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GENERAL VIEW OF SLAB IMPACT TESTS

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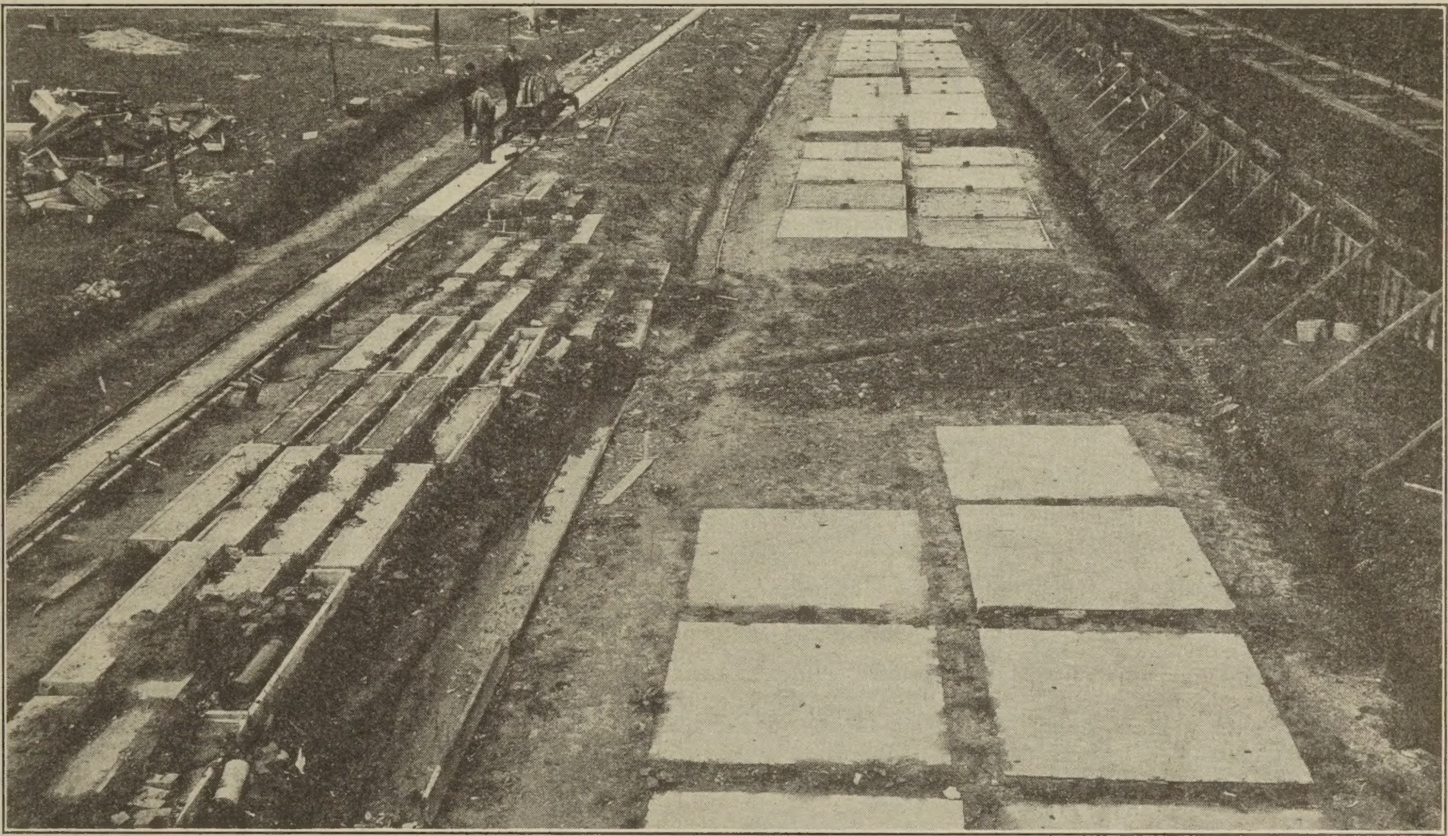
TESTS OF IMPACT ON PAVEMENTS BY THE BUREAU OF PUBLIC ROADS

By C. A. HOGENTOGLER, Highway Engineer, Bureau of Public Roads

The first of a series of two articles.



GENERAL VIEW OF SLABS. WATERED DITCHES IN FOREGROUND; DRY DITCHES IN BACKGROUND. TEST BEAMS AT THE LEFT.

FOR the intelligent selection of a road surface there must be known (1) the character and magnitude of the loads to be supported, (2) the condition of support offered by the subgrade and (3) the resistance of various kinds of pavements under the required conditions of loading and support. Intelligent selection differs from design in that the latter involves for roads as well as other engineering structures, investigations of the stresses which are developed in the materials comprising the structure and a determination of the resistance of these materials to the given stresses. While the ultimate aim of all highway research is to secure such data as will permit the rational design of road surfaces, it must be realized that considerable time will elapse before the information derived from investigations of this kind can be made available for use and that highway construction can not be postponed until such information is available. The U. S. Bureau of Public Roads, realizing the extreme need of immediate information, inaugurated three projects the purpose of which was to make available immediately, information which would help the highway engineer to make a rational selection of pavements.

From the first project, involving a study of impact forces produced by motor trucks,[1] it was hoped to determine to some extent the magnitude and character of the forces delivered to a road by motor truck wheels. The second project, that of impact tests on road slabs, was designed to throw light on the behavior and resistance of various types of pavements when subjected to forces similar to those produced by heavy motor trucks. The third project, an investigation of subgrades, was undertaken for the purpose of determining the conditions of support that can be expected to be offered to the road surface by the subgrade. The present paper concerns only project No. 2, the impact tests on slabs, and gives the results obtained from observations made for the purpose of determining the resistance of the various types of pavements to impact forces similar to those produced by the wheels of heavily loaded motor trucks, and while its purpose is principally to help in the selection, there is also included information which might assist in the design of pavements.

[1] The Motor Truck Impact Tests of the Bureau of Public Roads, E. B. Smith, Public Roads, Vol. 3, No. 35, March, 1921.

TABLE 1–A.—*Details of test sections laid on wet subgrade.*

Slab No.	Base.			Cushion.		Surface.			Joint filler.	
	Thickness.	Material.	Date laid.	Thickness.	Material.	Thickness.	Material.	Date laid.	Material.	Date poured.
	Inches.		1919.	*Inches.*		*Inches.*		1919.		1919.
1	12	Macadam	July 3	1	Screenings	4	Wire cut lug brick	July 3	Cement grout 1:1	July 3
2	4	1:3:6 concrete	May 20	½	Tar-sand	4	do	do	Tar sand 1:1	July 9
3	6	Macadam	June 25	1	Screenings	4	do	June 25	Cement grout 1:1	June 25
4	4	1:3:6 concrete	May 20	1	Sand-cement 4:1	3½	Vert. fiber brick	June 16	Asphalt	June 17
5	6	do	do	1	Sand	3½	do	June 14	do	Do.
6	4	do	do	1	do	3½	do	do	do	Do.
7	6	do	do	1	Sand-cement 4:1	4	Wire cut lug brick	June 12	Cement grout 1:1	June 12
8	4	do	do	1	do	4	do	do	do	Do.
9	6	do	do	1	Sand	4	do	June 11	do	June 11
10	6	do	do	1	Sand-cement 4:1	3½	Vert. fiber brick	June 16	Asphalt	June 17
11	6	do	do	1	Sand	4	Wire cut lug brick	June 10	Cement grout 1:1	June 10
12	4	do	do	1	do	4	do	do	do	Do.
13						10	1:1½:3 concrete	Mar. 29		
14						8	do	do		
15						6	do	do		
16						6	do	do		
17						4	do	do		
18						2	do	do		
19	6	1:3:6 Concrete	June 19							
20	3	do	June 22	¼	Sand-cement 3:1	3	Wire cut lug brick	June 22	Cement grout 1:1	June 22
21	4	do	do	¼	do	3	do	do	do	Do.
22	2	do	June 23	¼	do	4	do	June 23	do	June 23
23	6	do	do	¼	do	4	do	June 22	do	June 22
24	1	do	do	¼	do	4	do	June 23	do	June 23
25	4	do	do	¼	do	4	do	do	do	Do.

TABLE 1–B.—*Details of test sections laid on dry subgrade.*

Slab No.	Base.			Cushion.		Surface.			Joint filler.	
	Thickness.	Material.	Date laid.	Thickness.	Material.	Thickness.	Material.	Date laid.	Material.	Date poured
	Inches.		1919.	*Inches.*		*Inches.*		1919.		1919.
101	6	1:3:6 concrete	May 23	1	Sand	3½	Vert. fiber brick	June 13	Asphalt	June 17
102	4	do	do	1	Screenings	4	Wire-cut lug brick	June 17	Cement grout	Do.
103	6	do	do	1	Sand-cement 4:1	3½	Vert. fiber brick	June 13	Asphalt	June 16
104	4	do	do	1	Screenings	3½	do	June 16	do	June 17
105	6	do	do	1	Sand-cement 4:1	4	Wire-cut lug brick	June 13	Cement grout 1:1	June 13
106	4	do	do	1	do	4	do	June 12	do	June 12
107	6	do	do	1	Sand	4	do	June 11	do	June 11
108	4	do	do	1	do	4	do	do	do	Do.
109						10	1:1½:3 concrete	Mar. 25		
110						8	do	do		
111						6	do	do		
112						6	do	Mar. 29		
113						4	do	Mar. 25		
114	6	1:3:6 concrete	June 17	1	Screenings	4	Wire-cut lug brick	June 18	Cement grout 1:1	June 18
115						2	1:1½:3 concrete	Mar. 29		
116	6	1:3:6 concrete	June 17	½	Tar-sand	4	Wire-cut lug brick	July 8, 12	Tar-sand 1:1	July 9, 12
117	6	do	May 24	1	Screenings	3½	Vert. fiber brick	June 16	Asphalt	June 16
118	4	do	June 17	¼	Sand-cement, 3:1	3	Wire-cut lug brick	June 17	Cement grout, 1:1	June 17
119	3	do	do	¼	do	3	do	do	do	Do.
120	6	do	June 18	¼	do	4	Repressed brick	June 18	do	June 18
121	4	do	do	¼	do	4	do	do	do	Do.
122	6	do	June 19	¼	do	3½	Vert. fiber brick	June 19	do	June 19
123	4	do	do	¼	do	3½	do	do	do	Do.
124	6	do	do							
125				1	Screenings	4	Wire-cut lug brick	do	Cement grout 1:1	Do.
126	6	1:3:6 concrete	June 20	¼	Sand cement, 3:1	4	do	June 20	do	June 20
127	1	do	do	¼	do	4	do	do	do	Do.
128	4	do	do	¼	do	4	do	do	do	Do.
129	2	do	do	¼	do	4	do	do	do	Do.
130	12	Macadam	July 3	1	Screenings	4	do		do	
131	6	do	June 25	1	do	4	do		do	

DESCRIPTION OF TEST SLABS.

