application of a small amount of test traffic on the sections of series 1 later proved that thorough compaction had not been obtained.

traffic were applied in small daily increments, bringing the total to 75,000 wheel-trips. During this time the moisture contents of the three sections decreased to approximately those at which the sections were originally laid. A new surface treatment was then constructed and compacted with 25,000 wheel-trips of distributed traffic, bringing the total to 100,000 wheel-trips.

The behavior of the five sections under the regular traffic test from 100,000 to 425,000 wheel-trips will be discussed fully later. At this point the behavior of sections 2, 3, and 4 after recompaction, will be discussed in comparison with their above described earlier behavior when not fully compacted.

During the traffic test the water level was gradually raised until a height of 4½ inches above the top of the sub-base was reached at 370,000 wheel-trips and this water elevation was maintained to a total of 425,000 wheel-trips. Under these extreme conditions sections 2 and 3, because of their increased density, absorbed only 0.3 and 0.4 percent more moisture than they had contained at 75,000 wheel-trips and section 4 actually showed a loss of 0.4 percent moisture. All three sections were quite stable throughout the test in marked contrast to their behavior from 50,000 to 50,300 wheel-trips when each absorbed approximately 3½ percent of water and became highly unstable because of insufficient compaction.

No difficulties such as those encountered in connection with series 1 were encountered during the compaction of the materials of series 2 because, as previously stated, the original moisture contents were high enough to allow for appreciable drying during compaction. Thus compaction was able to proceed to the maximum density obtainable under traffic before the moisture content passed below the optimum.

ONLY ONE SECTION OF SERIES 1 FAILED DURING TRAFFIC TEST

Table 4 shows the procedure followed in testing the track sections in series 1 with notations on the behavior of each section during the test. Table 5 gives similar information for series 2.

Series 1.—After all construction and compaction operations had been completed at 100,000 wheel-trips, water was introduced into the sub-base and set at an elevation of ½ inch above the bottom of the test base course. Distributed traffic was applied to a total of 183,000 wheel-trips and then, without changing the water elevation, concentrated traffic was applied to 256,000 wheel-trips, making a net total of 156,000 wheel-trips of test traffic. Section 5 became unstable and was rated as having failed at 150,000 wheel-trips (50,000 wheel-trips of test traffic). Figure 2, left, shows the appearance of section 5 at 150,000 wheel-trips when its failure was recorded. On the right is shown the same section at 233,000 wheel-trips when measurements of its surface displacement were discontinued. The other four sections in the series, although showing some movement under traffic and slight cracking in section 4, were in good condition at 256,000 wheel-trips which marked the conclusion of that phase of the test in which the water was held at the ½-inch level.

As shown in table 4, the test with concentrated traffic was then continued with the moisture conditions being made progressively less favorable until the water level had reached an elevation of 4½ inches and a total of 425,000 wheel-trips had been applied. Sections 1, 2, and 3 remained in good condition. Section 4, although exhibiting a high degree of resistance to softening, considering the severity of the test, developed sufficient rutting and cracking to require its classification as a doubtful or border-line material.

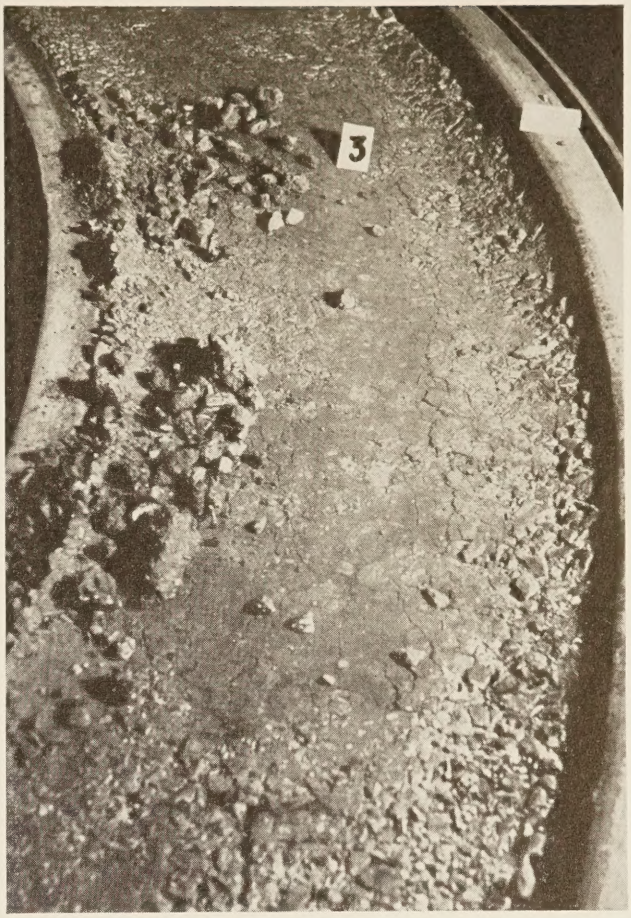

Figure 1.—Appearance of Section 3 of Series 1 After 58,000 Wheel-Trips of Traffic.

Measurements of average vertical displacement made with the transverse profilometer at various stages of the test are shown graphically in figure 3. In the tests of sand-clay materials described in the previous report, it was found that unmistakable visual evidence of failure such as marked instability, breaking up of the surface treatment, and extrusion of mud through the surface was noted at about the time the average vertical displacement of the surface reached 0.25 inch. Section 5 of series 1 of the sand-clay-gravel materials showed an average vertical displacement of only 0.17 inch at the time failure became visually evident but the vertical displacement continued to increase rapidly, reaching 0.34 inch when measurements were discontinued on the section at 233,000 wheel-trips. The increase in average vertical displacement for the other four sections, none of which actually failed, was very gradual and the total displacement never reached more than 0.20 inch during the regular traffic test.

Section 2, judged by its rate and total amount of vertical displacement, was markedly superior to any of the other sections in series 1 and its general behavior in the track as judged by visual inspection confirmed the evidence of the displacement measurements. In this respect, it conformed to the behavior of the corresponding section of the sand-clay materials from which it differed physically only in having 46.5 percent of the sand-clay replaced with rounded gravel ranging in size from No. 10 to 1 inch.

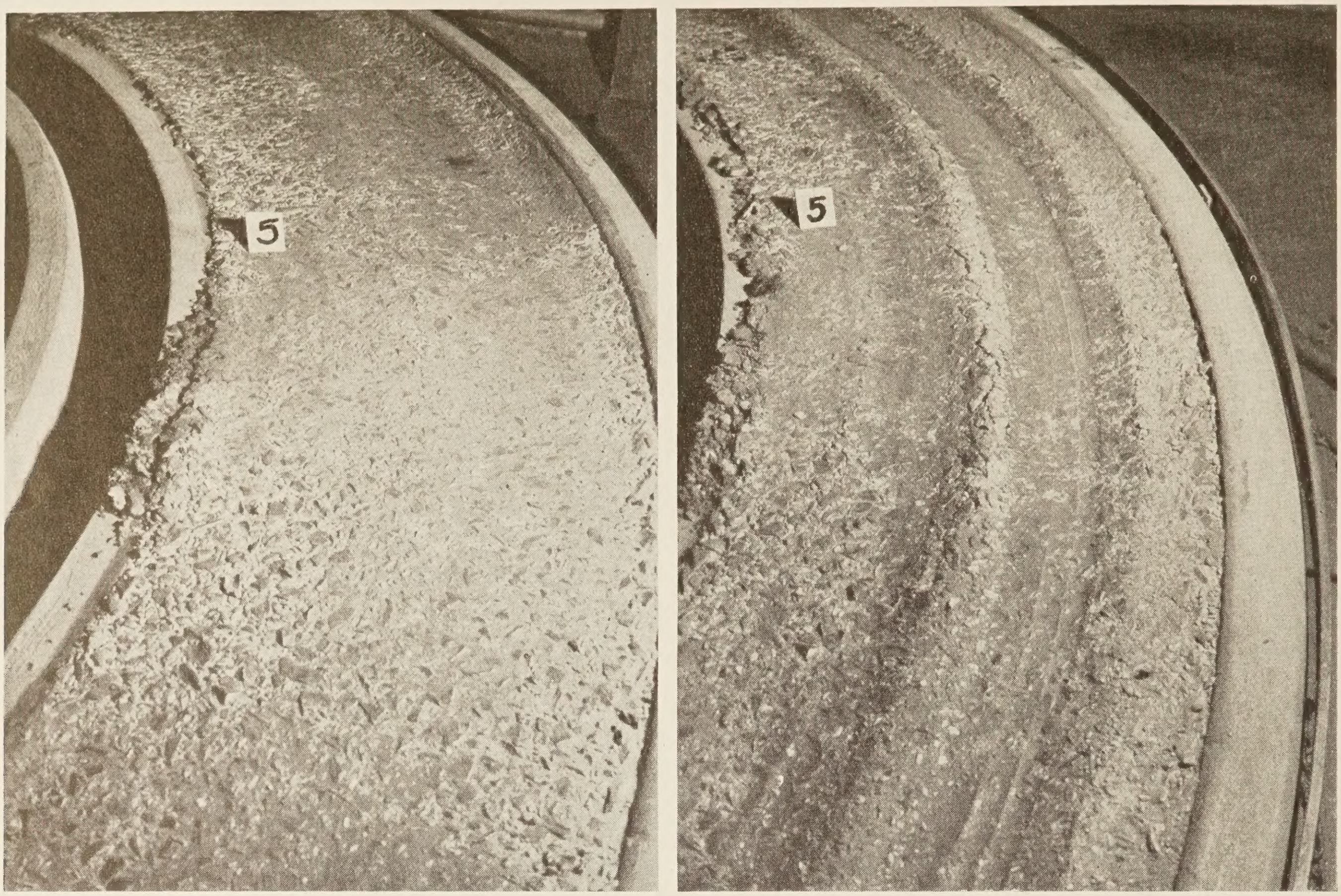

FIGURE 2.—APPEARANCE OF SECTION 5 OF SERIES 1: LEFT, AFTER 150,000 WHEEL-TRIPS, WHEN ITS FAILURE WAS RECORDED. RIGHT, AFTER 233,000 WHEEL-TRIPS, WHEN MEASUREMENTS OF ITS SURFACE DISPLACEMENT WERE DISCONTINUED.

TABLE 4.—*Schedule of operations and behavior of test sections in circular track tests, series 1*

Operation	Traffic	Water level above top of sub-base	Behavior				
			Section 1 (plasticity index=0)	Section 2 (plasticity index=5)	Section 3 (plasticity index=9)	Section 4 (plasticity index=11)	Section 5 (plasticity index=16)
	Wheel-trips	*Inches*					
Compacting base course	0- 30,000	(1)	Stable but raveled [2]	Stable but raveled [2]	Stable but raveled [2]	Stable but raveled [2]	Unstable at first.[3]
Compacting base and surface treatment.	30,000- 50,000	(1)	Good	Good	Good	Good	Good.
Testing with distributed traffic.	50,000- 50,300	½	do.[4]	Unstable [5]	Unstable [5]	Unstable [5]	Do.
Compacting base course	50,300- 58,000	(6)	do	Surface treatment destroyed.[7]	Surface treatment destroyed.[7]	Surface treatment badly damaged.[7]	Do.
Drying and recompacting base course.	58,000- 75,000	(1)	do	Unstable at first but improved rapidly.	Unstable at first but improved gradually.	Unstable at first but improved gradually.	Do.
Compacting base and new surface treatment.	75,000-100,000	(1)	do	Good	Good	Good	Do.
Testing with distributed traffic.	100,000-183,000	½	do	do	do	Good but moved slightly under traffic.	Quickly became unstable and failed at 150,000 wheel-trips.
Testing with concentrated traffic.	[8] 183,000-256,000	½	Good but developed slight rutting.	Good but developed slight movement.	Good but developed slight movement.	Good but developed some cracking.	
Do	256-000-320,000	2½	do	do	do	do	
Do	320,000-370,000	3½	Good but cracked somewhat along center line.	Good but cracked somewhat along center line.	Good but cracked somewhat along center line.	Movement increased appreciably.	
Do	370,000-425,000	4½	Good; some rutting and cracking.	Good	Good; some rutting and cracking.	Appreciable rutting and cracking.	
A 2-foot segment of each section was frozen with dry ice and tested after thawing.	425,000-445,000	4½	No change in behavior.	No change in behavior.	No change in behavior.	Frost heave, 0.03 inch; increased rutting and cracking.	Frost heave, 0.1 inch; extremely unstable.

[1] No water in sub-base.

[2] Raveling was caused by a deficiency of moisture.

[3] The early instability of sec. 5 indicated that its initial moisture content of 6.5 percent was sufficient to permit proper compaction.

[4] Sec 1 was stable but its marked subsidence under traffic when water was admitted indicated a deficiency of moisture during compaction.

[5] This temporary loss of stability and the subsidence of the surface when water was admitted indicated a lack of compaction resulting from an initial deficiency of moisture.

[6] Water drained out of sub-base to allow unstable sections to dry and compact.