For the experiment there were constructed at the Arlington (Va.) Experimental Farm 56 7-foot by 7-foot sections of standard types of pavements. This series of slabs, as detailed in Tables 1–A and 1–B, was comprised of concrete, monolithic, semimonolithic, bituminous, and grout-filled brick with sand and screening cushions on concrete and macadam bases.

The slabs were constructed in two sections with ditches surrounding each section. In order to determine the effect of moisture in the subgrade the ditch around one section was kept filled with water at all times, for the purpose of effecting an extremely wet condition of the subgrade; while the ditch around the remaining slabs was used to keep the subgrade as dry as possible. As the majority of the slabs in the dry section were duplicated in the wet section this arrangement permitted a direct comparison under the two conditions. To insure a natural condition of the subgrade the top layer of soil was removed, after which the earth was carefully graded by cutting to the desired elevation. There were no fills and there was no compacting by tamping.

On the sub-bases thus prepared the concrete, which was machine mixed, was poured, thoroughly tamped, and finished with a wooden float. After final set the slabs were cured by covering for two weeks with a layer of wet earth. For the concrete surfaces a 1 : 1½ : 3 mix was used, while for the bases the mix was 1 : 3 : 6.

TABLE 2.—*Test of sand used as concrete aggregate.*

Source of material: Potomac River, Washington, D. C.

Mechanical analysis:	Per cent.
Retained on ¼-inch screen	....
Passing ¼-inch, retained on 10-mesh	15. 2
Passing 10-mesh, retained on 20-mesh	12. 4
Passing 20-mesh, retained on 30-mesh	14. 0
Passing 30-mesh, retained on 40-mesh	19. 2
Passing 40-mesh, retained on 50-mesh	11. 6
Passing 50-mesh, retained on 80-mesh	17. 6
Passing 80-mesh, retained on 100-mesh	1. 6
Passing 100-mesh, retained on 200-mesh	4. 4
Passing 200-mesh	4. 0
Total	100. 0
Loss by washing (silt and clay)	2. 4

Tensile strength (cement-sand briquets, 1 : 3):

Standard Ottawa sand.		Sample sand.	
7 days.	28 days.	7 days.	28 days.
250	280	285	365
240	320	285	335
245	270	285	350
[1] 245	[1] 290	[1] 285	[1] 350

[1] Average.

Strength ratio (7 days) 116.3 per cent.

Strength ratio (28 days) 120.6 per cent.

Character of material: Sample consists essentially of angular quartz sand containing some chert and very little clay.

TABLE 3.—*Test of sand for grout.*

Source of material: Washington, D. C.

Mechanical analysis:	Per cent.
Retained on ¼-inch screen	0. 0
Passing ¼-inch, retained on 10-mesh	1. 0
Passing 10-mesh, retained on 20-mesh	12. 6
Passing 20-mesh, retained on 30 mesh	18. 6
Passing 30-mesh, retained on 40-mesh	25. 8
Passing 40-mesh, retained on 50-mesh	13. 6
Passing 50-mesh, retained on 80-mesh	16. 2
Passing 80-mesh, retained on 100-mesh	1. 4
Passing 100-mesh, retained on 200 mesh	4. 6
Passing 200-mesh	6. 2
Total	100. 0
Loss by washing (silt and clay)	4. 0

Tensile strength (cement-sand briquets, 1: 3), 7 days:

Standard Ottawa sand.	Sample sand.
285	230
265	235
285	245
[1] 278	[1] 237

[1] Average.

Strength ratio, 85.3 per cent.

Character of material: Sample consists essentially of angular quartz sand stained by iron oxide.

TABLE 4.—*Test of gravel for concrete aggregates.*

Source of material: Washington, D. C.

Mechanical analysis.

Sand:	Per cent.
Retained on ¼-inch screen	86. 5
Passing ¼-inch, retained on 10-mesh	11. 9
Passing 10-mesh, retained on 20-mesh	. 2
Passing 20-mesh, retained on 30-mesh	. 1
Passing 30-mesh, retained on 40-mesh	. 1
Passing 40-mesh, retained on 50-mesh	....
Passing 50-mesh, retained on 80-mesh	. 2
Passing 80-mesh, retained on 100-mesh	. 1
Passing 100-mesh, retained on 200-mesh	. 1
Passing 200-mesh	. 8
Total	100. 0
Gravel:	
Retained on 3-inch screen	....
Passing 3-inch, retained on 2½-inch screen	....
Passing 2½-inch, retained on 2-inch screen	....
Passing 2-inch, retained on 1½-inch screen	....
Passing 1½-inch, retained on 1-inch screen	2. 9
Passing 1-inch, retained on ¾-inch screen	6. 8
Passing ¾-inch, retained on ½-inch screen	29. 6
Passing ½-inch, retained on ¼-inch screen	47. 2
Passing ¼-inch screen	13. 5
Total	100. 0

Loss by washing (silt and clay) 0.75 per cent.

Character of material: Sample consists essentially of subangular fragments of quartz with some chert and sandstone.

TABLE 5.—*Analysis of refined coal tar filler.*

General characteristics: Semisolid.	
Water (per cent)	1. 5
Specific gravity, 25° C./25° C	1. 2389
Float test, 50° C. (seconds)	260
Total bitumen soluble in carbon disulphide (per cent)	81. 5
Free carbon, organic matter insoluble (per cent)	18. 2
Inorganic matter insoluble (per cent)	0. 3

Distillation:

Fractions.	Character.	Per cent by volume.	Per cent by weight.
170° C.	Liquid	2. 0	1. 02
170° C. to 235° C.	do.	1. 5	0. 97
235° C. to 270° C.	do.	4. 0	2. 62
270° C. to 300° C.	½ solid	4. 0	2. 65
Residue	Soft pitch	88. 5	92. 58
		100. 0	99. 84

TABLE 6.—*Analysis of oil-asphalt filler.*

General characteristics: Semisolid.	
Specific gravity, 25° C./25° C	1. 026
Flash point (° C.)	245
Penetration, 0° C. 200 grams, 60 seconds	22
Penetration, 25° C. 100 grams, 5 seconds	35
Melting point (° C.)	69
Loss, 163° C., 5 hours (per cent)	0. 042
Characteristics of residue: Smooth.	
Consistency of residue—Penetration, 25° C., 100 grams, 5 seconds	25
Total bitumen (soluble in carbon disulphide) (per cent)	99. 8
Organic matter insoluble (per cent)	0. 2
Inorganic matter insoluble (per cent)	0. 0

Tables 2 to 6, inclusive, show the results of tests of the sand and gravel used for aggregate and of the sand, tar, and asphalt used for fillers. In the monolithic sections a three-sixteenths inch sand-cement dry 1:1 mortar was

IMPACT MACHINE IN POSITION OVER A SLAB.

placed on the green base and leveled for receiving the brick. After the brick were laid, tamped, and sprinkled, the cement grout filler which was mixed by hand in a box was applied to the surface with buckets and spread by means of a broom and squeegee until all joints were filled, when the excess filler was pushed off the sides of the slabs. In the monolithic slabs the construction was begun and completed the same day. The semi-monolithic construction differed from the above only in the detail that a 1-inch instead of a three-sixteenth-inch layer of dry mortar was used and this mortar was not laid on the base while it was green. On the bituminous filled sections, the hot filler was poured into the joints by means of a pouring pot with a spout as soon as the bricks were laid and rolled on the different cushions.

The mastic filler was made of tar mixed with hot sand, in proportions of 1:1 by volume, and for the mastic cushion the tar was mixed with hot sand in the proportion of 1 gallon to 1 cubic foot. The analyses of the tar and asphalt used as fillers and in the mastic are shown in Tables 5 and 6. The macadam bases were constructed by means of a hand roller and heavy tampers. After the maximum compaction was secured the 1-inch screening cushions were spread and leveled and the brick tops were laid in a manner similar to those on the concrete bases.

During the construction, test beams similar in material and thickness to the slabs and 13 inches wide by 7 feet long were made, and 6-inch by 12-inch compression test cylinders, were made to represent the concretes used for bases and surfaces. It was expected that the tests on the beams would supply information in regard to the elasticity and moduli of rupture of the different types when subjected to static loads, and also afford a means of comparing the effects produced by static and impact forces. Tests of the cylinders will make possible a comparison between compressive strength and resistance to impact. The beams and cylinders were cured in the same manner as the slabs, and it was intended that both should be tested at the same time.

DESCRIPTION OF THE IMPACT MACHINE.

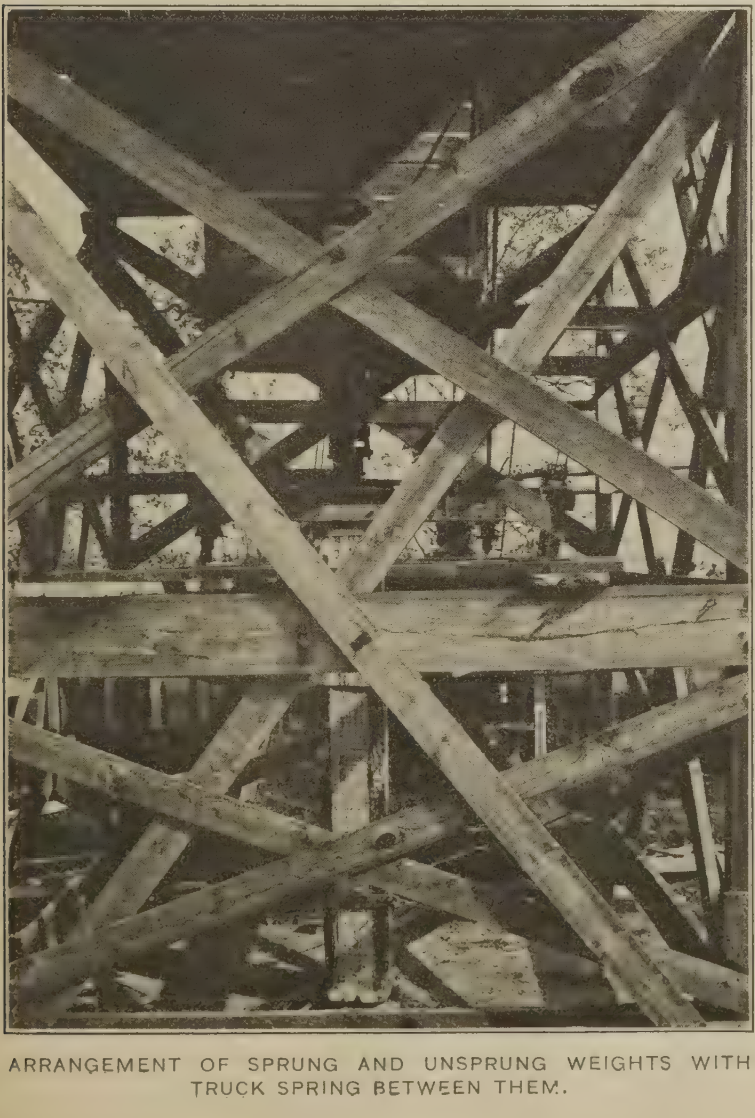
A special machine was designed and built for the purpose of delivering impact blows to the road slabs. The paramount idea controlling the design of this apparatus was that it should deliver a blow, the effect of which would be exactly the same as that caused by the dropping of a wheel of a heavy motor truck. To satisfy this condition it was deemed essential that the spring, the weights above and below it, and the tire or cushion be identical with those found on trucks. The machine as finally constructed consisted essentially of a loaded box riding on a 5½-ton spring which in turn was supported by a loaded frame or plunger on the bottom of which was a double 2-inch by 6-inch solid rubber tire. The box and plunger representing the sprung and unsprung weights, respectively, could be so loaded as to represent a truck of any size. By means of a motor, gears, and cam, this plunger or unsprung weight carrying the spring and sprung weight could be lifted and dropped from any height so that the effect produced was identical with that of a truck dropping from one level to another, dropping into a hole or falling to the pavement after striking an obstruction. The plunger was lifted and dropped 6 times per minute. The illustration on page 7 gives a close view of the apparatus showing, at the top, the box representing the sprung weight supported on the spring which rests on the plunger, while at the bottom can be seen the straps and rods which serve as guides for the plunger. Above is a view of the apparatus in position for testing over a slab. For the tests described in this article the machine was loaded to represent a 5-ton truck having 1,800 and 6,000 pounds, respectively, for unsprung and sprung weights.

A specially designed apparatus, supported independent of the impact machine, autographically recorded space-time curves, showing the movements of sprung and unsprung weights, as well as the vibrations of the slabs under impact blows. This apparatus is shown on page 7. These records, which are the chief source of information on the impact blows, will be described and discussed later. An enlargement of a typical record is shown on page 8.

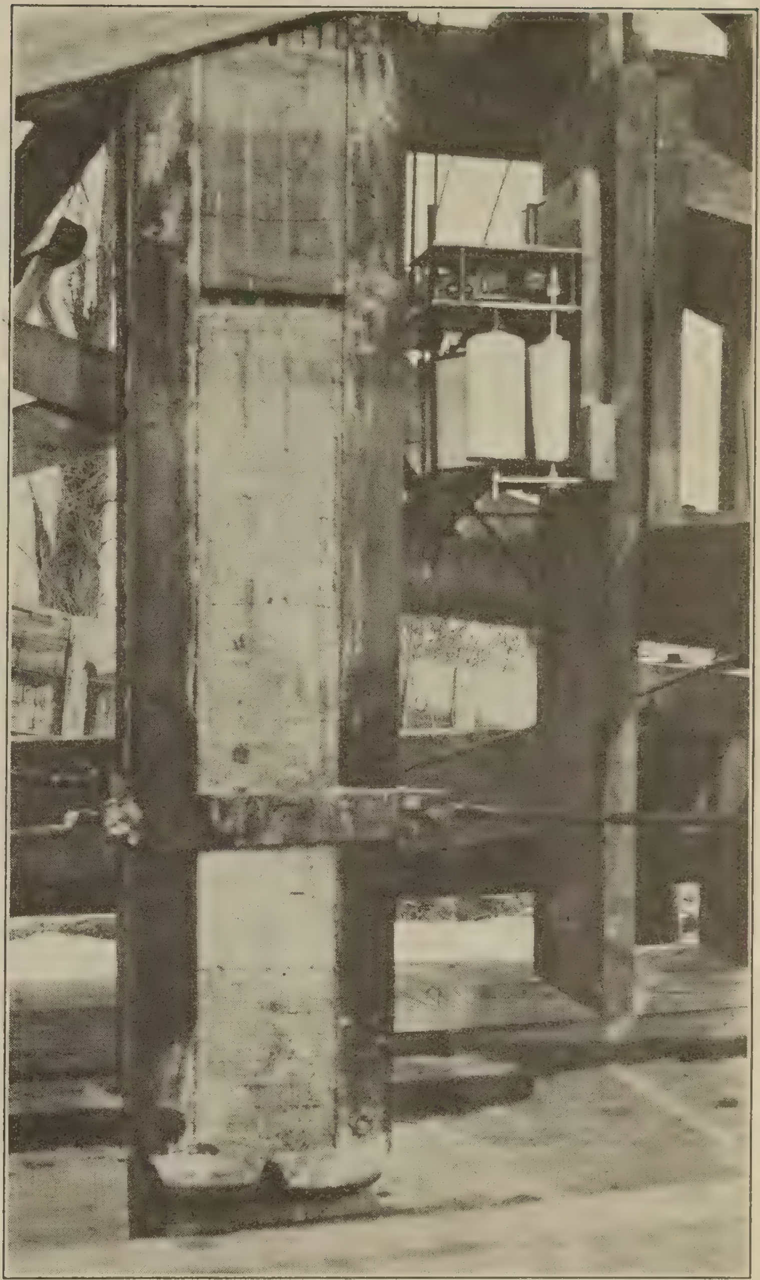
METHOD OF DETERMINING BEARING POWER OF SUBGRADE.

Knowing that the resistance of a pavement is more or less dependent upon the support offered by the subgrade it was desired in connection with the tests on slabs to secure information on the relative resistance to impact blows offered by the subgrades under the various slabs so that the behavior of the slabs under test might be more intelligently interpreted. For securing this information the deformations of the subgrade caused by blows from a small impact device were taken as an indication of the supporting value of the soil. This impact device consists of a steel rod and footing and a steel cylinder, riding on the rod, which can be dropped from any height, and thus deliver a blow to the soil through the footing. The rod, footing, and cylinder weigh approximately 10 pounds, and the footing has an area of about 15 square inches. This device is shown in the illustrations on page 8.

At a point about the middle of each side of the slab under test, the soil was cleared away to the level of the top of the subgrade after which the footing was placed on this level, care being taken to secure uniform bearing. The movable weight or cylinder was then dropped from a height of 3 feet, and the penetration was measured by means of an engineer's scale. Measurements were recorded for every drop up to the tenth, every second drop between the tenth and twentieth, every fourth drop between the twentieth and fortieth, and after the fitieth drop. After similar observations had been made on each of the four sides of the slab the data obtained were plotted on cross-section paper using



ARRANGEMENT OF SPRUNG AND UNSPRUNG WEIGHTS WITH TRUCK SPRING BETWEEN THEM.

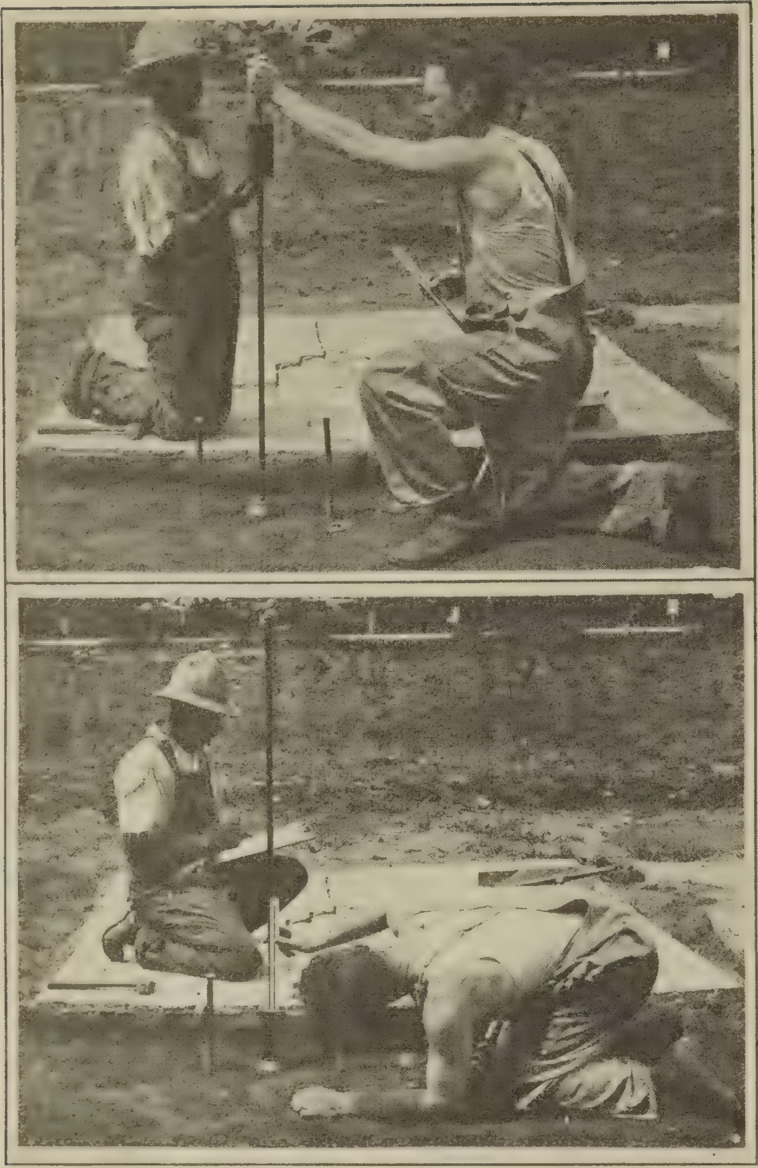


THE UNSPRUNG WEIGHT OR PLUNGER AND AUTOGRAPHIC RECORDING DEVICE.

penetration in inches and number of drops as coordinates. From the four curves thus obtained the record was completed by drawing a curve representing the average of the four. A typical record is shown in fig. 1. Since it is desirable to know the relative bearing power of the soil throughout the time of test, the length of test and change of weather at times necessitated making several determinations.

DETERMINATIONS OF MOISTURE CONTENT OF SOILS.

In connection with the bearing power tests and at the same locations, samples of soil were taken for determining the moisture content. Four samples were taken at each point with a soil auger $1\frac{3}{8}$ inches in diameter. The first sample was taken by forcing the auger down to a depth of 6 inches as indicated by a mark on the stem. The auger was then pulled up without turning, and the soil on it was pulverized or broken up and placed in a pint-size, glass fruit jar and sealed; the point, depth, and jar number being recorded. The



VIEWS SHOWING APPARATUS AND METHOD OF DETERMINING BEARING POWER OF SUBGRADE UNDER IMPACT BLOWS.

hole from which the sample was taken was then cleaned out thoroughly and the auger run down to a depth of 12 inches and a similar sample taken. Additional samples were taken at depths of 18 and 24 inches at each point.

The samples were then weighed in the jars without tops or rubber gaskets to the nearest 0.1 gram and were then placed in an electric oven where they were heated for 24 hours at a temperature of about 120°C. It has been found that this will dry out the ordinary sample weighing 200 or 300 grams, and that tests show no loss of weight on further heating. After drying, the jars were again weighed as soon as they were cool enough to handle. The weights of the empty jars were kept on record so that the moisture content could be computed as soon as the dry weights were obtained.