[7] Evaporation of the excess capillary moisture, admitted because of the incomplete early compaction, was so slow that the base course material had to be partially dried by remixing

[8] Load on each wheel increased from 800 pounds to 1,000 pounds at 233,000 wheel-trips

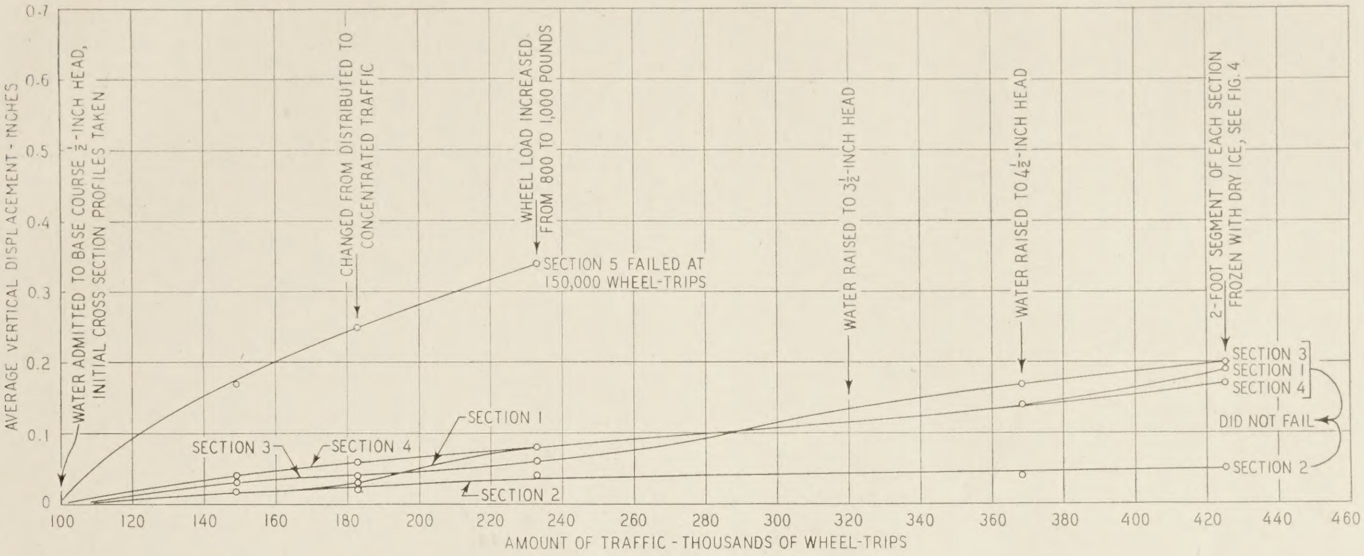

FIGURE 3.—RATE OF SURFACE DISPLACEMENT UNDER TRAFFIC, SERIES 1.

TABLE 5.—*Schedule of operations and behavior of test sections in circular track tests, series 2*

Operation	Traffic	Water level above top of sub-base	Behavior					
			Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
	Wheel-trips	*Inches*						
Compacting base course.	0– 40,000	(1)	Rutted badly at first but quickly became stable.[2]	Slightly unstable at first; stable later.	Very unstable at first; gradually became stable.	Stable at first; slightly unstable later.	Decidedly unstable at first; became stable later.	Stable at first; unstable and cracked later.
Compacting base and surface treatment.	40,000– 65,000	(1)	Good	Good	Good	Good	Good	Movement continued.
Testing with distributed traffic.	65,000–125,000	½	do	Good but developed slight movement under traffic.	do	do	do	Decidedly unstable.
Testing with concentrated traffic.	[3]125,000–205,000	½	Excellent	Developed more movement and failed.	do	do	Good but developed slight movement.	Rutted, corrugated and cracked.
Do	205,000–255,000	2½	do		do	do	Good	Failed.
Do	255,000–330,000	3½	do		do	Developed 2 chuck holes; section was near failure.	do	

[1] No water in sub-base.

[2] Because of its ability to drain readily, sec. 1 required frequent sprinkling during compaction.

[3] Load on each wheel increased from 800 pounds to 1,000 pounds at 175,000 wheel-trips.

After the conclusion of the regular traffic test on series 1 at 425,000 wheel-trips, the effect of freezing and thawing was investigated to a limited extent. A segment of each section about 2 feet long and 18 inches wide was frozen by placing a layer of crushed dry ice over it and covering the dry ice with blankets. Freezing to a minimum depth of 2½ inches was accomplished in about 5 hours. Measurements of surface elevations at this time revealed a heave of 0.1 inch on section 5 and 0.03 inch on section 4 with no change in surface elevation for the other three sections. After the frozen segments had thawed out, 20,000 additional wheel-trips of concentrated traffic were applied. Cross section profiles indicated additional average vertical displacements as shown in figure 4 from 425,000 wheel-trips to 445,000 wheel-trips.

WATER ELEVATION OF ½ INCH PROVED SEVERE TEST CONDITION

The average vertical displacements at 370,000 and 425,000 wheel-trips from figure 3 are repeated in figure 4 to show the effect of freezing and thawing on the rate of displacement. The nonplastic material of section 1 was apparently not affected, displacement caused by traffic continuing at the same rate after freezing and thawing as before. The plastic materials in sections 2, 3, and 4, were affected roughly in direct proportion to their plasticity indexes. Section 2, with a plasticity index of 5, showed only a slightly increased rate of displacement after freezing while section 4, with a plasticity index of 11, showed a very marked increase. Section 3 was intermediate between sections 2 and 4 in this respect.

Series 2.—As shown in table 5, preliminary compaction of the base and surface treatment was completed at 65,000 wheel-trips. Throughout the subsequent traffic test with water in the sub-base and at gradually increasing heights in the test base course, sections 1, 3, and 5 remained stable and showed no indications of failure. Section 2, as shown in figure 5, developed considerable movement and local depressions under concentrated traffic while the water level was still at ½ inch and was rated as having failed at 205,000 wheel-trips. Section 6 was decidedly unstable throughout the test period, indicating impending failure while the water level was at ½ inch, and was rated as having failed at 250,000 wheel-trips or shortly after the water level was raised from ½ inch to 2½ inches. Its appear-

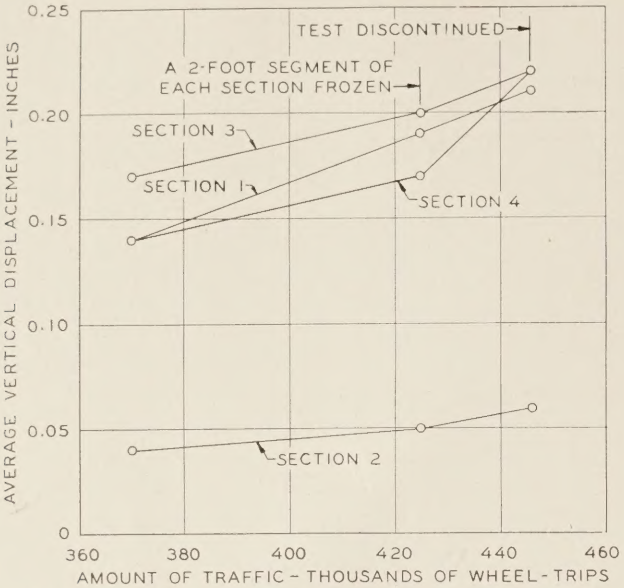

Figure 4.—Effect of Freezing and Thawing Circular Track Sections, Series 1. (The Displacements at 370,000 and 425,000 Wheel-Trips Are Replotted from Figure 3.)

ance shortly before complete failure is shown in figure 6.

Section 4 behaved well under the test traffic until after the water level had been held at 3½ inches for some time. It then developed two chuck holes and was definitely nearing failure when the test was discontinued at 330,000 wheel-trips. The latter circumstance necessitated its classification as a doubtful or borderline material.

The development of vertical displacement as measured with the transverse profilometer on the six sections of series 2 is shown in figure 7. For sections 2 and 6 the average vertical displacement at the time visual evidence of complete failure was noted was approximately 0.24 inch, which is in close agreement with the results of tests on sand-clay materials. Although section 4 showed only a slight increase in displacement up to 255,000 wheel-trips, the curve (fig. 7) broke abruptly upward after the water level was raised to 3½ inches and apparently would have passed 0.25 inch at about 350,000 wheel-trips had the test been continued.

In tests of both the sand-clay materials previously reported and the sand-clay-gravel materials here discussed, the definitely unsatisfactory materials were clearly distinguished from the rest by the fact that they either failed completely or showed unmistakable evidence of impending failure during the portion of the test when the water level was only ½ inch above the bottom of the test base course, and in no case were more than 140,000 wheel-trips of test traffic necessary to bring out this initial distinction. This initial classification was facilitated by the fact that the displacement curves of the unsatisfactory materials invariably

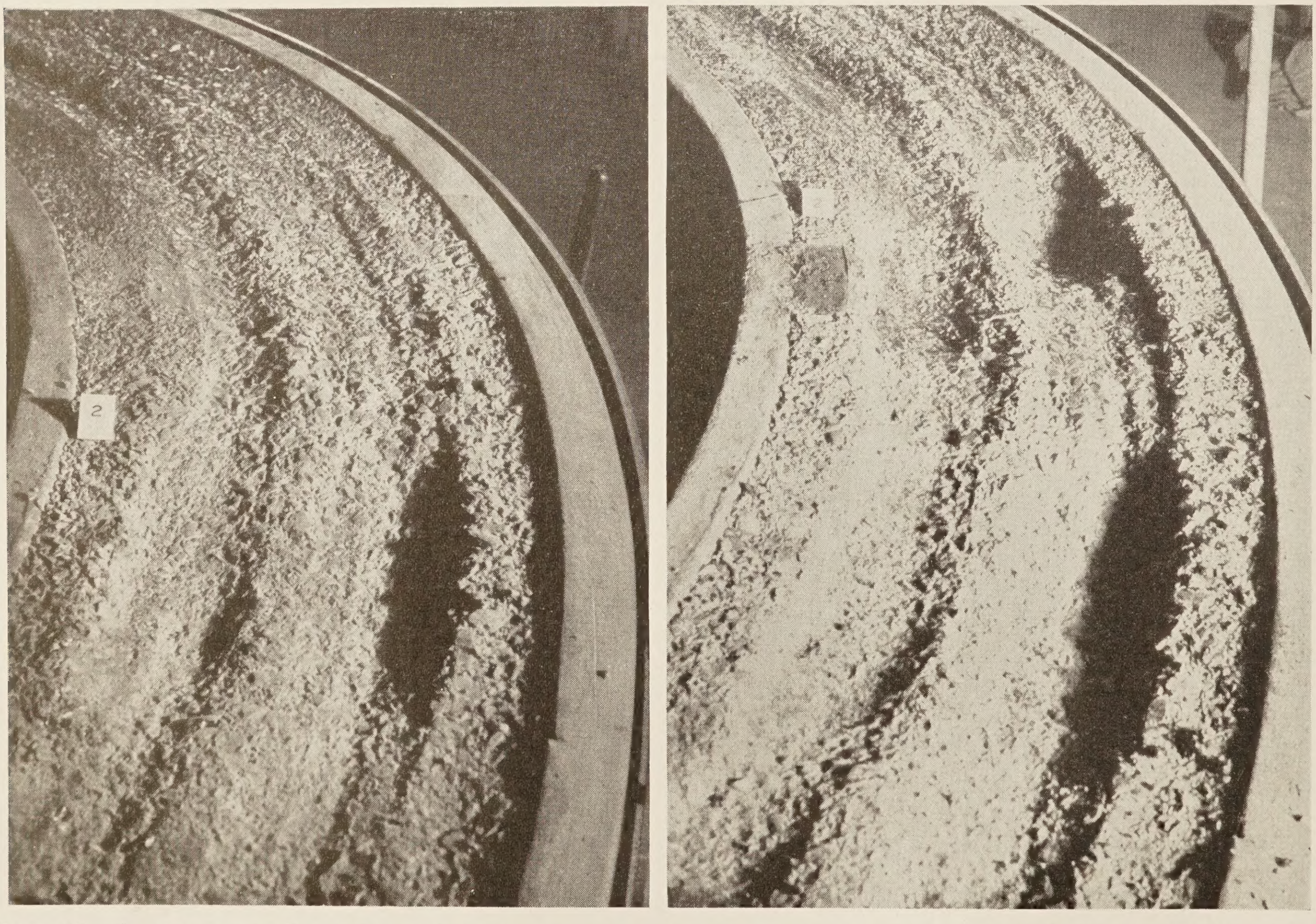

Figure 5.—Appearance of Section 2 of Series 2: Left, After 205,000 Wheel-Trips, When Failure Became Evident (Note That the Surface Treatment Was Completely Sheared Through at the Depression in the Outside Rut); Right, After 255,000 Wheel-Trips.

rose steeply or broke upward fairly early in the test whereas the displacement curves for the satisfactory and borderline materials tended to flatten out after the first few thousand wheel-trips of test traffic (see figs. 3 and 7).

Additional traffic and elevation of the water level were resorted to only after the definitely unsatisfactory materials had been identified, the purpose being to ascertain if any of the remaining sections were composed of borderline materials.

Figure 8, showing section 4 of series 1, well illustrates the appearance of one of the borderline materials at various stages of the test. The two upper views show the section in excellent condition after, respectively, 50,000 and 133,000 wheel-trips of test traffic. At these stages its condition was typical of that of any of the wholly satisfactory sections during the traffic test. The two lower views show the results of prolonged application of concentrated traffic under highly unfavorable conditions. Even at these stages the indications of failure, although sufficient to place the section in the border classification, were not extensive.

Figure 9 shows the condition of the other borderline material, section 4 of series 2, at 330,000 wheel-trips (the conclusion of the traffic test). Complete failure had not occurred but impending failure was clearly indicated by the deep depression in the inside wheel lane. The test conditions had been made so severe during the later stages of the tests of both series that not even the complete failure of a section could have been construed to indicate a seriously inferior material.

NEW INSTRUMENT USED TO TAKE LONGITUDINAL PROFILES

In addition to the transverse profiles which were taken at two stations on each section and from which the average vertical displacements of the surface were calculated (see figs. 3 and 7), longitudinal profiles were taken along the center lines of the wheel lanes with a new instrument designed especially for use on the circular track and used for the first time in these tests.