The average of the contents shown by the 6 samples was assumed to represent the general moisture condition of the subgrade. More than one series of tests for moisture were made on slabs when length of test or weather conditions warranted.

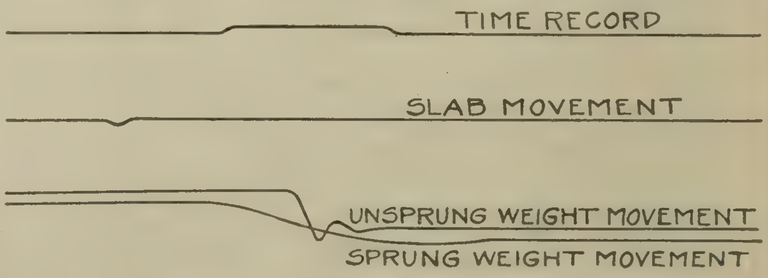
METHOD OF DELIVERING IMPACT BLOWS.

In preparing to deliver impact blows the first step was to take a set of initial levels over the surface of the slab to be tested. The machine was then set up over the center of the slab and the frame raised or lowered by means of a screw jack, so as to allow a one-eighth inch drop. A space-time curve was taken of the first 5 drops at this height, after which the blows were continued until 250 had been delivered. A new elevation was then taken on the center of the slab, and the machine was again set in motion for 250 more blows at the same height, taking a space-time curve for the first 5 drops. After the five-hundredth blow levels were again taken on all points of the slab as described under "surface readings," after which the machine was set to operate at a height three-eighths inch greater, and the operations of delivering the blows and leveling were repeated as for the first setting of the machine.

After 750, 1,250, 1,750 blows, etc., levels were taken only at the center points of the slabs; after 1,000, 1,500, 2,000 blows, etc., they were taken on all points as described for the five-hundredth blow. After each 500 blows the height of fall was increased three-eights inch, and the same setting of the machine was maintained for 500 blows. Thus at the beginning of the test and after 500, 1,000, 1,500, 2,000, 2,500, and 3,000 blows the height of fall was $\frac{1}{8}$, $\frac{1}{2}$, $\frac{7}{8}$, $1\frac{1}{4}$, $1\frac{5}{8}$, 2, and $2\frac{3}{8}$ inches respectively. Slabs which did not fail before 3,000 blows were given an additional 3,000 blows at the $2\frac{3}{8}$-inch height; and if failure had not occurred as a result of these additional blows the effort to break them was abandoned. If the settlement of the slab after the first 500 blows was equal to or greater than three-eights inch, the drop was not increased for the second 500 blows. A center settlement of this amount generally indicated the beginning of failure.

AUTOGRAPHIC AND PHOTOGRAPHIC RECORDS.

The autographic space-time curves which were taken of the first 5 blows in each series of 500 and of the 5 blows succeeding the two hundred and fiftieth, were



A TYPICAL AUTOGRAPHIC RECORD.

taken for the purpose of securing information in regard to the behavior of the different factors influencing the force of the impact blow. Because of the vibration caused by the blow of the plunger the apparatus for securing the curves was mounted on a frame support which was entirely independent of the impact apparatus. The records were made by 4 brass points bearing against silicated paper which moved horizontally over a 5-inch drum at a rate recorded by means of an instrument designed to break electrical contact every second and thus cause a movement of the time-recording point. The other 3 points trace the movements of the unsprung weight, the sprung weight and the slab vibration under the blow. These curves give all information concerning the force of the blow, the height of fall, the deformation of cushions, the relation of the movements of sprung and unsprung weight, etc. The illustration on page 8 shows a typical autographic record.

For the purpose of comparing the behavior of the different slabs under test, photographs of both the surface and the base with the top course removed were taken immediately after the tests were completed.

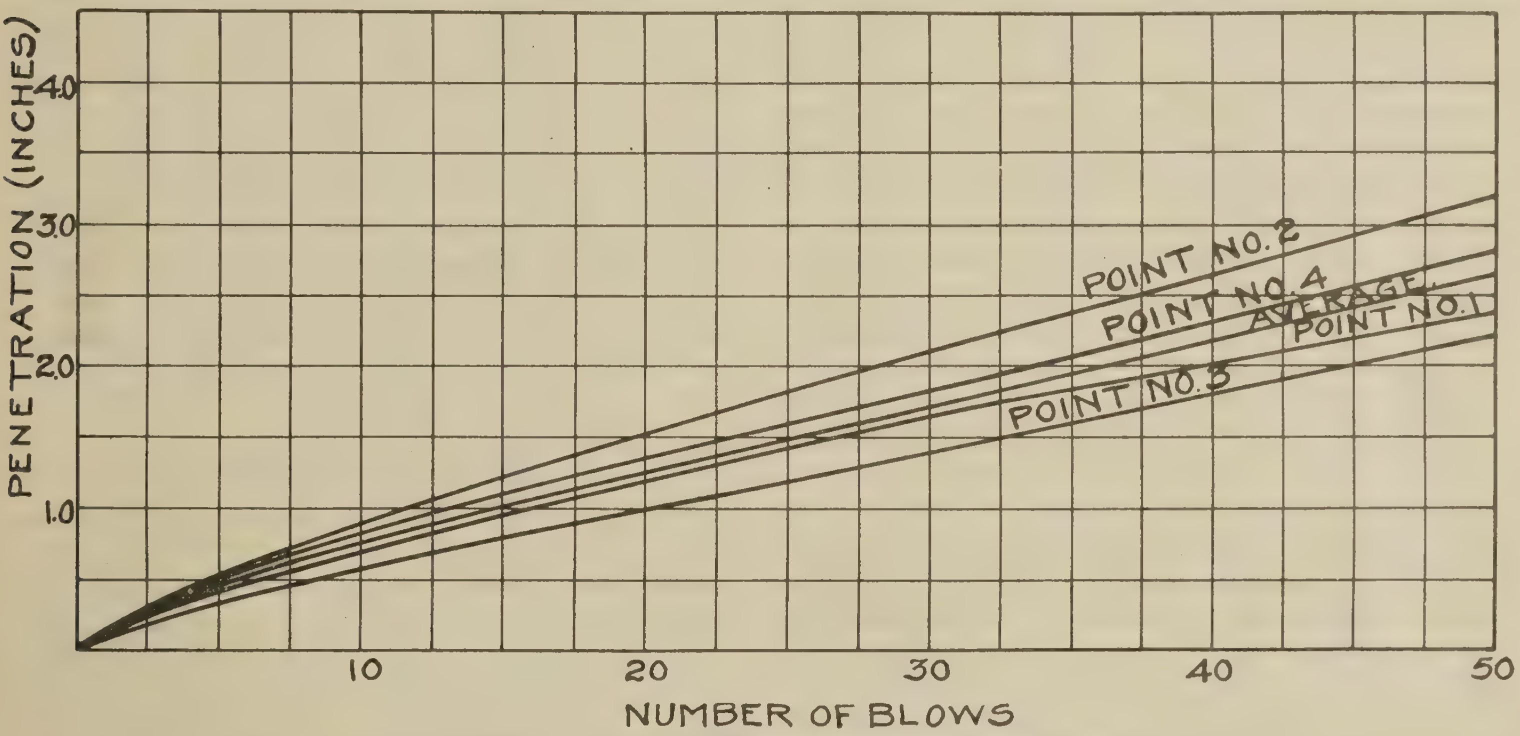


FIG. 1.—TYPICAL RECORD OF BEARING POWER OF SUBGRADE UNDER IMPACT BLOWS.

LEVELS FOR DEFLECTION AND SETTLEMENT.

In order to determine the effect of the impact blows upon the pavement slab under test, either in the way of general settlement or in the deformation of the slab or a combination of these two, it was necessary to have some sort of measurements made on the slab throughout the test.

Points for the reading of elevations were established at the center of the slab and at the corners and midpoints of the sides of concentric squares laid out on the slab. A bench mark was carefully set near by and readings were taken with a high-grade Y level. The level rod was made of a brass rod about 5 feet long and three-eighths inch in diameter. To this a 12-inch engineer's scale was attached by an adjustable clamp which allowed the scale to be moved freely up and down the rod and then clamped firmly in place as desired. Readings were made on the edge of the scale which was graduated in fiftieths of an inch, and by estimating tenths a reading to within 0.002 inch could be obtained.

The most troublesome sources of error were due to the failure of the rodman to hold his rod plumb and to irregularities in the slab surface at the points where the rod was placed. It was to overcome the latter trouble that the use of a small steel disk with a crowned upper surface was introduced. This disk, which might be more properly described as a hemisphere, was laid on its flat side over the points on the slab whose elevations were desired. As this disk was used on all of the points and throughout the test, no account of its thickness need be taken.

From the notes of the levels thus taken, profiles of any section of the slab could be drawn and a series of these profiles for a given section were found to furnish a valuable means of determining the behavior of the section during the run of the impact test. By plotting the change in elevation against the number of blows, a curve is obtained that gives a basis for comparison between the different slabs. Curves of this type have been drawn for the center point on each slab and are kept as part of the record of the test.

NECESSITY FOR CALIBRATING THE IMPACT MACHINE.

As stated in the beginning, these tests were inaugurated principally for the purpose of making available information which would aid in the intelligent selection of a pavement. For this purpose the resistance of the slabs is given in terms of the height of fall of the wheel of a loaded 5-ton truck required to produce failure. With this general information it is necessary only to determine the maximum drop due to obstructions, character and condition of surface, use of chains, etc., and then select from the table a pavement that will resist the wheel load falling from that height. This method of selection, however, is not very scientific and can be considered only as a preliminary step. In the attempt to supply an improved method the impact blows have been expressed in terms of equivalent static loads, and the resistance of the slabs in terms of the static load equivalent to the impact which caused their failure. Knowing, then, the kind of traffic to be accommodated, and finding from the data furnished by the truck-impact tests,[1] the equivalent static force which can be expected from traffic, it is only necessary to select a surface that will safely resist the required force.

Stating the impact in terms of equivalent static load necessitated the calibration of the impact machine. In order that a comparison could be made between the effects produced by impact blows and static loads some medium was required upon which the effects produced by both kinds of force could be observed. The medium used to afford the desired comparison was a one-half by one-half-inch annealed copper cylinder similar to those used in the impact motor-truck tests. By first noting the deformations produced on these cylinders by given static loads, then comparing with these static deformations the deformations of other cylinders produced by the impact blows, a comparison of the effects of impact and static forces was secured. The calibration of the impact machine then included (1) the determination of the static loads which would produce the same deformations on copper cylinders as were produced by the plunger of the impact machine falling from different heights, (2) the determination of the equivalent static loads corresponding to the fall of the plunger from different heights when the cushioning effects of the copper cylinder's deformation were eliminated, and (3) the development of a method of determining the equivalent static load from the space-time curves which were secured during the tests on the different slabs.