Figure 6.—Appearance of Section 6 of Series 2 After 255,000 Wheel-Trips of Traffic. Failure is Indicated by the General Roughness, Rutting, and Breaking of the Surface-Treatment.

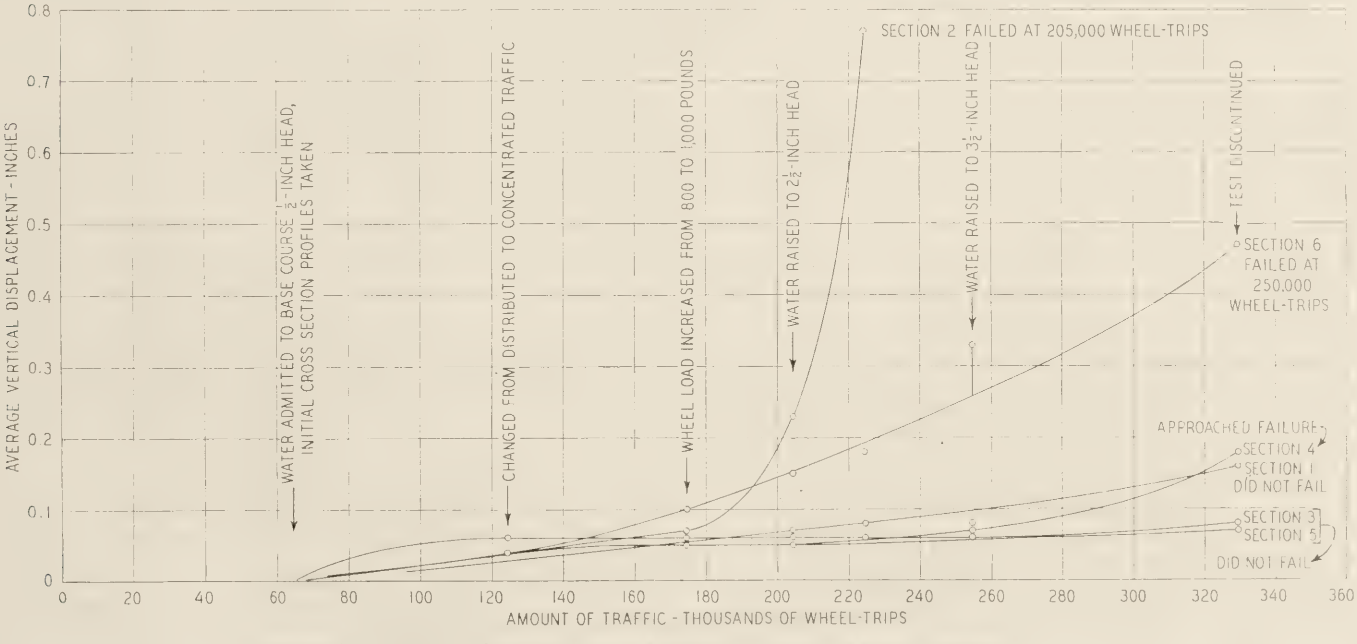

Figure 7.—Rate of Surface Displacement Under Traffic, Series 2.

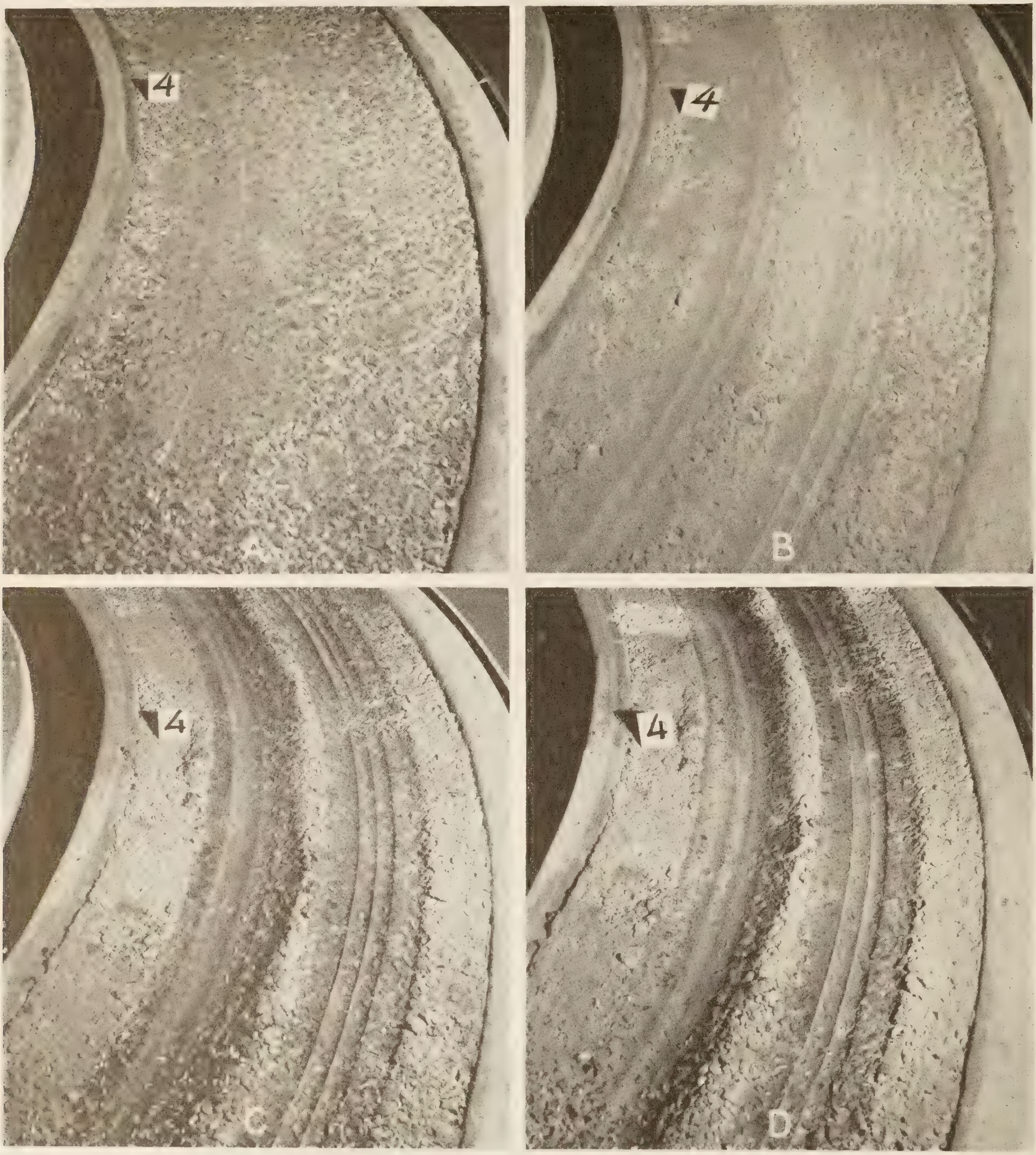

Figure 8.—Appearance of Section 4 of Series 1 After Various Amounts of Traffic: A, After 150,000 Wheel-Trips; B, After 233,000 Wheel-Trips; C, After 425,000 Wheel-Trips; and D, After Freezing, Thawing, and the Application of 20,000 Additional Wheel-Trips, Bringing the Total Traffic to 445,000 Wheel-Trips.

Figure 10 is a photograph of the new longitudinal profilometer in position for making a recording of the profile of the track surface. It consists of a radial frame pivoted at the central pedestal of the track structure and supported at its outer end by two flanged wheels arranged in tandem and running on a peripheral steel track attached to the outer curb of the track. One of these wheels drives, through an appropriate transmission system, the vertical drum that carries the record sheet as shown in figure 10. This drum is mounted on a radially sliding cage that can be clamped at any desired radius within the width of the track. The cage also carries a vertical sliding measuring rod on the lower end of which is a small caster that rests on the track surface and moves up and down in conformity with the contour of the surface. At the rod's upper end is a stylus which draws the surface profile on the drum as it revolves when the instrument is moved around the track. The drum makes one revolution while the profilometer is making one trip around the track, so that a continuous profile of all the test sections in a track is made on one sheet 21¼ inches long.

Longitudinal profiles of the test sections in both series 1 and 2, taken on the wheel courses where concentrated traffic was applied, are shown in figure 11. The upper one of each pair of profiles shown was taken at the conclusion of the compaction period before any test traffic had been applied. The corresponding lower ones were taken at the conclusion of the traffic test and show the depth of the ruts that were formed.

These longitudinal profiles were found to be fully as satisfactory as the cross-section profiles as a means of evaluating the comparative quality of the materials. Tests with both instruments on this series of materials indicated that the average depth of rut was about 1.8 times the average vertical displacement as calculated from the cross-section profiles. While this factor might vary somewhat for different types of materials, the comparative results in a series of tests on similar materials are consistent and if desired the value of the factor is easily obtained for other types.

Compaction tests similar to those used in determining the moisture contents for constructing the sections of series 2 were made on the aggregates of both series. The vibratory compaction test was modified to the extent that about 5 percent by weight of kerosene was mixed with the aggregates before vibrating them, to prevent segregation of the coarse stone. It was found that this produced somewhat higher densities than were obtained by vibrating the dry aggregates as was done in setting the moisture contents.

A comparison of the densities obtained by the modified vibration method with those of the track sections at the conclusion of the traffic test is shown in table 6.

TABLE 6.—*Comparison of densities obtained by vibration and by testing in the circular track*

	Density (aggregate volume per unit of total compacted volume)		Behavior of section under traffic
	Compacted by vibration	Track section at end of test	
SERIES 1	*Percent*	*Percent*	
Section 1	89.7	82.8	Satisfactory.
2	88.0	87.0	Do.
3	87.5	86.4	Do.
4	87.1	86.2	Essentially satisfactory.
5	87.2	84.0	Failed.
SERIES 2			
Section 1	86.9	77.8	Satisfactory.
2	86.7	83.9	Failed.
3	89.9	89.1	Satisfactory.
4	87.5	87.3	Approached failure.
5	89.9	89.3	Satisfactory.
6	87.7	85.1	Failed.

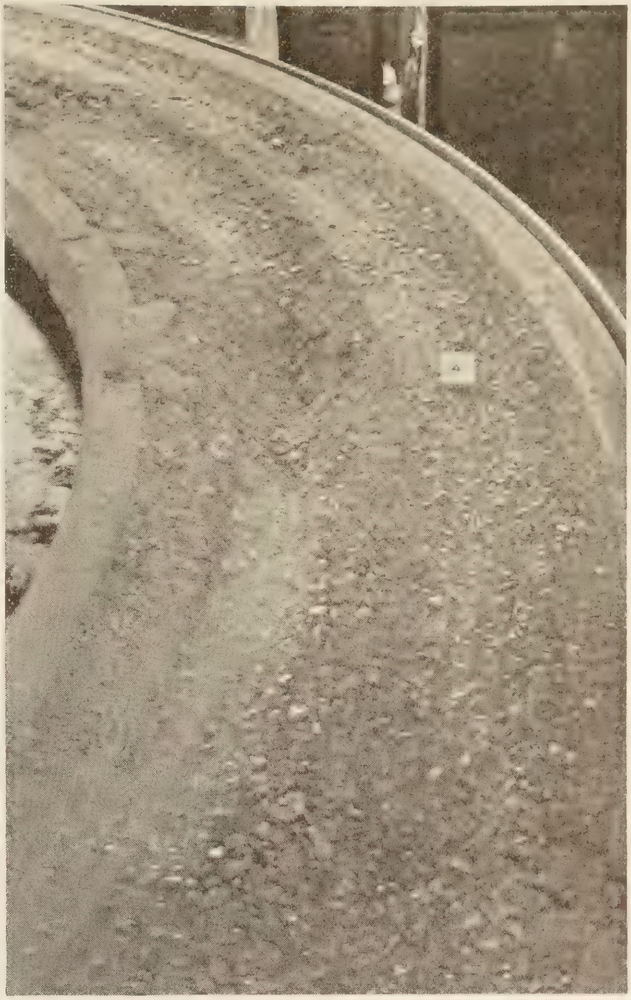

FIGURE 9.—APPEARANCE OF SECTION 4 OF SERIES 2 AT THE END OF THE TRAFFIC TEST (330,000 WHEEL-TRIPS). THE DEEP RUT IN THE INSIDE LANE INDICATED AN IMPENDING FAILURE.

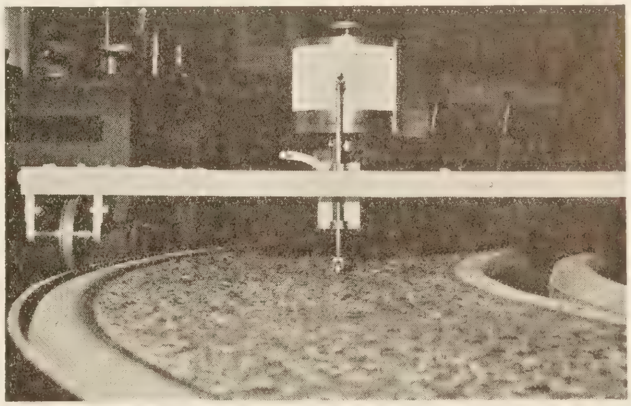

FIGURE 10.—LONGITUDINAL PROFILOMETER USED FOR RECORDING LONGITUDINAL PROFILES OF CIRCULAR TRACK SECTIONS.

SATISFACTORY PLASTIC MATERIALS HAD GREATEST COMPACTION IN TEST TRACK

The relations between service behavior and relative density, as shown in table 6, were consistent with those noted for the sand-clay materials of the previous investigation.

The satisfactory and borderline plastic sand-clay-gravels (sections 2, 3, and 4 of series 1 and sections 3, 4, and 5 of series 2) attained densities in the track within from 0.2 to 1.1 percent of the densities of the vibrated samples. The unsatisfactory materials (section 5 of series 1 and sections 2 and 6 of series 2) all of which were plastic, had densities that were 3.2, 2.8, and 2.6 percent, respectively, less in the track than in the vibrated samples. The two nonplastic materials, section 1 of series 1, and section 1 of series 2, because of their harshness, were the least compactible under

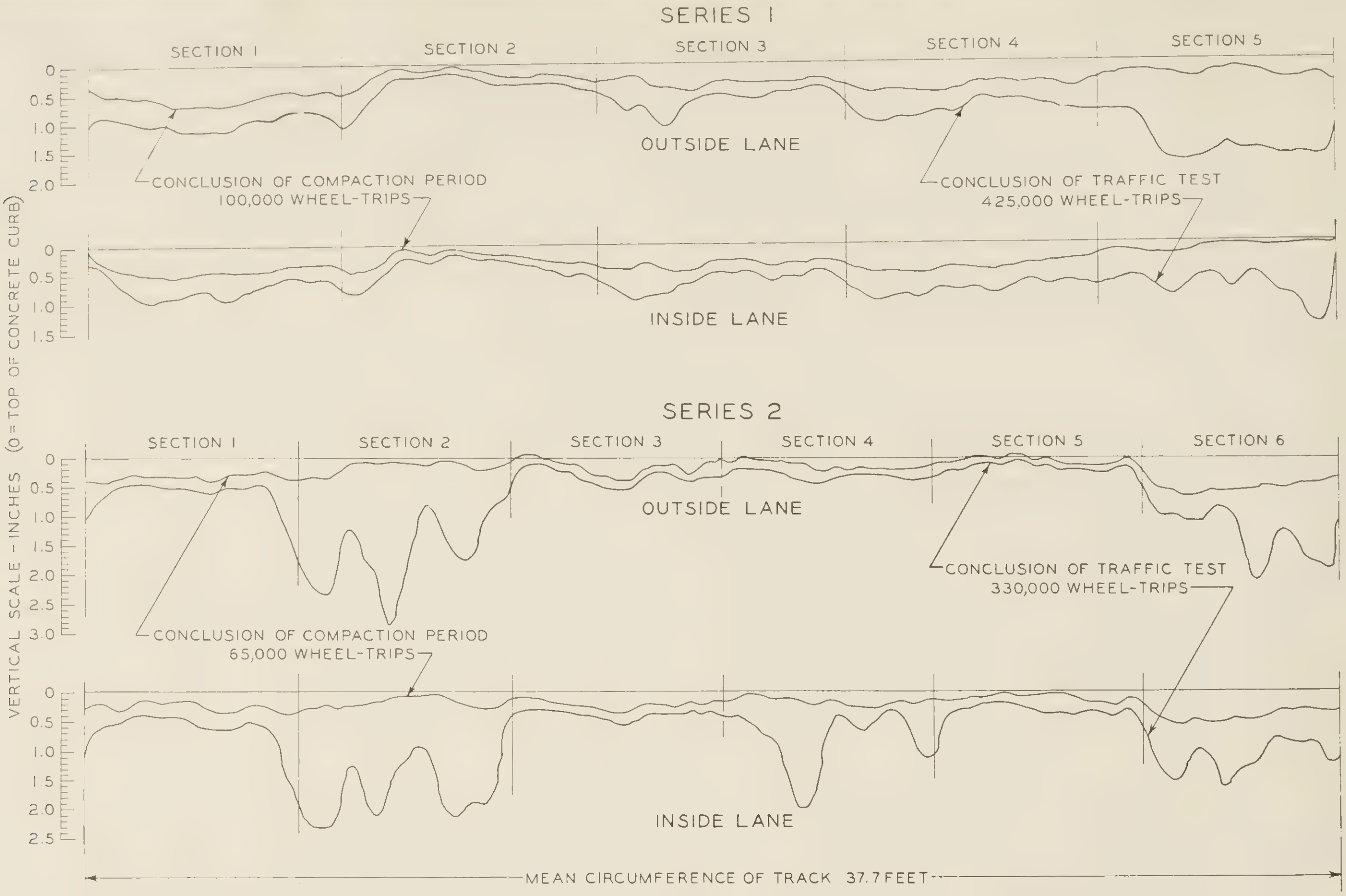

Figure 11.—Longitudinal Profiles of Circular Track Sections Showing Maximum Displacement or Rutting.

traffic, their densities in the track being 6.9 and 9.1 percent less than those of the vibrated samples. However, both gave satisfactory service because of the same inherent characteristic that caused their noncompactibility under traffic, namely their harshness.

The numerical differences in density of the plastic materials appear small and for that reason, their importance might easily be overlooked. To realize their importance where plastic materials are concerned, it is only necessary to analyze the data showing the densities of sections 2, 3, and 4 of series 1 at 58,000 wheel-trips when absorbed water had rendered them extremely unstable, the densities of the same sections at 425,000 wheel-trips after further compaction had made them highly resistant to the action of water, and their maximum obtainable densities as determined by vibration (see table 7).

Table 7.—*Comparison of densities obtained by vibration with densities of track sections after various amounts of traffic*

Series 1	Densities		
	In track at 58,000 wheel-trips (unstable)	In track at 425,000 wheel-trips (stable)	Samples compacted by vibration
	Percent	*Percent*	*Percent*
Section 2	83.2	87.0	88.0
3	84.5	86.4	87.5
4	84.3	86.2	87.1

At 58,000 wheel-trips, when the track sections were highly unstable, the densities of the three sections were respectively only 4.8, 3, and 2.8 percent less than the maximum densities obtained by vibration. The additional compaction obtained by the application of additional traffic in conjunction with the drying out of from 1.1 to 2.1 percent of moisture (see table 3) increased their densities by, respectively, 3.8, 1.9, and 1.9 percent or to within 1, 1.1, and 0.9 percent of their maximum densities obtained by vibration. This small increase in density accounted for their alteration from a condition in which they were highly susceptible to softening in the presence of capillary water to one in which they had a high resistance to the action of water.

A volumetric analysis of the composition of all of the test sections at the conclusion of the traffic tests is shown in table 8. The highly capillary nature of the plastic materials, comprising all of the test sections except section 1 of each series, is strikingly shown by the very low percentage of residual or air-filled voids. These residual or air-filled voids represent, in each section, less than 2 percent of the total volume of the traffic-compacted plastic materials. The water contents show considerable variation, being relatively low for the more compactible materials and high for the noncompactible ones. In other words, the capacity of these materials to absorb water seems to be limited only by the volume of pore space available with a small allowance for nondisplaceable air. Thus again is emphasized the importance of obtaining thorough compaction in plastic, highly capillary materials.

In contrast to the plastic sections, the nonplastic materials of section 1 of series 1, and section 1 of series 2, had higher percentages of residual or air-filled voids and water contents no higher than those of the plastic materials indicating low capillarity and a susceptibility to gravity drainage.

TABLE 8.—*Composition of track sections at conclusion of traffic tests, series 1 and 2*

	Water content by weight	Composition by volume		
		Aggregate	Water	Air
SERIES 1 [1]	*Percent*	*Percent*	*Percent*	*Percent*
Section 1	5.3	82.8	11.7	5.5
2	4.9	87.0	11.4	1.6
3	5.1	86.4	11.7	1.9
4	5.5	86.2	12.6	1.2
5	6.6	84.0	14.8	1.2
SERIES 2 [2]				
Section 1	6.9	77.8	14.2	8.0
2	6.9	83.9	15.4	.7
3	4.0	89.1	9.4	1.5
4	4.9	87.3	11.3	1.4
5	4.1	89.3	9.7	1.0
6	6.2	85.1	14.0	.9

[1] At 425,000 wheel-trips.
[2] At 330,000 wheel-trips.

TESTS SHOWED IMPORTANCE OF CONTROLLING PLASTICITY AND GRADING

As in the tests of sand-clay mixtures the delineation between good, serviceable materials and those of inferior quality was distinct. Again, the great importance of close control of both plasticity and grading was demonstrated and it was also shown that, where plastic materials are concerned, no amount of control of the quality of the materials will prevent failure if thorough compaction of the materials is not obtained during the construction operations.

Confirmation was found for the belief of some authorities that the behavior of a graded aggregate base-course material is largely dependent on the quality of the soil mortar or material passing the No. 10 sieve. The results of these tests indicate this to be true if more than about 40 percent of the total aggregate passes the No. 10 sieve, while if the total aggregate contains less than about 40 percent of soil mortar the effect of the quality of the soil fraction is modified or obscured by the coarser material. A discussion of the test results leading to this conclusion follows.

Figure 12 which was prepared from the data in table 1 shows the grading curves for the 11 sand-clay-gravel materials used in these tests. The shaded areas which are identical for both series were drawn to include the grading curves of all of the wholly satisfactory materials. They are limited on the left or fine side, as nearly as possible without introducing misleading undulations, by curves for the two borderline materials, section 4 of series 1 and section 4 of series 2. Their limit on the right or coarse side is established by curves for the materials of sections 1 and 3 of series 2, since theirs were the coarsest gradings used.

Figure 13 shows the gradings of the mortars or fractions passing the No. 10 sieve of the 11 sand-clay-gravel materials. The two identical shaded zones, reproduced from figure 13 of the report on sand-clay materials, include the gradings of all the wholly satisfactory sand-clay materials tested in the previous investigation and are limited on the left by curves for the borderline sand-clays and on the right by curves for the coarsest materials used in that investigation.

As shown in figure 13, the grading curves of the mortars of all but one of the sand-clay-gravel materials fall either partially or almost entirely outside the shaded area on the left or fine side. The amount of this divergence has no significance in the case of the nonplastic material of section 1 of series 1, and may not be sufficient for sections 2, 3, and 4 to impair seriously their quality as sand-clay materials for base courses. The divergence is extensive for section 5 of series 1, and sections 2, 3, 4, 5, and 6 of series 2, which leads to the conclusion that the mortars of these sections would be unsatisfactory for use as base-course materials by themselves. The mortar of section 4 of series 2 was the extreme example in this respect and yet because this inferior mortar comprised only 41.9 percent of the total base-course material as tested, the section withstood traffic well enough to be classed in the borderline group.

The mortars of the unsatisfactory sections 2 and 6 of series 2 were virtually identical in grading with those of the satisfactory sections 3 and 5 of series 2. The plasticity indexes of sections 2 and 6, which were respectively 9 and 7, did not differ sufficiently from those of sections 3 and 5, which were respectively 8 and 6, to account even in part for their difference in behavior. The only significant difference was in the percentage of the total aggregate passing the No. 10 sieve. For the unsatisfactory sections 2 and 6, these percentages were 65 and 66.1 as compared to 31.9 and 38 for the satisfactory sections 3 and 5.

FINDINGS USED IN DRAFTING SPECIFICATIONS FOR SOIL AND GRAVEL BASE COURSES

Section 5, series 1, in which a sand-clay material known to be unsatisfactory for use as a base course by itself comprised 47 percent of the sand-clay-gravel mixture, failed quite early in the traffic test.

Thus with definite failures recorded when poorly graded or highly plastic soil appreciably exceeded 40 percent of the aggregate and borderline behavior when 41.9 percent of an unsatisfactorily graded soil mortar was used, while satisfactory service was recorded for sand-clay-gravel mixtures containing 31.9 and 38 percent of poorly graded soil mortar, the critical percentage seems to be quite well established as being in the neighborhood of 40 with the rounded-gravel coarse aggregate used in these tests.

For convenience in studying these relationships, the percentages passing the No. 10 sieve and the plasticity indexes of all the sand-clay-gravel materials as shown in table 1 are repeated in table 9.

TABLE 9.—*Quantity and character of mortar fractions of track sections, and behavior under traffic*

	Fraction of total aggregate passing No. 10 sieve	Plasticity index of fraction passing No. 40 sieve	Behavior of section under traffic
SERIES 1	*Percent*		
Section 1	53.5	0	Satisfactory.
2	47.9	5	Do.
3	47.9	9	Do.
4	50.3	11	Essentially satisfactory.
5	47.0	16	Failed.
SERIES 2			
Section 1	42.3	0	Satisfactory.
2	65.0	9	Failed.
3	31.9	8	Satisfactory.
4	41.9	7	Approached failure.
5	38.0	6	Satisfactory.
6	66.1	7	Failed.