For determining the static load which produced the same effect as the plunger dropping from different heights a jack similar to that described in the report of the truck-impact tests was used. During January, 1921, when the subgrade under the slabs was frozen, the impact machine was set over slab No. 15 and the jack in which the copper cylinders were to be deformed was placed under the plunger. The machine was loaded with sprung and unsprung weights of 6,000 and 2,000 pounds respectively. Deformations of the copper cylinders were secured for heights of fall of the unsprung weights ranging from 1 to 3 inches as measured by the space-time curves which were taken for each drop. With these deformations the equivalent static load was found from the calibration curve for one-half by one-half-inch cylinders, shown in fig. 2. The data for this curve were secured by subjecting cylinders to static loads of from 0 to 50,000 pounds in an Olsen 200,000-pound testing machine and recording the corresponding deformations. The equivalent static loads found for the different drops are given in Table 7. It will be noted that height of fall as used in this connection means the distance from the highest position to the final resting place of the plunger.

[1] See Public Roads, vol. 3, No. 35.

TABLE 7.—*Equivalent static loads and maximum force for impacts from various heights of fall, as measured by one-half by one-half inch copper cylinders.*

No.	Free fall (H. F.).	Unsprung wt.+avg. spring pressure (w+f).	Total height of fall (h).	Total cushion (d).	Equivalent static load.	Maximum force (computed).	Ratio equivalent static load to max. force.
	Inches.	*Pounds.*	*Inches.*	*Inches.*	*Pounds.*	*Pounds.*	*Per cent.*
1	0.77	7,100	1.187	0.719	22,500	23,400	104.0
2	.78	7,125	1.176	.700	21,700	23,900	110.0
3	.97	6,900	1.440	.776	26,300	25,600	97.5
4	.97	6,925	1.432	.766	25,600	25,840	101.0
5	1.33	6,575	1.848	.823	29,750	29,500	99.3
6	1.41	6,525	1.920	.814	29,150	30,760	105.5
7	0.30	7,600	0.536	.534	13,700	15,260	111.5
8	0.33	7,550	0.580	.553	14,450	15,850	109.7
9	0.20	7,700	0.380	.380	12,100	14,700	129.02
10	0.15	7,750	0.344	.344	11,900	13,600	114.0
11	0.69	7,150	1.088	.688	20,775	22,600	109.0
12	0.64	7,200	1.016	.674	20,050	21,700	108.0
13	0.92	6,950	1.352	.731	23,300	25,720	110.0
14	0.84	7,050	1.260	.718	22,500	24,740	110.0
15	1.09	6,800	1.552	.766	25,000	27,560	110.0
16							
17	1.11	6,775	1.568	.764	25,500	27,780	109.0
18	1.47	6,500	1.972	.801	28,050	32,000	114.0
19	1.50	6,475	1.988	.793	27,500	32,440	118.0
20							
21							
22	1.97	6,100	2.500	.835	30,650	36,220	118.0
23	2.01	6,100	2.552	.842	31,300	36,940	118.0
24	2.25	5,850	2.800	.851	32,050	38,500	120.0
25	2.28	5,850	2.840	.859	32,900	38,700	117.5
26	2.70	5,500	3.260	.867	33,650	40,660	121.0
27	2.54	5,600	3.102	.862	33,200	40,300	121.5
28							
29	3.00	5,250	3.568	.874	34,350	42,400	123.5
30	3.31	5,000	3.884	.879	34,850	44,300	127.0
31	3.30	5,000	3.872	.878	34,700	44,000	126.7
32	3.04	5,100	3.608	.875	34,400	42,000	122.0

Unsprung weight (w)=2,000 pounds. Sprung weight=6,000 pounds.
Equivalent static load determined from ½ by ½-inch copper cylinders.
Average F. for free fall (H. F.) of from 1 to 3 inches is 120.5 per cent of equivalent static load.
Average F. for free fall (H. F.) of from 0 to 1 inch is 104.5 per cent of equivalent static load.

CUSHIONING EFFECT OF THE COPPER CYLINDERS.

While the results from the above investigation were better than nothing, it was realized that they did not give the required information. The calibration of the impact machine was undertaken to determine the effect of the drop of the plunger from different heights on the various slabs, whereas the results obtained by these means showed the effect of the plunger dropping on a copper cylinder, which is a somewhat different matter. The main difference between static and impact forces lies in the fact that a static force is entirely dependent upon the weight of the load, while the impact force produced by a mass moving with a given velocity is dependent upon the time or distance in which the velocity of the mass is changed or brought to zero. That is, an impact force is dependent upon the deceleration of the given mass which is dependent upon the character of the body struck as well as of the striking mass. When two bodies, each highly resistant to deformation, are brought into contact the force is exceedingly high. The effect of any cushion is to increase the time in which change of velocity occurs and consequently to reduce the deceleration. For this reason it can be seen that the copper cylinder used in the calibration is, in effect, an additional cushion between the plunger and the slab, and the force of the blow causing a certain deformation of the copper cylinder would be greater if the cushioning of the blow due to the deformation of the copper could be eliminated.

It therefore became necessary to determine the effect of the copper cushion; and the most convenient means which suggested itself for a study of the effect of reduction of copper cushion was by repeating a blow on the same cylinder. When this was tried it was found that the second drop from the same height produced an additional deformation smaller than the first. A third drop from the same height produced a further but still smaller deformation. Continuing the process it was found that each succeeding blow from the same height produced a smaller deformation than the preceding, but each blow nevertheless produced additional deformation. Now, it had been found previously that cylinders which had been subjected to static load in the testing machine, if retested, were not deformed further by any load less than or equal to the load under which the original deformation took place; and it was not until the second application of load exceeded the first that further deformation resulted. The coupling of this observation with the observed effects of repeated impact seemed to indicate that the blows which caused the succeeding deformations were equivalent to greater static loads than the first blow. Moreover it appeared that there was a definite relation between the amount of the deformation and the intensity of the blow.

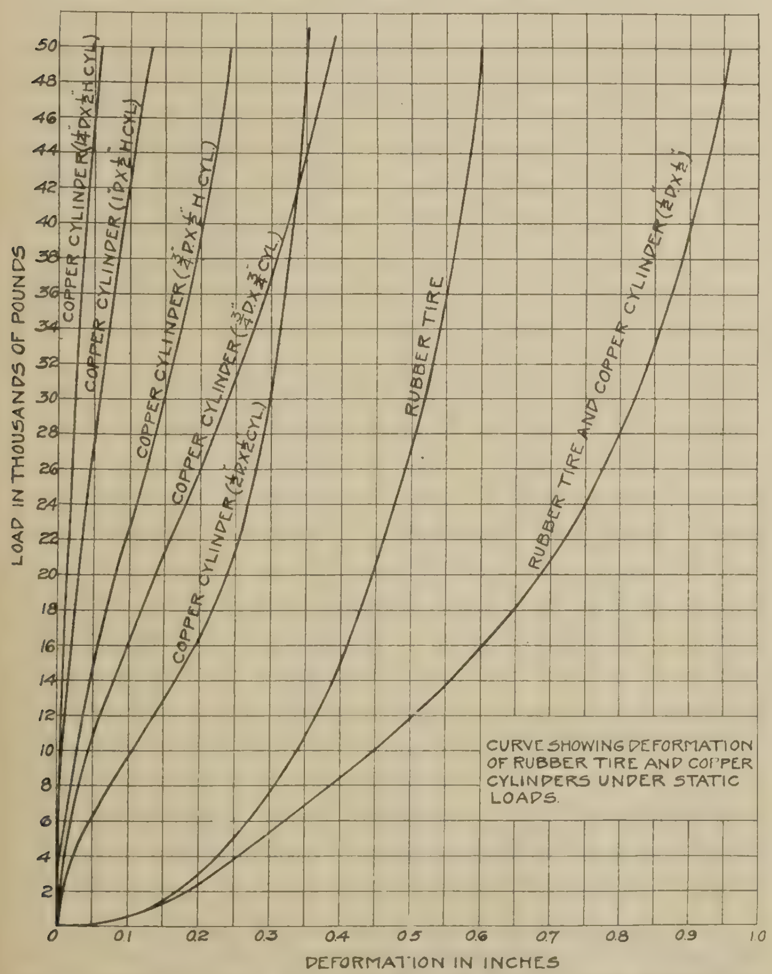


FIG. 2. DEFORMATION OF RUBBER TIRE AND COPPER CYLINDERS UNDER STATIC LOADS.

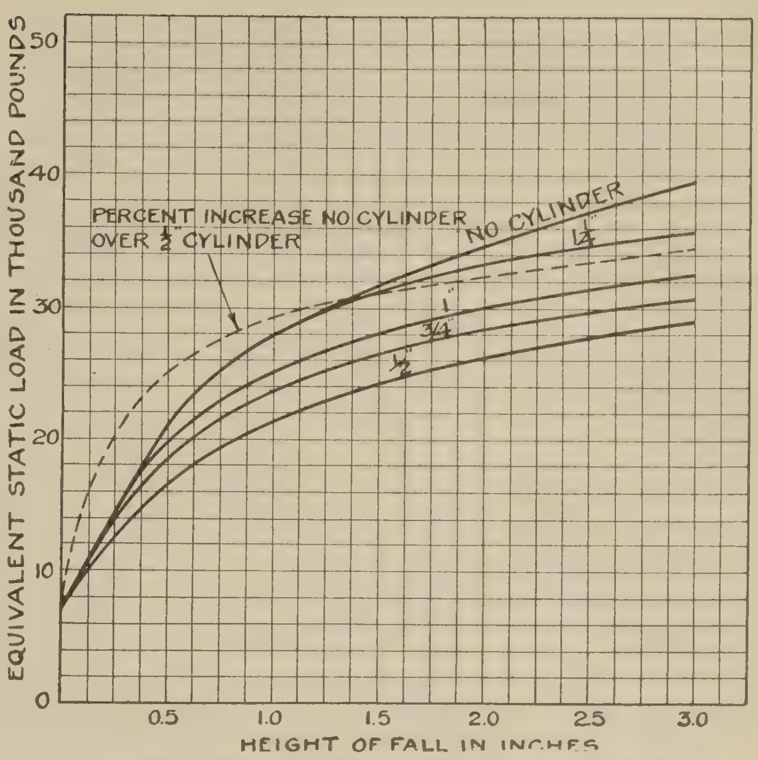


FIG. 3.—CURVES SHOWING CUSHIONING EFFECT OF COPPER CYLINDERS OF THE SEVERAL SIZES.

Considering the copper cylinder as a cushion, it appeared that reduction of the deformation or cushioning effect of the blow increased its static equivalent.

CHARACTER OF COPPER UNCHANGED BY IMPACT.