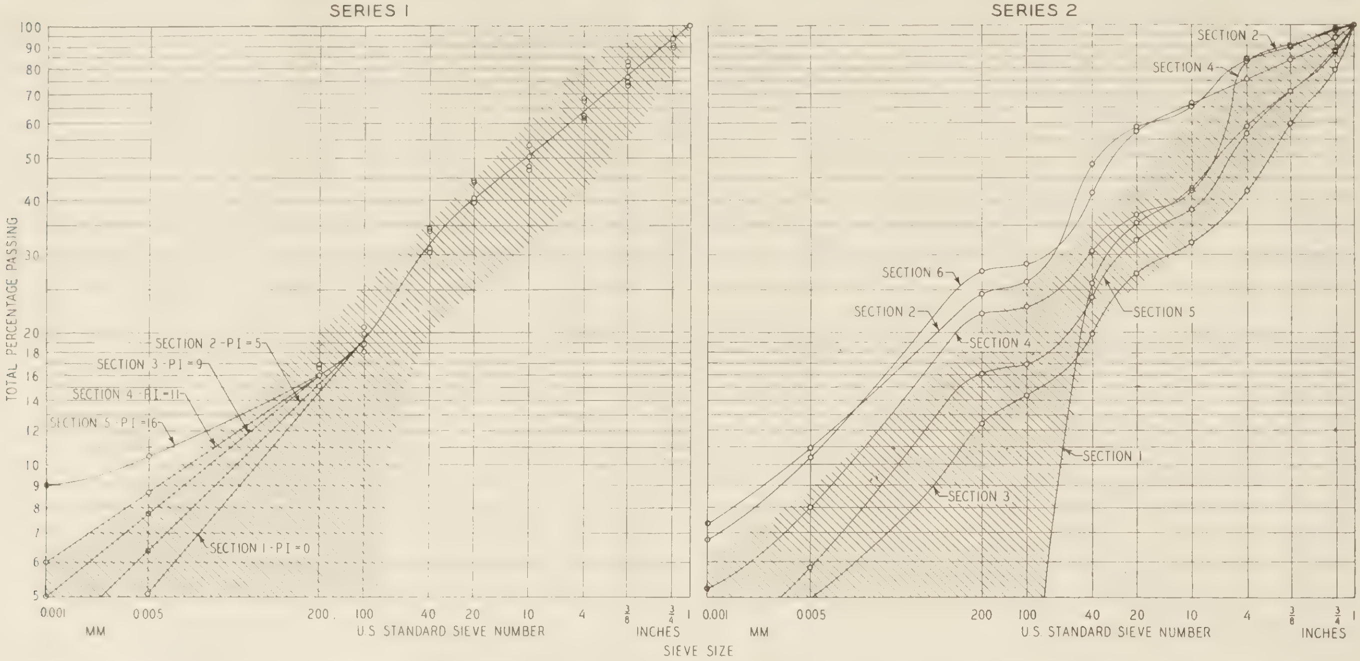

Figure 12.—Gradings of Materials in Series 1 and 2. Shaded Area Indicates Zone Within Which All the Wholly Satisfactory Materials Are Included.

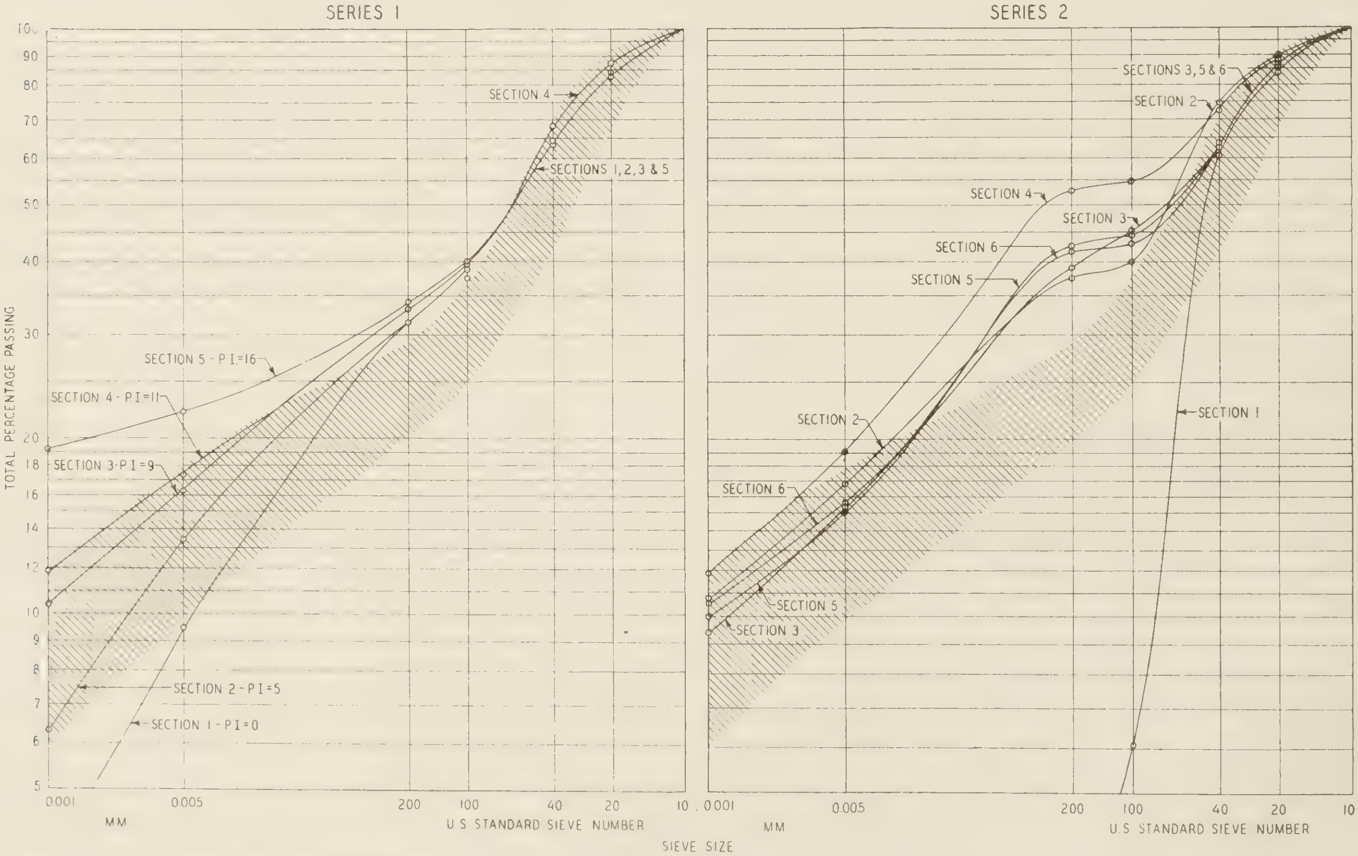

Figure 13.—Gradings of the Mortars of the Sand-Clay-Gravel Materials Tested. The Shaded Areas, Reproduced from Figure 13 of the Previous Report on Sand-Clay Materials, Show the Grading Range of the Satisfactory Sand-Clay Base-Course Materials.

None of the nonplastic materials, either in the tests of sand-clays or of the sand-clay-gravels, showed any indication of lack of stability and it is obvious that mixtures of nonplastic, satisfactorily graded sand-clay materials with coarser aggregate could be expected to make satisfactory base courses for bituminous surfaces regardless of whether 40 percent or even as much as 100

(Continued on page 16)

SIMPLIFIED COMPUTATION OF HYDROMETER TEST DATA FOR SOIL

BY THE DIVISION OF TESTS, BUREAU OF PUBLIC ROADS

Reported by EDWARD S. BARBER, Junior Highway Engineer

USE is made of a hydrometer in standard methods of test[1] [2] to determine the size distribution of soil grains smaller than 0.05 millimeter in diameter. Direct computation of the size distribution by means of the formulas involved in interpreting the test data is rather laborious. To simplify this work a graphical method of computation was devised by the Bureau of Public Roads.[3] The present report describes a slide rule with special indicator and scales that is particularly useful in obtaining the size distribution when the data are reported as an accumulation curve. Each method has certain advantages and the choice of a particular one depends upon individual preference and the testing equipment used.

In the hydrometer method of mechanical analysis, Stokes' law for the velocity at which a small solid sphere falls through a liquid is used to determine equivalent grain size, which is the diameter of a sphere that would fall at the same velocity as the soil particle. Stokes' formula with reference to soil tests may be written

$$d=\sqrt{\frac{30nL}{980(G-G_1)t}} \qquad (1)$$

in which

d=equivalent grain size in millimeters.

n=viscosity of water, in poises, for any temperature T.

L=distance, in centimeters, through which the soil particles fall during a time, t, in minutes.

G=specific gravity of the soil.

G_1=specific gravity of water.

The numerical values presented in this paper are for a particular Bouyoucos hydrometer calibrated to read grams of soil per liter of suspension (in water) at 67° F. with a soil whose specific gravity is 2.65. However, the method of computation is applicable to any hydrometer of either the Bouyoucos or specific gravity type.

Table 1 gives the equivalent grain size in millimeters under standard conditions of temperature and specific gravity for various combinations of hydrometer reading and time. The viscosity of water is taken as 0.0102 poise at 67° F. and its specific gravity is taken as 1. Following the practice of the Bureau of Public Roads,[4] L in formula (1) is taken as 0.42 times the distance from the surface of the suspension to the bottom of the hydrometer.

Table 2 gives the factors by which the grain sizes of table 1 are multiplied to correct for variations in temperature and specific gravity. The temperature correction factor for $G=2.65$ is $\sqrt{\frac{n}{0.0102}}$ and the specific gravity correction factor for $T=67°$ F. is $\sqrt{\frac{2.65-1}{G-1}}$.[4] The combined correction factor for both temperature and specific gravity is obtained by multiplying the temperature correction factor by the specific gravity correction factor.

For example, if t is 2 minutes and the hydrometer reading, H, is 34, table 1 gives a grain size of 0.0266 millimeters. Then for $T=70°$ F. and $G=2.6$, table 2 gives a combined correction factor of 0.995. The product 0.0266 times 0.995 gives 0.0265 millimeters as the corrected value of the equivalent grain size.

TABLE 1.—*Equivalent grain sizes in millimeters under standard conditions [1] computed from Stokes' formula*

Bouyoucos hydrometer reading, H	Equivalent grain size for periods of sedimentation of—							
	1 minute	2 minutes	5 minutes	15 minutes	30 minutes	60 minutes	250 minutes	1,440 minutes
	Mm.	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*
0	0.0435	0.0307	0.0194	0.0112	0.0079	0.0056	0.00275	0.00115
2	.0432	.0305	.0193	.0111	.0079	.0056	.00273	.00114
4	.0428	.0303	.0192	.0111	.0078	.0055	.00271	.00113
6	.0425	.0300	.0190	.0110	.0078	.0055	.00269	.00112
8	.0422	.0298	.0189	.0109	.0077	.0054	.00267	.00111
10	.0418	.0296	.0187	.0108	.0076	.0054	.00265	.00110
12	.0415	.0293	.0186	.0107	.0076	.0054	.00262	.00109
14	.0411	.0291	.0184	.0106	.0075	.0053	.00260	.00108
16	.0408	.0288	.0182	.0105	.0074	.0053	.00258	.00107
18	.0404	.0285	.0180	.0104	.0074	.0052	.00255	.00106
20	.0400	.0283	.0179	.0103	.0073	.0052	.00253	.00105
22	.0397	.0281	.0178	.0102	.0072	.0051	.00251	.00105
24	.0394	.0279	.0176	.0102	.0072	.0051	.00249	.00104
26	.0391	.0276	.0175	.0101	.0071	.0050	.00247	.00103
28	.0387	.0274	.0173	.0100	.0071	.0050	.00245	.00102
30	.0383	.0271	.0172	.0099	.0070	.0050	.00243	.00101
32	.0380	.0269	.0170	.0098	.0069	.0049	.00240	.00100
34	.0377	.0266	.0168	.0097	.0069	.0049	.00238	.00099
36	.0373	.0264	.0167	.0096	.0068	.0048	.00236	.00098
38	.0369	.0261	.0165	.0095	.0067	.0048	.00234	.00097
40	.0366	.0259	.0164	.0094	.0067	.0047	.00231	.00096
42	.0362	.0256	.0162	.0094	.0066	.0047	.00229	.00095
44	.0359	.0254	.0160	.0093	.0066	.0046	.00227	.00094
46	.0355	.0251	.0159	.0092	.0065	.0046	.00224	.00093
48	.0351	.0248	.0157	.0091	.0064	.0045	.00222	.00092
50	.0347	.0245	.0155	.0090	.0063	.0045	.00220	.00091

[1] This table is for a particular hydrometer calibrated to read grams of soil per liter of suspension at 67° F. with a soil whose specific gravity is 2.65. The calibration for distance of fall is given in table 4.

TABLE 2.—*Combined correction factors [1] for temperature and specific gravity applied to Stokes' formula*

Temperature, degrees (F.)	Correction factor for soils having specific gravities of—								
	2.2	2.3	2.4	2.5	2.6	2.65	2.7	2.8	2.9
60	1.228	1.182	1.138	1.100	1,065	1.048	1.033	1.004	0.977
65	1.190	1.144	1.102	1.064	1.031	1.015	1.000	.972	.946
67	1.172	1.127	1.086	1.048	1.016	1.000	.985	.958	.932
70	1.149	1.104	1.064	1.027	.995	.980	.965	.939	.913
75	1.113	1.068	1.029	.995	.965	.949	.935	.909	.885
80	1.077	1.035	.998	.963	.934	.919	.905	.880	.857
85	1.044	1.004	.968	.934	.905	.891	.878	.853	.830
90	1.015	.976	.940	.908	.880	.866	.853	.829	.807

[1] A grain size under standard conditions as given in table 1 is multiplied by a correction factor from this table to correct for values of temperature and specific gravity other than 67° F. and 2.65, respectively.