It was suggested at this point that the deformation caused by the first blow might change the character of the copper so that the results of the succeeding blows would not be true indications of the force. To secure light on this phase of the matter different cylinders which had received from 5 to 50 blows were subjected to additional static loads in a testing machine and the corresponding deformations were compared with those shown by the calibration curve in figure 2. It was found that the variation was less than 1 per cent thus indicating that the character of the copper had not changed as a result of the deformations occasioned by impact blows. Also, at this time it was found that there was an elastic deformation of the copper cylinder which amounted to slightly less than 0.01 inch under a 50,000-pound load, but this elastic deformation does not enter into any of the derivations herein described. When it was concluded that the deformation of the copper influenced the force of the blow, the following investigation was carried on for the purpose of securing definite information on the effects of reduction of copper cushion.

Knowing that under the same load and for the same height of cylinder the deformation decreases with an increase in area, copper cylinders of different diameters were prepared for a second calibration of the impact machine. A special concrete foundation 4 feet in diameter and 2 feet thick was constructed to hold the jack.

The different sized cylinders as well as the cast-iron shoe and rubber tire of the plunger were carefully calibrated in a testing machine, and the results are shown by the curves in figure 2. The machine for this run had for sprung and unsprung weights 6,000 and 1,800 pounds, respectively, the same as the loading which was used in testing all of the slabs. The procedure in obtaining copper deformations for the various heights of fall was similar to that followed in the first calibration, except that the height of fall was checked by means of precise levels, that copper cylinders of different sizes were used, and, also, that in this run every observation, both static and impact, was made by two men; one reading and the other checking. The results obtained are shown in Table 8 and by the curve in figure 3. These results show very definitely the increase of force with the decrease of copper deformation.

TABLE 8.—*Equivalent static loads and maximum force for impacts from various heights of fall as measured by copper cylinders of different sizes.*

No.	Free fall (H. F.)	Unsprung weight +avg. spring pressure (w+f).	Total height of fall (h).	Total cushion (d).	Copper cylinder.	Equivalent static load.	Maximum force (computed).	Ratio equivalent static load to maximum force.
	Inches.		*Inches.*	*Inches.*	*Inches.*	*Pounds.*	*Pounds.*	*Per cent.*
2-1	0.490	0.7125	0.844	0.654	½ by ½	16,200	18,400	113.5
2-2	.495	.7180	.812	.617	½ by ½	17,300	18,900	109.0
3-1	.482	.7110	.872	.690	½ by ½	16,350	18,000	110.0
3-2	.486	.7200	.784	.598	½ by ½	17,400	18,880	108.4
3-3	.494	.7200	.784	.590	½ by ½	17,900	19,120	106.8
No Cyl.	.532	.7125	.856	.624	....	....	20,640	....
4-1	1.097	.6500	1.696	.899	½ by ½	21,700	24,500	113.0
4-2	1.093	.6600	1.532	.739	½ by ½	23,700	27,400	115.5
4-3	1.067	.6600	1.548	.781	½ by ½	25,300	26,160	103.3
5-1	1.090	.6500	1.712	.922	½ by ½	22,600	24,140	106.7
No Cyl.	1.124	.6575	1.564	.740	....	....	27,760	....
6-1	1.675	.5950	2.416	1.041	½ by ½	25,000	27,560	110.0
6-2	1.711	.6125	2.180	.769	½ by ½	27,700	34,740	125.0
6-3	1.724	.6125	2.184	.760	½ by ½	28,700	35,200	122.5
7-1	1.680	.6000	2.368	.988	½ by ½	25,500	28,760	112.5
No Cyl.	1.696	.6125	2.184	.788	....	....	33,920	....
8-1	2.280	.5450	3.052	1.072	½ by ½	26,500	31,000	117.0
8-2	2.311	.5550	2.956	.945	½ by ½	30,200	34,660	115.0
8-3	2.289	.5550	2.936	.947	½ by ½	31,600	34,360	108.5
16-1	2.811	.5000	3.626	1.115	½ by ½	28,600	32,540	113.8
16-2	2.820	.5150	3.454	.934	½ by ½	32,900	38,100	116.0
17-1	2.813	.5000	3.652	1.139	½ by ½	29,000	32,100	110.5
18-1	2.585	.5250	3.352	1.067	¾ by ¾	28,900	33,100	114.5
18-2	2.533	.5350	3.208	.975	¾ by ¾	32,100	35,220	109.7
18-3	2.532	.5350	3.198	.966	¾ by ¾	33,600	35,380	105.2
19-1	....	....	....	....	....	29,300	....	....
20-1	2.027	.5700	2.730	1.003	¾ by ¾	27,200	30,980	113.8
21-1	1.363	.6300	1.960	.897	¾ by ¾	24,200	27,540	113.7
21-2	1.378	.6400	1.842	.764	¾ by ¾	26,500	30,900	116.5
21-3	1.387	.6400	1.848	.761	¾ by ¾	27,700	31,080	112.0
22-1	.811	.6850	1.208	.697	¾ by ¾	20,500	23,720	115.5
23-1	1.100	.6650	1.584	.784	¾ by ¾	22,800	26,900	118.0
24-1	.487	.7175	.840	.653	¾ by ¾	17,200	18,460	107.1
24-2	.495	.7200	.800	.605	¾ by ¾	18,300	19,060	104.0
25-1	.272	.7400	.532	.532	¾ by ¾	13,200	14,060	106.5
26-1	.288	.7375	.556	.556	½ by ½	12,300	14,420	117.0
No Cyl.	.304	.7450	.468	.464	....	....	15,050	....
51	.427	.7250	.692	.565	¾ by ½	16,600	17,760	107.0
52	.412	.7225	.708	.596	1 by ½	17,200	17,140	99.7
53	.408	.7275	.686	.578	1¼ by ½	17,800	17,260	97.0
54	.641	.7050	.976	.635	¾ by ¼	20,800	21,660	104.0
55	.653	.7050	.956	.603	1 by ½	22,000	22,360	101.5
56	.724	.6900	1.152	.728	1¼ by ½	22,600	21,840	96.7
57	1.151	.6500	1.672	.821	¾ by ½	24,600	26,500	107.5
58	1.176	.6550	1.600	.724	1 by ½	26,600	28,960	108.7
59	1.147	.6600	1.576	.729	1¼ by ½	29,400	28,540	97.0
60	1.733	.6000	2.372	.939	¾ by ½	27,100	30,340	112.0
61	1.740	.6050	2.256	.816	1 by ½	28,800	33,400	116.0
62	1.716	.6050	2.240	.824	1¼ by ½	32,600	32,900	101.0
63	2.283	.5500	3.024	1.041	¾ by ½	28,450	31,960	112.0
64	2.234	.5550	2.904	.970	1 by ½	30,600	33,300	109.0
65	2.225	.5600	2.840	.915	1¼ by ½	33,800	34,760	103.0

Unsprung weight, 1,800 pounds. Sprung weight, 6,000 pounds.

Average ratio of equivalent static load to maximum force for different heights of fall.

Copper cylinder.	Free fall (H. F.).	Average ratio.
	Inches.	*Per cent.*
½ by ½ inch...	1	112.4
Do.......	2	113.1
Do.......	3	110.3
¾ by ¾ inch...	1	112.7
Do.......	2	110.0
Do.......	3	108.6

Average ratio of equivalent static load to maximum force for all heights of fall.

Copper cylinder.	Average ratio.
	Per cent.
½ by ½ inch....	112.7
¾ by ¾ inch....	111.4
¾ by ½ inch....	108.5
1 by ½ inch....	106.9
1¼ by ½ inch...	98.9

But while the values shown were nearer those desired, there yet remained to be found the force when there was no copper cushion, i. e., the actual force of blow when the plunger hit the slab. For this information it was necessary to resort to the space-time curves. A study of available information on the magnitude of impact forces is, to say the least, confusing. There is considerable disagreement on such questions as the relation of maximum to average force produced during a blow as well as the connection between static and impact forces. It is true there are fundamental theoretical formulæ for deriving the force of impact as well as energy-work relations for determining average resistance. But when the impact force values are obtained, what do they mean and how do they help us? It will be remembered that this investigation of impact force was carried on only for the purpose of determining equivalent static load in the absence of the cushioning effect of the copper cylinder.

SPACE-TIME CURVES TURNED TO PRACTICAL USE.

The point to be stressed is that in the investigation of the space-time curves a means of turning these curves to practical use is being developed. The actual value of the maximum, or the average or of any other impact force, is of little or no moment. What is desired is a knowledge of the effect produced by these forces. In other words, we would like to compare the effects produced by given impact forces with those produced by static loads. To do this, the impact force must be obtained from the space-time curves by means of theoretical computations, and then a relation must be found between the force and the equivalent static load. For obtaining usable impact values from the curves the following general relations were tried:

1. The maximum force produced by an impact blow is equal to the greatest acceleration times the mass of the moving body.

2. The average force of an impact blow is equal to the average acceleration during time or distance of contact times the mass of the moving body.

3. The average force of an impact blow is equal to the total energy of the blow divided by the distance through which this energy is expended.

The first attempt to secure the force of the impact exerted by a drop of the plunger was made with the autographic curves secured during the first calibration. Since all authorities seem to agree that the maximum force of the blow is exerted at or near the point of greatest deformation a position near the lowest point of the curve was selected for the solution. An enlarged typical space-time curve and the graphical solution used in this derivation are shown in figure 4.

The relation used was;

$$F = Ma.$$

In which,

F = Maximum force of blow.
a = Maximum acceleration.
M = Mass of unsprung weight.

To obtain a, the following formula was used:

$$a = \frac{V_1 - V_2}{t}$$

In which,

t = Time in seconds.
V_1 = Velocity before the point of maximum deformation.
V_2 = Velocity after the point of maximum deformation.

The procedure, as shown in figure 4, was first to draw a horizontal line through the curve near its lowest point. Tangents were then drawn to the curve at its intersection with the horizontal line. These tangents or first derivatives gave the values V_1 and V_2 while the time was given by the length of the horizontal line contained between the two sides of the curve. Because of defects in the autographic recording device the results from this set of computations were of value only in so far as they indicated that dependable results could be secured from curves of proper size with correlated accurate time records. While the actual results were not usable, it was strongly suggested that a definite relation existed between the force as computed and the equivalent static load as given by the copper cylinder.

For a further investigation of impact force, several defects were eliminated from the recording apparatus, and the impact machine was loaded with 3,050 pounds unsprung and no sprung weight, the plunger being in effect a freely falling body. The sprung weight was eliminated in this calibration in order that the velocity as obtained by the tangent method might be checked by the theoretical velocity of a freely falling body. The procedure in securing deformations of the copper cylinders was the same as that followed in the first calibration described above.