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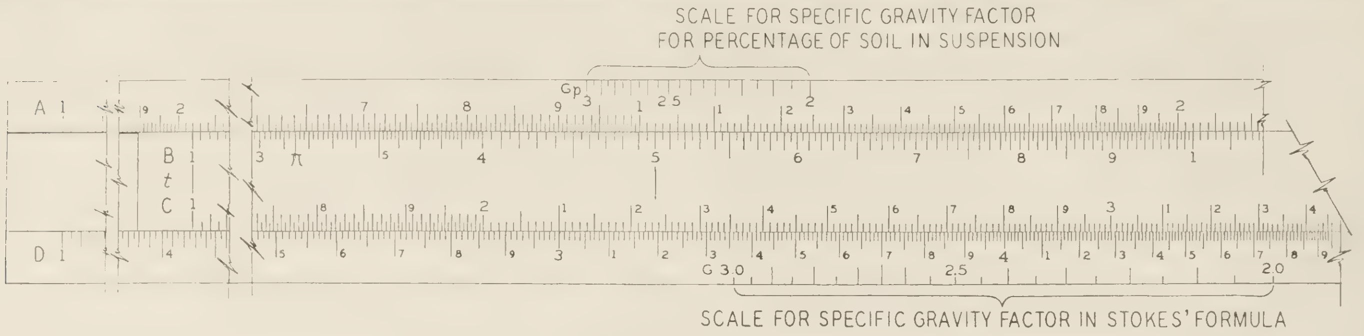
[1] Tentative Method of Mechanical Analysis of Soils. Proceedings of the American Society for Testing Materials, vol. 35, pt. I, 1935, p. 953.

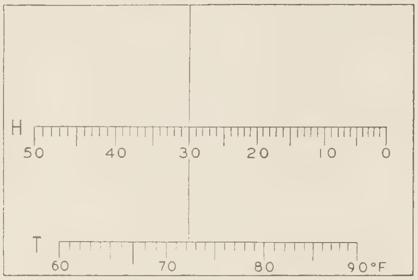
[2] Standard Method of Mechanical Analysis of Soils, Method T-88-38 Standard Specifications for Highway Materials and Methods of Sampling and Testing, 1938, p. 291. Published by the American Association of State Highway Officials.

[3] Graphical Solution of the Data Furnished by the Hydrometer Method of Analysis, by E. A. Willis, F. A. Robeson, and C. M. Johnston. PUBLIC ROADS, vol. 12, No. 8, October 1931.

[4] Procedures for Testing Soils for the Determination of the Subgrade Soil Constants, by A. M. Wintermyer, E. A. Willis, and R. C. Thoreen. PUBLIC ROADS, vol. 12, No. 8, October 1931.



SLIDE RULE PROPER



SCALED INDICATOR

FIGURE 1.—SLIDE RULE AND INDICATOR WITH SUPPLEMENTARY SCALES.

SLIDE RULE USED TO COMPUTE PARTICLE SIZES

Values shown in tables 1 and 2 may be indicated graphically on a slide rule. The desirability of doing this will depend upon the operator's preference and the test method used. For example, if all tests are made at the same temperature and an average specific gravity is assumed, a tabulation such as table 1 gives the grain sizes directly. For the more general case, where both temperature and specific gravity are different for each test, the following method can be used for adapting a slide rule so as to facilitate computation of grain sizes by Stokes' formula without the use of tables or charts.

Stokes' formula may be written

$$d^2=\frac{30\times0.0102}{980\times1.65}\times\frac{n}{0.0102}\times\frac{1.65}{G-1}\times L\times\frac{1}{t}\text{------}(2)$$

with the specific gravity of water taken as 1.

Table 3 gives values of $\frac{n}{0.0102}$ for various temperatures. As shown in figure 1, marks for these temperatures are scribed as the T scale on the indicator so as to abut the lower edge of the face of the rule with the indicator in place (see fig. 2). The positions of the marks for the temperature values correspond to the positions of the values of $\frac{n}{0.0102}$ on the A (or B) scale with the direction reversed. To mark the T scale on the underside of the indicator, it is turned over in the direction of the length of the rule and the lower edge of the indicator is placed over the A scale so as to cover the interval from 0.749 to 1.10 on that scale, the range of values of table 3. The mark for $T=60°$ F. is then scribed on the indicator at 1.10 on the A scale, the mark for 65 at 1.03, the mark for 67 at 1.00, etc.,

TABLE 3.—*Temperature factors in Stokes' formula*

Temperature T	Temperature factor $\frac{n}{0.0102}$
Degrees F.	
60	1.10
65	1.03
67	1.000
70	.959
75	.899
80	.844
85	.794
90	.749

Similarly, the hydrometer readings given in table 4 are scribed on the indicator, giving the H scale (see fig. 1). The positions of the marks on the H scale correspond to the positions of the values of L on the A (or B) scale, but this time with the indicator in its normal position. Thus, when the mark for zero hydrometer readings is opposite 1 (or 10) on the A scale, the mark for 50 grams per liter on the H scale will be opposite the corresponding height of fall which is 6.37.

TABLE 4.—*Distances of fall in Stokes' formula*

Hydrometer reading, H	Distance of fall,[1] L
Grams per liter	*Centimeters*
0	10.00
10	9.25
20	8.47
30	7.78
40	7.07
50	6.37

[1] These values, for a particular Bouyoucos hydrometer, are taken as 0.42 times the distance from each hydrometer reading or the surface of the suspension to the bottom of the hydrometer.

The values of the specific gravity factors, as given in table 5, are scribed below the D scale of the slide rule proper (see upper diagram of fig. 1). The position of

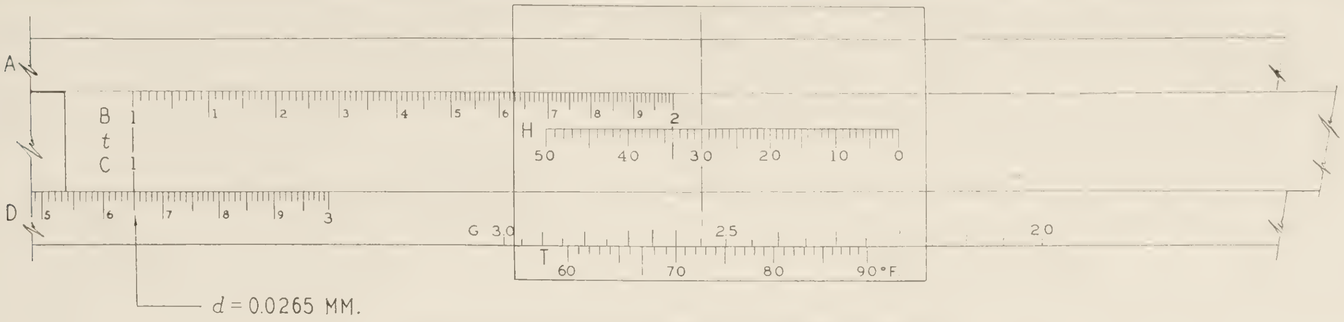


FIGURE 2.—SLIDE RULE SET FOR STOKES' FORMULA.

this scale in relation to the A scale is important. The value of the right-hand side of equation (2) is 0.001892 for $t=1$ minute, $G=2.65$, $n=0.0102$ poise ($T=67°$ F.), and $L=10$ centimeters ($H=0$). To determine the position of the mark for $G=2.65$, the indicator is placed so that the mark for $H=0$, is directly opposite 1892 on the A scale. The mark for 2.65 on the specific gravity scale (fig. 1) is scribed directly opposite the mark for $T=67°$ F. This corresponds to a specific gravity factor of 1.00. The remainder of the scale (2.0 to 3.0) is scribed relative to the mark for 2.65 using the A scale in its normal direction as the measure of length.

The time, t, is given directly on the B scale although it may be convenient to draw lines across the longitudinal center line of the slide (as shown in fig. 1 at 1 and 5 of upper diagram) corresponding to the usual time schedule for reading the hydrometer.

The solution of the same example as given in the description of the use of tables 1 and 2 is illustrated in figure 2. The indicator is moved to bring 70° F. on the T scale opposite 2.6 on the G scale. With the position of the indicator thus fixed, the slide is moved to bring 2 minutes on the B (or t) scale opposite 34 on the H scale. The grain size in millimeters is then read as 0.0265 on the D scale opposite 1 (or 10) on the C scale as shown in figure 2.

TABLE 5.—*Specific gravity factors in Stokes' formula*

Specific gravity G	Specific gravity factor $\frac{1.65}{G-1}$
2.0	1.650
2.1	1.500
2.2	1.375
2.3	1.268
2.4	1.178
2.5	1.099
2.6	1.031
2.65	1.000
2.7	.971
2.8	.917
2.9	.869
3.0	.825

COEFFICIENT OF PERMEABILITY COMPUTED USING SLIDE RULE

If the temperature is kept practically constant during a single test, one setting of the indicator will do for all of the time readings so that only one movement of the slide is required to determine each grain size, the indicator remaining fixed in position.

The slide rule may also be used conveniently for the reverse procedure of determining the time interval corresponding to a specific grain size for any temperature and specific gravity.

A slide rule method very similar to the one just described is now being used in computing the coefficient of permeability from test data in which the principle of the falling-head permeameter is used.

The formula used for determining the percentage of initially dispersed soil remaining in suspension[4] when the hydrometer method of mechanical analysis is used may be conveniently computed on a slide rule. This formula is

$$P=\frac{(H+\Delta H)f}{W_0}\times 100 \text{-------------} (3)$$

in which

P=percentage of initially dispersed soil remaining in suspension at the time a hydrometer reading is taken.

W_0=weight in grams of soil per liter of suspension initially dispersed.

H=hydrometer reading, grams of soil per liter of suspension.

ΔH=temperature correction for density of water (see values of table 6).

f=correction factor for G, the specific gravity of the soil (see table 7).

that is

$$f=\frac{2.65-1}{2.65}\times\frac{G}{G-1}$$

TABLE 6.—*Temperature corrections in formula for percentage of soil in suspension*

Temperature T	Temperature correction,[1] ΔH
Degrees F.	*Grams per liter*
60	−0.8
61	−.7
62	−.6
63	−.5
64	−.4
65	−.3
66	−.1
67	.0
68	.1
69	.2
70	.4
71	.5
72	.7
73	.8
74	1.0
75	1.2
76	1.4
77	1.6
78	1.8
79	2.0
80	2.2
81	2.4
82	2.6
83	2.8
84	3.0
85	3.2
90	4.3

[1] Experimental values.

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[4] Procedures for Testing Soils for the Determination of the Subgrade Soil Constants, by A. M. Wintermyer, E. A. Willis, and R. C. Thoreen. PUBLIC ROADS, vol. 12, No. 8, October 1931.

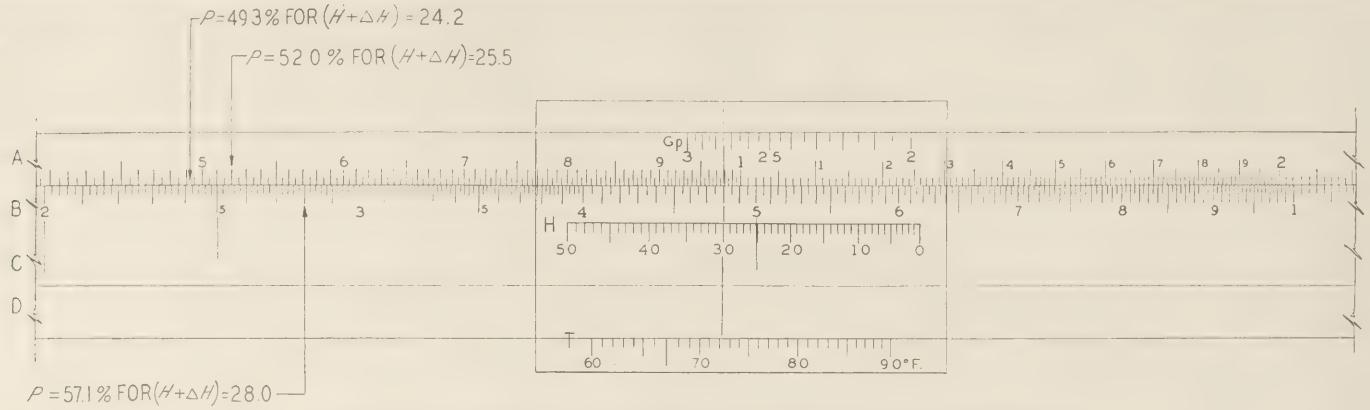

FIGURE 3.—SLIDE RULE SET FOR PERCENTAGE OF SOIL IN SUSPENSION.

TABLE 7.—*Specific gravity correction factors in formula for percentage of soil in suspension*

Specific gravity G	Specific gravity correction factor $f=\frac{2.65-1}{2.65}\times\frac{G}{G-1}$
2.0	1.242
2.1	1.187
2.2	1.141
2.3	1.101
2.4	1.067
2.5	1.038
2.6	1.012
2.65	1.000
2.7	.989
2.8	.969
2.9	.951
3.0	.934

Values of f are given in table 7. Marks for values of G are scribed above and opposite corresponding values of f on the A scale to make the G_p scale shown in figure 1. Thus, the mark for $G=3.0$ on the G_p scale is opposite a value of f of 0.934 on the A scale, $G=2.0$ is opposite 1.242 on the A scale, etc. The temperature correction is to be applied by mental arithmetic and to aid in this a table of values such as table 6 is fixed on the back of the slide rule or in any other convenient place. This completes the equipment.

To illustrate the method of computation, assume the specific gravity of the soil=2.75, the temperature=75° F., $W_0=48$ grams, and $H=26.8$, 24.3, 23.0, etc. As shown in figure 3, the indicator is moved to bring its index line to 2.75 on the G_p scale. The slide is moved to bring 48 on the B scale under the index line. The position of the slide remains thus set for the series of hydrometer readings. Referring to table 6 for values of T and ΔH, it is found that for $T=75°$ F., $\Delta H=1.2$. Opposite $H+\Delta H=26.8+1.2=28.0$ on the B scale, $P=57.1$ percent is read on the A scale as shown in figure 3. Similarly, opposite 24.3+1.2=25.5 on the B scale, 52.0 percent is read on the A scale as the value of P; opposite 24.2, $P=49.3$ percent, etc.

The slide rule method of computing the percentage of soil in suspension is further simplified when used in conjunction with the calculating board [3] devised by the Bureau for computing, correcting, and interpolating values for specific grain sizes. In this case, the temperature correction in grams per liter is taken care of by moving vertically the transparent paper on which the uncorrected hydrometer readings in grams per liter are plotted on a vertical scale. In this way, both the temperature correction table and mental arithmetic are eliminated.

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[3] Graphical Solution of the Data Furnished by the Hydrometer Method of Analysis, by E. A. Willis, F. A. Robeson, and C. M. Johnston. PUBLIC ROADS, vol. 12, No. 8, October 1931.

(Continued from page 12)

percent of the total aggregate passed the No. 10 sieve. The same should be true of plastic sand-clays that would be satisfactory as base-course materials without coarse aggregate.

The nonplastic materials raveled somewhat before the bituminous surface was applied and thorough compaction was difficult to obtain unless the material was kept very wet either by frequent sprinkling or by maintaining the ground water at a high elevation.

In general the materials having a plasticity index of 5 (section 2 of series 1 of the sand-clays and section 2 of series 1 of the sand-clay-gravels) were superior to either the nonplastic materials or the more plastic ones, both as to ease of compaction and resistance to displacement in the traffic tests.

The results of some of the early tests in this investigation were made available to the Committee on Materials of the American Association of State Highway Officials at the time it was considering requirements for soil and gravel base courses and were utilized in connection with the drafting of the specifications given in table 10.

TABLE 10.—*Specifications for soil and gravel base courses*

	Type B base courses			
	B–1, 1 inch maximum size		B–2, 2 inch maximum size	
	Minimum	Maximum	Minimum	Maximum
Percentage passing:				
2-inch sieve	--------	--------	--------	100
1½-inch sieve	--------	--------	70	100
1-inch sieve	--------	100	55	85
¾-inch sieve	70	100	50	80
⅜-inch sieve	50	80	40	70
No. 4 sieve	35	65	30	60
No. 10 sieve	25	50	20	50
No. 40 sieve	15	30	10	30
No. 200 sieve	5	15	5	15
Percentage of material finer than No. 40 sieve passing No. 200 sieve	--------	50	--------	50
Liquid limit (material finer than No. 40 sieve)	--------	25	--------	25
Plasticity index (material finer than No. 40 sieve)	--------	6	--------	6

Final analysis of the test data after completion of the entire test program indicated that the limits established are well drawn to insure that highly satisfactory base-course materials will be obtained. It was realized at the time the specifications were written that some fully satisfactory materials would be excluded.

Complete analysis of the test data indicates that if the amount of soil mortar in a well-graded sand-clay-gravel is low, the quality of the material depends largely on the grading of the coarse fraction and that the grading and plasticity of the soil mortar is of relatively less vital importance. Thus, for example, if a material fails to meet specification B–1 because less than 25 percent passes the No. 10 sieve, it is doubtful whether it should be classified as a sand-clay-gravel at all even though the plasticity index of the small amount of soil present might be quite high. It is believed that numerous materials of this type are likely to be encountered and that, provided they are well graded from the No. 10 sieve to the maximum size and that the aggregate particles are somewhat angular, they can be used successfully without applying such rigorous requirements to the character of the soil fraction as are set for the sand-clay-gravels. A special specification may be desirable to cover such materials.

Compaction and surface interlocking of such materials would be slow and somewhat difficult to obtain and the temptation would be great to add clay or other soil binder to hasten surface bonding. However, once compacted to a degree producing interlocking of the aggregate, and bonded at the top with a mixed or drag type of prime treatment, rolled to set the surface, they could be expected to provide a more satisfactory base structure than would be obtained by the addition of plastic soil binder in an attempt to bring these granular materials into conformity with the specifications for sand-clay-gravel base-course materials.

CONCLUSIONS

1. Control of grading is essential to insure satisfactory stability.
2. Control of plasticity index is essential, particularly when the aggregate contains as much as 40 percent of soil mortar.
3. As the amount of soil mortar decreases below 40 percent, the importance of the grading of the coarse material becomes relatively more important and the grading and plasticity index of the soil mortar becomes of relatively less vital importance.
4. Although there may be many instances where carefully mixed and placed aggregates having relatively low mortar contents would give satisfactory service even though the plasticity index of the soil mortar might be in excess of 6, the possibility of segregation and collection of the fine aggregate into rich spots or layers must not be overlooked and makes the limit of 6 for the plasticity index a desirable if not vitally necessary requirement.
5. A well-graded sand-clay-gravel material having a plasticity index of about 5 is to be preferred to absolutely nonplastic materials of comparable grading and is decidedly superior to those having appreciably higher plasticity indexes.
6. Thorough compaction of even the best plastic base-course materials to essentially the maximum density obtainable in the laboratory by the vibratory method of compaction is absolutely essential to prevent softening and loss of stability where water may reach the material after construction.
7. Thorough compaction of the plastic materials was obtained in the circular track tests by starting compaction operations with an excess of moisture of about 1.5 to 2 percent over the optimum as determined by the Proctor test on the portion of the aggregate passing the No. 10 sieve or, for the total sand-clay-gravel aggregate, sufficient moisture to fill the aggregate voids when compacted to the maximum obtainable density by vibration.
8. It is most important that compaction operations be continued during the drying out of the above-mentioned excess water since the combined action of compaction and drying is necessary to produce the required densities.
9. Some additional moisture may be required in handling plastic materials to provide for drying losses during mixing and leveling operations, but care should be taken not to surpass actual needs since any great excess of moisture will delay final compaction.
10. In connection with nonplastic materials, the term "optimum moisture content" has little or no significance. It is therefore not necessary to limit the amount of water used in mixing and compacting such materials since water drains out rapidly, making it difficult to maintain them in a wet enough condition to aid materially in obtaining compaction. The only precaution necessary is that softening of the subgrade shall not be caused by the excessive use of water.
11. Compaction should be as complete at the bottom of the base course as at the top, particularly with plastic materials, since even minor deficiencies in the compaction of plastic materials make them susceptible to softening and loss of stability when wet.
12. The tests on the materials of series 1, which contained from 47 to 53.5 percent of soil mortar, indicated that freezing and thawing would be likely to cause failure of the borderline material of section 4, the plasticity index of which was 11, and that serious damage might be done to section 3, with a plasticity index of 9, since the one cycle of freezing and thawing caused a marked increase in the rate of displacement under traffic in this section (see fig. 4). This is a further argument for placing a maximum limit on the plasticity index for base-course materials.
13. It might be desirable to promulgate a separate specification to cover essentially stone or gravel base-course materials having satisfactory gradings but very low soil-mortar contents to allow the use of such materials without too rigorous limitation of plasticity index. The design of such base courses would necessitate provision for a mixed type of prime using somewhat more viscous bituminous materials than are commonly used for the ordinary penetration prime treatment.

THE COVER PICTURE

Rounding cut slopes encourages vegetative growth and accomplishes the dual purpose of improving roadside appearance and preventing erosion along the Connecticut highway shown in the cover picture. Further flattening and rounding would have been desirable, but in this instance were prevented by limitations imposed by the right-of-way width. Establishing growth of native plants on cut slopes serves to reduce erosion and consequent clogging of drainage ditches, thereby reducing highway maintenance costs.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF FEBRUARY 28,1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 5,769,382	$ 2,600,520	174.4	$ 8,529,342	$ 4,252,875	343.0	$ 806,180	$ 402,485	22.0	$ 3,568,580
Arizona	2,046,153	1,529,291	109.0	1,341,336	930,543	57.8	376,056	232,676	7.8	2,036,457
Arkansas	1,152,857	1,138,638	81.4	3,467,312	3,463,658	212.4	529,044	526,119	34.9	1,865,756
California	9,322,768	5,103,695	207.5	5,322,952	2,866,205	80.8	1,486,000	792,749	37.7	4,897,534
Colorado	2,565,088	1,372,939	99.3	2,734,853	1,456,727	85.0	1,531,850	851,780	31.5	2,858,094
Connecticut	934,030	455,835	8.9	684,518	337,455	7.9				2,149,026
Delaware	485,437	241,521	14.1	708,131	349,289	9.9	259,491	125,600	6.6	1,625,207
Florida	2,046,100	1,020,204	47.6	3,208,138	1,604,069	57.5	618,200	309,100	13.0	3,781,441
Georgia	4,621,212	2,252,348	226.8	5,118,910	2,559,455	258.1	1,325,000	662,500	83.3	7,430,333
Idaho	2,089,523	1,214,155	200.7	1,189,537	710,407	38.9	270,262	161,091	10.9	2,174,894
Illinois	11,001,009	5,459,081	299.7	7,612,426	3,802,614	161.6	3,247,011	1,623,460	84.2	4,858,999
Indiana	5,587,556	2,743,351	146.5	2,798,314	1,399,157	51.6	2,580,951	1,238,090	63.7	4,129,102
Iowa	7,638,612	3,567,962	258.4	4,555,632	1,922,833	146.5	489,798	147,600	34.5	2,635,539
Kansas	5,044,710	2,510,360	708.5	4,202,257	2,101,103	192.0	3,165,218	1,575,609	166.9	4,692,076
Kentucky	5,592,733	2,776,123	209.3	2,743,030	1,371,515	59.0	1,117,168	558,782	33.3	3,883,951
Louisiana	1,294,187	646,891	38.2	11,144,987	2,656,864	31.7	1,479,276	634,892	27.1	3,229,166
Maine	2,797,885	1,394,536	65.5	1,570,121	785,059	32.8	174,108	87,054	1.4	1,015,391
Maryland	1,085,456	542,728	17.1	2,510,978	1,235,351	40.7	776,570	374,000	10.3	2,349,285
Massachusetts	1,870,824	935,409	9.0	2,953,970	1,476,526	19.4	1,233,099	612,765	15.5	3,295,441
Michigan	7,866,671	3,752,055	166.1	4,152,608	2,075,652	120.5	1,093,995	536,721	27.0	3,865,266
Minnesota	4,758,194	2,294,739	289.3	6,028,875	2,991,668	279.3	1,153,760	575,975	61.2	4,659,945
Mississippi	2,049,958	940,417	82.8	10,802,762	4,159,632	476.7	1,380,700	552,400	48.5	3,337,471
Missouri	5,731,742	2,730,036	151.9	2,868,298	1,405,166	66.8	5,000,559	2,375,530	223.2	4,871,311
Montana	1,658,740	932,323	83.6	826,978	464,810	17.6	994,424	559,348	69.9	5,906,459
Nebraska	3,472,047	1,684,635	329.6	5,453,601	2,749,345	411.1	4,027,832	1,906,864	377.9	2,888,027
Nevada	1,443,091	1,236,906	168.8	1,323,594	1,141,689	51.0	465,486	402,580	10.0	1,602,137
New Hampshire	983,828	487,160	22.4	382,110	190,095	3.3	93,802	46,900	1.4	1,635,822
New Jersey	1,897,135	939,155	16.7	2,497,376	1,246,963	15.9	1,513,280	755,810	14.5	2,860,028
New Mexico	2,034,273	1,239,748	241.8	2,153,263	1,380,102	85.7				2,006,595
New York	14,147,393	6,883,224	253.2	9,977,597	4,942,852	158.8	3,347,230	1,527,398	60.2	4,985,830
North Carolina	6,559,903	3,150,078	264.3	4,978,219	2,488,152	332.8	1,021,360	492,020	54.7	3,636,840
North Dakota	3,375,916	3,236,625	261.5	500,901	290,805	57.5	69,522	37,236	6.8	5,096,362
Ohio	8,337,363	4,082,883	99.0	7,235,262	3,608,602	72.8	2,502,440	1,190,920	27.0	8,758,868
Oklahoma	5,720,508	2,991,823	246.4	3,101,863	1,593,951	64.3	1,487,800	791,645	46.7	4,500,059
Oregon	3,154,227	1,849,620	110.7	1,524,478	930,767	83.5	810,717	494,470	39.0	2,791,357
Pennsylvania	8,432,467	4,174,025	140.6	7,652,531	3,807,110	78.3	3,791,468	1,744,007	31.4	5,627,630
Rhode Island	1,179,290	589,645	16.4	372,212	186,106	3.5	63,560	31,780	.6	1,516,518
South Carolina	4,841,632	2,134,948	249.2	3,074,433	1,377,876	92.3	278,191	133,400	11.1	2,493,886
South Dakota	1,928,842	1,080,884	245.7	4,674,676	2,585,190	441.5	339,070	187,490	27.8	4,182,927
Tennessee	5,454,830	2,699,117	176.7	2,802,829	1,402,136	42.8	1,305,780	652,890	42.8	5,475,339
Texas	12,315,146	6,090,670	803.1	13,549,227	6,686,521	611.7	3,792,062	1,765,950	244.3	8,485,063
Utah	1,063,013	740,744	102.1	2,139,223	1,517,650	73.4	109,720	78,320	4.2	1,605,990
Vermont	1,281,653	577,197	33.9	722,784	343,793	17.7	196,970	98,295	4.3	661,932
Virginia	5,951,973	2,973,806	205.5	2,940,176	1,466,528	89.0	849,440	424,135	10.5	2,169,747
Washington	4,011,591	2,090,017	99.6	2,679,151	1,402,216	35.8	537,730	282,400	3.0	2,023,120
West Virginia	1,772,403	1,273,366	64.6	1,296,682	649,266	26.5	715,470	357,735	25.4	3,091,790
Wisconsin	4,765,180	2,352,799	165.9	6,840,374	3,202,280	180.9	215,800	105,600	2.5	3,493,786
Wyoming	2,571,344	1,544,992	281.4	586,552	356,921	64.5	676,930	420,310	43.9	1,405,554
District of Columbia										487,500
Hawaii	821,861	408,514	18.0	845,010	414,380	9.3	303,340	149,310	7.7	1,546,517
Puerto Rico	189,737	92,320	4.4	1,502,199	747,055	30.2	217,822	107,520	6.8	774,980
TOTALS	202,717,473	104,760,058	8,317.1	187,882,588	93,086,984	5,981.6	59,821,542	29,701,311	2,218.9	170,920,928