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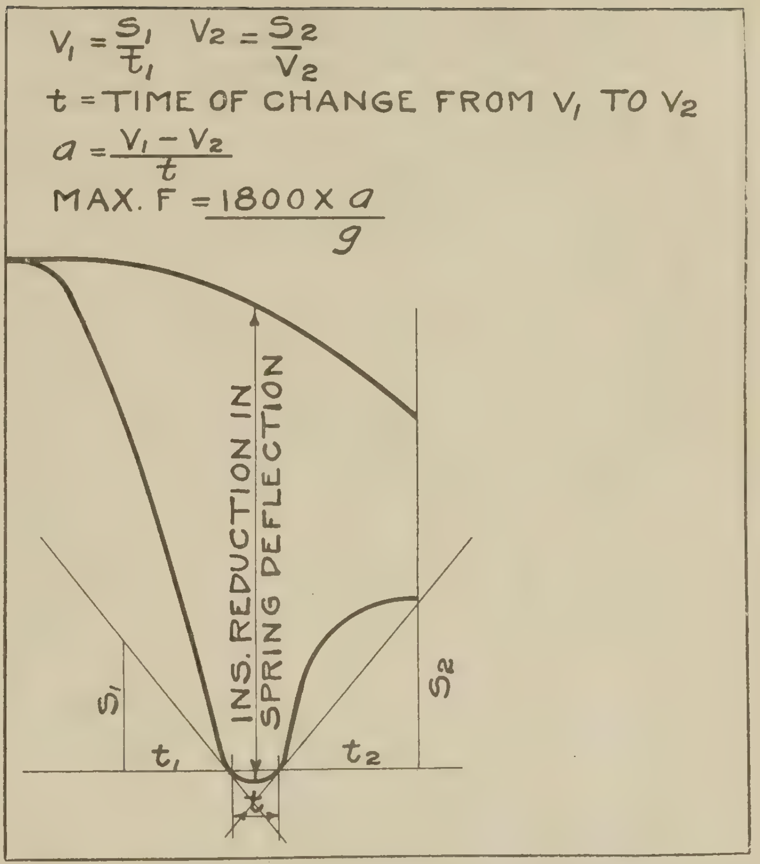


FIG. 4.—DERIVATION OF MAXIMUM ACCELERATION FROM SPACE-TIME CURVE USING THE VELOCITY-TIME RELATION.

METHOD OF DERIVING IMPACT FORCES CHANGED.

For deriving the impact forces from the curves the method used was somewhat different from that previously described and involved the assumption that the maximum velocity of a falling body which is being stopped by a cushion occurs when the body has penetrated the cushion to such a depth that the resistance of the cushion equals the weight of the body. Since an inspection of the rubber and copper curves, figure 2, shows that a resistance of 3,050 pounds occurs with a deformation of 0.225 of an inch, it was assumed that the maximum velocity of the plunger occurs at a distance of 0.225 of an inch below the point of first contact and becomes 0 at the lowest tip of the curve. The average acceleration can be expressed in two ways:

1. Ave. $a = \frac{V}{t}$

V = Maximum velocity.
t = Time required to change from maximum to 0 velocity.

2. Ave. $a = \frac{V^2}{2D}$

V = Maximum velocity.
D = Distance from point of maximum velocity to lowest or point of zero velocity.

Figure 5 shows how the values are taken from the curve. From the tangent is obtained the maximum velocity; the time, t, is the horizontal distance from the

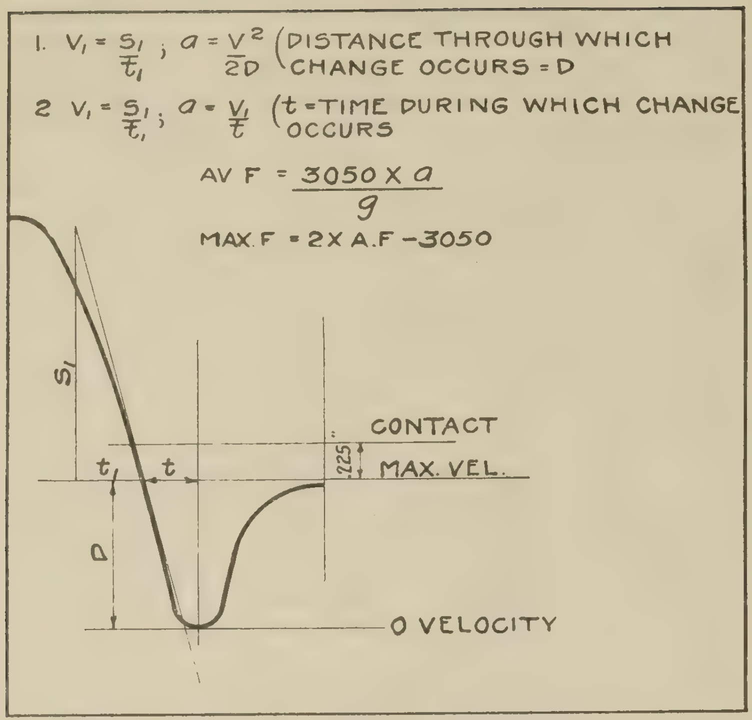


FIG. 5.—DERIVATION OF AVERAGE ACCELERATION BETWEEN POINTS OF MAXIMUM AND ZERO VELOCITY.

point of tangency to the lowest tip of the curve, while D is the vertical distance from the point of tangency to the lowest tip of the curve. Having determined the average acceleration from the curves the average force, R, is obtained from the relation $R = Ma$. It is noted that R is the average force exerted from an initial force of 3,050 to a maximum to be determined.

The second assumption is expressed by the relation

Max. $F = 2R - \mathrm{I}$

R = Average force

I = Force at point of maximum velocity (in these computations, 3,050 pounds).

TABLE 9.—*Comparison between equivalent static load as indicated by the copper cylinder and impact force as computed from space-time curves by means of both velocity squared-space and velocity-time relations between the points of maximum and zero velocity.*

No.	Copper cylinder static equivalent.	Approximate computed maximum velocity.	Maximum velocity as obtained from tangent to curve.	Velocity squared-space relation.		Velocity-time relation.	
				Ave. $a = \frac{V^2}{2D}$.	F=2R−I.	Ave. $a = \frac{v}{t}$	F=2R−I.
1	22400	3.190	3.254	134.5	22450	143.8	24210
2	24400	3.440	3.700	148.7	25090	145.5	24510
3	26000	3.610	3.885	154.2	26150	183.4	31870
4	28600	4.080	4.150	167.1	28610	183.0	31510
5	30200	4.235	4.287	176.2	30310	178.5	33900
6	21500	3.280	3.360	132.0	21950	151.3	25590
7	20000	3.060	3.140	123.5	20350	154.2	....
8	16500	2.530	2.700	105.0	16850	103.3	17610
9	15600	2.360	2.590	101.6	16200	110.2	17810
10	11100	1.580	1.746	72.4	10670	72.9	10770
11	8600	1.360	1.343	59.6	8250	60.65	8045

Sprung weight=0. Unsprung weight=3,050 pounds.

The comparison of the forces obtained by this series of drops is shown in Table 9. These results clearly indicate that the equivalent static load as given by the copper cylinder is about the same as the maximum force as computed from the curves by means of the above methods. It will be noted that the tangential velocities are slightly greater than the theoretical and also that the forces as computed from the velocity-time relation show more variation than those from the velocity-space relation. The reason for the latter condition unquestionably lies in the fact that more accurate measurements can be made on the curves for distance than for time.

Although the results shown for this study of the curves were encouraging, the methods employed for securing the results seemed too cumbersome for practical use. These results, however, are again indicative of a definite relation between equivalent static load and impact force.

MAXIMUM FORCE FROM MAXIMUM ACCELERATION.

There is being developed at present by the Bureau of Public Roads a device which when attached to a motor truck will give space-time curves showing the movements of the sprung and unsprung parts of the vehicle when passing over different types and conditions of pavements; and owing to the fact that the curves made by this apparatus can be solved by methods making use of the tip of the curve only, the next step in the development of force derivation involved the securing of the maximum force by means of the maximum acceleration. In the derivation of the maximum acceleration the velocity-distance rather than the velocity-time relation was used since previous study showed that space measurements were more accurate than the time. In the study of this method of force derivation the curves obtained during the investigation of the effect of copper cushion reduction were used. It will be noted that these curves represented drops on different sizes of copper cylinders as well as drops in which no cylinders were used. The maximum acceleration was computed from these curves and with this acceleration a maximum force was obtained from the formula:

$$\text{Max. } F = \frac{1,800 \times a}{32.2} \text{ (pounds).}$$

In which,

1,800 = Unsprung weight (pounds).

a = Acceleration (feet per second per second).

The procedure was as follows: Each curve was enlarged 10 times by means of a precise pantograph. (See fig. 6.) Four horizontal lines were then drawn through the bottom part of the space-time curve, these lines representing distances of one two-hundredth, one one hundred and fiftieth, one one-hundredth, and one fiftieth of an inch from the lowest point or point of zero velocity. Tangents to the curve for obtaining the velocities were drawn at the intersections of these horizontal lines. These velocities were squared and plotted as shown in figure 6, in which the vertical distances are the squares of the velocities and the horizontal distances are the above-noted distances from the point of zero velocity. Through these points as plotted a line is drawn which is the slope of the $\frac{V^2}{2D}$ curve. The slope of this line equals a, the acceleration.

EFFECT OF THE MAXIMUM FORCE DETERMINED.

Having found the maximum force the next step is to determine just what this force means. In other words, what is the actual effect produced by a maximum impact of a given magnitude. A means of determining this effect is afforded by the copper cylinders. By comparing the maximum impact forces as computed from the space-time curves with the static loads which cause equal deformations of copper a definite relation is found between the two, which is shown in figure 7. From this curve it will be seen that a maximum force causes the same deformation as would be occasioned by a static load of approximately two-thirds the magnitude. Having determined this relation an equivalent static load can be found for any maximum impact force, and knowing the maximum impact force when no cylinder is used, it is a simple matter to find the corresponding equivalent static load.

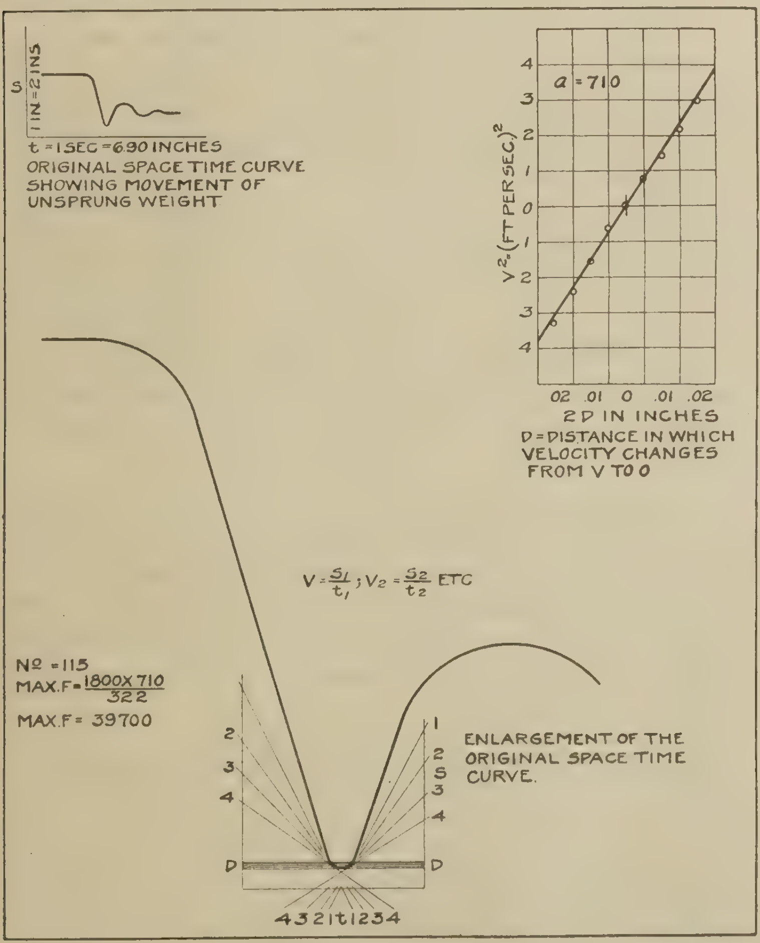


FIG. 6.—DERIVATION OF THE MAXIMUM ACCELERATION FROM THE RELATION, $a=\frac{V^2}{2D}$.