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF FEBRUARY 28,1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 234,900	$ 117,450	18.4	$ 834,850	$ 412,050	38.6				$ 833,746
Arizona	321,282	204,457	20.6	140,213	98,773	15.5	$ 65,597	$ 47,235	6.2	519,527
Arkansas	13,126	6,563		268,515	266,169	25.8	231,550	230,808	30.3	615,955
California	1,319,726	752,403	87.3	822,633	456,223	52.1	745,703	361,702	14.7	846,581
Colorado	850,097	457,492	52.1	402,820	223,165	18.3	220,370	113,009	7.8	399,090
Connecticut	69,450	34,705	1.3	41,584	20,632	.2	201,480	71,130	3.0	285,414
Delaware	18,950	9,475	4.1	47,050	23,525	8.8	45,790	22,410	9.9	264,590
Florida				482,755	240,561	9.8	120,900	60,450	5.4	574,094
Georgia	297,712	139,781	39.7	629,686	314,843	78.2	120,360	60,180	16.6	1,120,199
Idaho	451,521	204,347	46.9	166,441	87,870	11.9	24,812	14,825	1.1	350,797
Illinois	1,622,533	809,530	139.9	1,386,732	639,366	71.5	384,500	183,750	28.0	1,002,676
Indiana	594,468	252,894	64.8	818,900	391,650	71.5	507,968	244,306	45.7	717,475
Iowa										1,679,807
Kansas	142,690	71,344	14.5	140,362	70,181	10.3	399,116	199,558	33.8	1,365,764
Kentucky	790,621	245,084	106.1	701,106	181,576	23.0	899,303	254,970	96.2	410,817
Louisiana	64,068	31,900	6.9	718,131	309,375	54.8	381,278	177,160	34.0	421,213
Maine	361,909	180,746	23.3	262,662	126,214	12.5	27,500	13,750	2.1	140,191
Maryland				145,174	67,987	11.2	220,800	82,855	14.2	384,839
Massachusetts				139,441	69,604	2.4	222,970	110,905	4.9	672,214
Michigan	409,561	203,281	37.0	684,304	341,402	42.2	553,500	269,800	29.1	1,173,005
Minnesota	280,091	131,160	42.2	581,324	288,618	42.9	232,968	116,484	19.6	1,248,943
Mississippi				299,000	149,500	23.8	44,700	22,350	16.9	979,016
Missouri	418,039	201,627	52.8	464,930	190,770	38.6	600,590	274,300	92.1	846,939
Montana				27,601	15,525					1,324,368
Nebraska	499,150	247,436	85.5	432,748	210,143	73.5	482,500	237,780	91.4	609,099
Nevada	424,798	354,271	68.8	120,241	104,184	15.5	26,563	23,035	1.6	205,756
New Hampshire	245,058	121,630	6.0	60,759	29,708	2.3				168,662
New Jersey	123,040	61,520	2.4	199,860	91,195	2.6	119,150	59,575	2.9	658,688
New Mexico	563,056	343,405	36.9	619,603	377,887	41.0				324,774
New York	2,311,517	1,131,920	166.3	1,899,000	949,500	99.6				1,007,964
North Carolina	630,222	314,580	74.8	924,144	462,050	74.3	125,500	58,130	18.0	595,623
North Dakota	51,622	27,362	9.0	169,910	90,999	26.1	42,770	22,907	8.2	875,809
Ohio	147,535	73,767	3.8	100,970	57,260	1.8	496,000	248,000	27.1	1,990,092
Oklahoma	249,090	131,417	29.8	213,642	113,676	13.1	602,040	297,148	32.4	990,263
Oregon	425,096	247,170	56.3	59,085	36,102	5.0	194,932	116,570	23.9	601,114
Pennsylvania	1,722,413	827,559	123.1	1,789,367	876,902	97.5	659,038	329,519	32.3	716,964
Rhode Island	66,840	33,420	3.5	162,675	81,314	4.8	74,070	37,035	.9	109,247
South Carolina	404,550	174,382	43.5	834,787	349,369	90.5	190,290	75,500	14.4	278,661
South Dakota				11,300	6,250					1,058,050
Tennessee	259,120	129,560	14.8	601,844	228,022	26.8	136,580	61,820	3.2	952,058
Texas	2,650,179	1,190,664	367.0	1,839,444	850,653	211.4	978,260	445,439	95.4	1,572,076
Utah	450,730	230,606	41.1	303,702	152,870	21.1	144,360	72,004	19.4	263,600
Vermont	238,385	109,790	13.8	90,306	45,153	4.0	43,300	20,500	.5	107,278
Virginia	571,647	246,135	61.5	705,620	340,343	48.5	163,862	81,931	24.0	496,316
Washington	549,807	286,426	63.7	509,591	268,196	23.4	312,037	163,900	19.0	246,606
West Virginia	245,806	122,025	21.4	117,096	58,548	6.2	36,200	18,100	2.1	513,306
Wisconsin	509,819	242,528	23.1	672,417	329,580	31.6	74,771	37,260	1.4	965,276
Wyoming	416,281	254,573	59.0	321,002	198,349	15.8	85,578	52,861	6.5	266,767
District of Columbia										73,125
Hawaii				56,250	28,125	2.4	135,550	67,775	3.5	224,100
Puerto Rico	224,621	110,876	11.3	131,604	64,530	8.8	65,450	32,135	2.1	112,459
TOTALS	22,241,126	11,067,261	2,144.3	23,153,181	11,386,487	1,611.5	11,440,556	5,490,861	941.8	34,160,993

U. S. GOVERNMENT PRINTING OFFICE: 1939

PUBLICATIONS *of the* BUREAU OF PUBLIC ROADS

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C. As his office is not connected with the Department and as the Department does not sell publications, please send no remittance to the United States Department of Agriculture.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1933. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1934. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1935. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1936. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1937. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1938. 10 cents.

HOUSE DOCUMENT NO. 462

Part 1 . . . Nonuniformity of State Motor-Vehicle Traffic Laws. 15 cents.

Part 2 . . . Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.

Part 3 . . . Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.

Part 4 . . . Official Inspection of Vehicles. 10 cents.

Part 5 . . . Case Histories of Fatal Highway Accidents. 10 cents.

Part 6 . . . The Accident-Prone Driver. 10 cents.

MISCELLANEOUS PUBLICATIONS

No. 76MP. .The Results of Physical Tests of Road-Building Rock. 10 cents.

No. 191MP . . Roadside Improvement. 10 cents.

No. 272MP . . Construction of Private Driveways. 10 cents.

No. 279MP . . Bibliography on Highway Lighting. 5 cents.

Highway Accidents. 10 cents.

The Taxation of Motor Vehicles in 1932. 35 cents.

Guides to Traffic Safety. 10 cents.

Federal Legislation and Rules and Regulations Relating to Highway Construction. 15 cents.

An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.

Highway Bond Calculations. 10 cents.

Transition Curves for Highways. 60 cents.

DEPARTMENT BULLETINS

No. 1279D. .Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.

No. 1486D. .Highway Bridge Location. 15 cents.

TECHNICAL BULLETINS

No. 55T. . .Highway Bridge Surveys. 20 cents.

No. 265T. . .Electrical Equipment on Movable Bridges. 35 cents.

Single copies of the following publications may be obtained from the Bureau of Public Roads upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS PUBLICATIONS

No. 296MP. . . .Bibliography on Highway Safety.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y. .Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

UNIFORM VEHICLE CODE

Act I.—Uniform Motor Vehicle Administration, Registration, Certificate of Title, and Antitheft Act.

Act II.—Uniform Motor Vehicle Operators' and Chauffeurs' License Act.

Act III.—Uniform Motor Vehicle Civil Liability Act.

Act IV.—Uniform Motor Vehicle Safety Responsibility Act.

Act V.—Uniform Act Regulating Traffic on Highways.

Model Traffic Ordinances.

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U. S. Bureau of Public Roads, Willard Building, Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF FEBRUARY 28,1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
			NUMBER					NUMBER					NUMBER			
	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama	$ 243,609	$ 243,410	6		4	$ 1,182,479	$ 1,180,624	13	1	1	$ 55,400	$ 55,400	2		2	$ 899,107
Arizona						203,898	201,694	3			27,976	27,976				526,004
Arkansas	279,639	278,482	7			415,591	415,311	8			104,053	104,053	2			1,304,654
California	669,417	669,417	2	2		1,338,720	1,338,095	8	1		1,028,262	1,027,330	4			1,394,223
Colorado	32,559	29,328	1		2	266,218	266,218	4			344,269	340,508	2		19	903,473
Connecticut						18,930	12,665									998,900
Delaware	39,000	39,000			13						47,420	47,420	2		10	504,830
Florida						445,510	445,510	3			75,900	75,900	1			1,161,858
Georgia						365,090	365,090	6			86,460	86,460	2		1	2,443,120
Idaho	174,973	174,800	4			280,682	249,386	4			131,898	120,500	1			439,963
Illinois	369,500	369,500	2		1	2,160,925	2,160,925	14	2	60	1,057,740	989,740	8		16	2,715,261
Indiana	690,166	599,203	3	5		894,563	867,663	3	1	90	164,640	164,640		1	8	1,297,142
Iowa	1,034,174	980,296	10	2	19	208,821	196,400	3		1	189,213	174,408	8		1	1,761,925
Kansas	457,727	457,622	7		4	1,035,551	1,035,551	13		1	164,005	164,005	2		8	1,422,289
Kentucky	145,000	145,000	1			344,297	344,297	4	1	31	462,882	462,882	6	3		1,218,712
Louisiana						447,201	440,458	4			429,826	398,090	10			1,049,379
Maine	48,590	48,590	2			332,396	332,396	3	2		69,630	69,630	1		1	375,778
Maryland						72,188	72,188	1			18,200	18,200			4	1,137,108
Massachusetts	54,710	54,710		1		176,639	176,028	1	1		386,385	385,425	1	3		1,705,411
Michigan	930,783	924,372	8	1	35	653,796	653,796	6	2	10	114,000	114,000				2,242,164
Minnesota	39,556	39,556		1	1	760,185	759,864	3	5		18,297	18,297			3	2,152,975
Mississippi	70,800	70,800	1			667,960	667,960	8			127,500	127,500	1	1		1,028,541
Missouri	297,091	295,552	4	1		436,130	436,130	2			703,130	703,130	3	3		2,186,625
Montana	355,586	350,704	4			634,520	634,520	6			235,773	235,773	3			364,726
Nebraska	150,374	150,374	4			729,307	729,307	15			757,668	757,668	18		33	474,750
Nevada	149,761	149,761		3	2	202,591	202,591	2		1	15,478	15,478			6	188,743
New Hampshire	70,205	69,765		1	2	87,856	87,797	5		1						433,688
New Jersey	116,891	111,665	1	1		229,856	229,856	1	1	2						2,018,350
New Mexico	168,984	168,984	4	1		118,994	118,994	3								730,470
New York	992,501	991,800	4	3	2	1,816,551	1,792,101	5	8		394,130	315,180		3	1	5,006,797
North Carolina	121,550	121,550	1	1	1	887,900	855,200	6	5		707,680	705,280	4	2	26	1,263,341
North Dakota	197,294	196,341		1		651,738	603,336	4	1							1,088,708
Ohio						478,020	478,020	6			476,990	435,990	5	1	1	4,149,011
Oklahoma						203,223	169,223	2			190,305	190,305			55	2,377,022
Oregon	308,391	307,742	1	2		384,601	250,243	1			167,455	167,455	2			484,121
Pennsylvania	213,129	197,923	2			1,039,656	827,757	2			864,536	864,536	3			4,970,935
Rhode Island						335,019	335,019	1	2		103,772	103,772		1		152,459
South Carolina	33,376	33,376		1		342,323	287,357	15	1		180,175	180,175	2		40	1,281,944
South Dakota	118,596	118,596	2		9	282,188	282,188	3	2		16,910	16,910	2		2	1,171,221
Tennessee	2,660	2,660			1	121,490	121,490		2		688,910	688,910	4		8	1,452,160
Texas	34,033	33,377	2			1,709,704	1,679,202	17	6		991,712	959,420	10	1		3,759,979
Utah	101,648	101,648	2		4	47,359	47,359	2			146,200	146,200			57	407,092
Vermont	237,610	232,253	6	2	6	7,406	7,406				23,000	23,000			7	315,293
Virginia	330,059	330,059	13	1		398,070	398,070	7	1		495,511	387,861	3	2	24	1,056,673
Washington	247,816	244,475	2	3	2	730,308	728,897	9	1		269,115	269,115	2		13	443,248
West Virginia	225,190	224,170	1		3	308,341	292,581	3			31,400	31,400	2		3	1,036,663
Wisconsin	215,236	214,831	3			1,186,812	1,145,988	11			4,917	4,917			1	1,593,847
Wyoming	164,200	164,200		2	4	10,150	10,150				214,610	135,190	1	1	7	499,324
District of Columbia						30,215	30,215		1							392,716
Hawaii						201,200	201,200	3	1		30,460	30,460	1			359,590
Puerto Rico						214,569	213,370	4			73,009	72,439	4			594,567
TOTALS	10,132,384	9,935,892	110	35	115	26,097,737	25,377,666	247	48	198	12,886,802	12,412,928	122	22	357	68,936,880