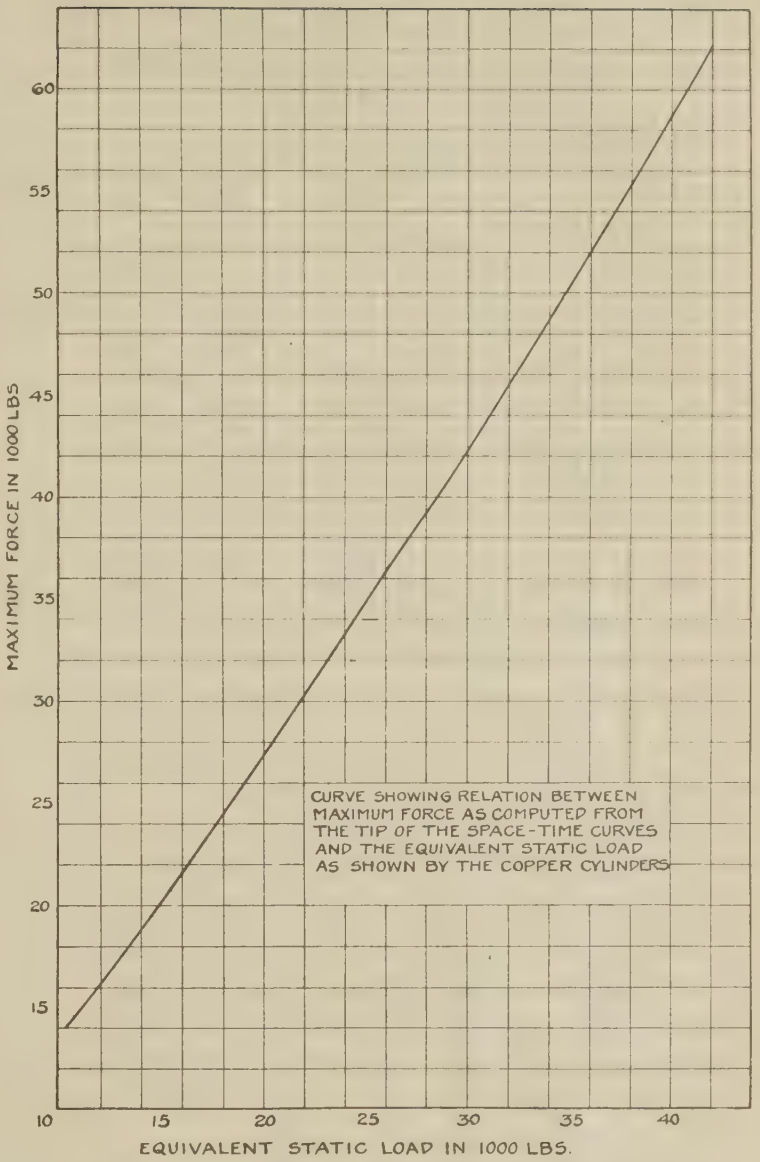


FIG. 7.—RELATION BETWEEN MAXIMUM FORCE AS COMPUTED FROM THE TIP OF THE SPACE-TIME CURVES AND THE EQUIVALENT STATIC LOAD AS SHOWN BY THE COPPER CYLINDER.

TABLE 10.—*Comparison of equivalent static load as obtained from copper cylinder deformations with maximum force as computed from space-time curves.*

$$M=\frac{1800\times a}{32.2}$$

No.	Maximum acceleration (a).	Maximum force.	Equivalent static load by copper cylinder.	Free fall (H. F.)	Remarks.
		Pounds.	*Pounds.*	*Inches.*	
26	297	16,600	12,500	0.25	½ by ½ cylinder.
25	313	17,500	13,200	.34	¾ by ¾ cylinder.
51	423	23,600	16,600	.40	¾ by ½ cylinder.
4	555	30,740	21,700	1.08	½ by ½ cylinder, 1st blow.
4	582	32,600	23,700	1.07	½ by ½ cylinder, 2d blow.
4	625	34,950	25,300	1.04	½ by ½ cylinder, 3d blow.
62	833	46,700	32,600	1.74	¼ by ½ cylinder.
55	556	31,000	22,000	.63	1 by ½ cylinder.
5	750	42,000	[1] 29,800	1.12	No cylinder.
103	608	34,000	[1] 24,500	.72	Do.
106	1,019	57,000	[1] 39,100	2.91	Do.
101	967	54,100	[1] 37,400	2.28	Do.
110	722	40,350	[1] 28,700	1.06	Do.
115	705	39,400	[1] 28,100	1.08	No cylinder; Time doubtful.
100	324	19,000	[1] 14,100	.24	No cylinder.
112	857	47,900	[1] 33,500	1.80	Do.
107	1,052	58,800	[1] 40,100	3.04	Do.
26	414	23,150	[1] 17,100	.28	Do.

[1] Equivalent static load computed.

TABLE 11.—*Investigation of effect of reduction of copper cushion on force produced by same height of fall.*

Percentage of increase of force produced when using rubber alone against that of rubber and ½ by ½ inch copper cylinders.

Free fall (H. F.)	Equivalent static load as shown by copper cylinders.					No. cyl.	Per cent Increase.
	½ by ½	¾ by ¾	¾ by ½	1 by ½	1¼ by ½		
Inches.							
0.25	**12,500**	**13,000**	**13,800**	**14,500**	**15,000**	15,100	20.7
	0.143	0.070	0.045	0.016	0.007		
.50	**16,600**	**17,600**	**19,300**	**20,200**	**21,600**	21,700	30.7
	.202	.114	.078	.030	.014		
.75	**19,200**	**20,200**	**22,000**	**23,400**	**25,700**	25,700	33.8
	.230	.140	.097	.038	.019		
1.00	**21,200**	**22,200**	**23,800**	**25,600**	**28,400**	28,400	33.9
	.250	.160	.109	.045	.023		
1.25	**22,900**	**23,800**	**25,200**	**27,100**	**30,200**	30,300	32.3
	.265	.178	.118	.050	.025		
1.50	**24,300**	**25,200**	**26,400**	**28,300**	**31,500**	32,100	32.8
	.271	.193	.127	.054	.027		
1.75	**25,500**	**26,300**	**27,300**	**29,300**	**32,300**	33,500	31.3
	.278	.204	.133	.058	.028		
2.00	**26,400**	**27,200**	**28,100**	**30,100**	**33,300**	34,900	32.3
	.283	.213	.137	.060	.030		
2.25	**27,100**	**28,000**	**28,900**	**30,700**	**33,900**	36,200	33.5
	.286	.222	.144	.062	.030		
2.50	**28,000**	**28,700**	**29,500**	**31,300**	**34,300**	37,400	33.6
	.291	.228	.148	.064	.031		
2.75	**28,600**	**29,400**	**30,200**	**31,800**	**34,700**	38,500	34.7
	.293	.236	.152	.065	.031		
3.00	**29,300**	**30,000**	**30,900**	**32,400**	**34,900**	39,700	35.5
	.296	.342	1.56	.067	.032		

NOTE.—Light-face figures under equivalent static loads show copper cylinder deformation or cushion in inches for the particular blow.

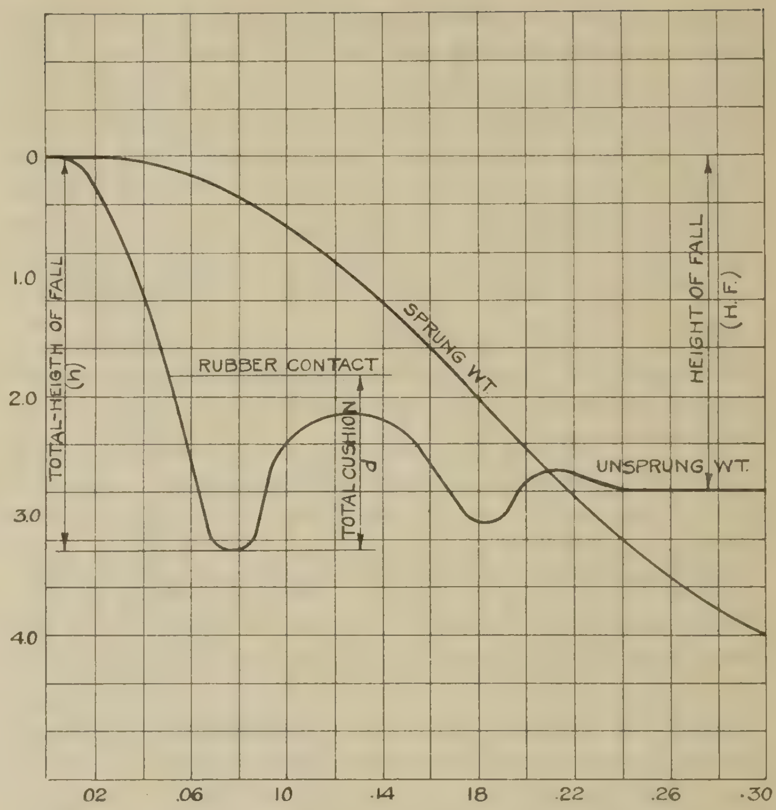


FIG. 8.—SPACE-TIME CURVE, SHOWING ENERGY-WORK RELATION.

The values shown in Tables 10 and 11 were obtained by first computing the maximum force and finding the corresponding equivalent static load from the curve. As noted before, it has been known that as the depth of cushion is decreased the impact increases. This effect or increase is shown very clearly in Table 11 and figure 3. It will be noted that in obtaining these results copper cylinders of the following sizes are used:

½ inch diameter by ½ inch long ...... 1 blow.
½ inch diameter by ½ inch long ...... 2 blows.
½ inch diameter by ½ inch long ...... 3 blows.
¾ inch diameter by ¾ inch long ...... 1 blow.
¾ inch diameter by ½ inch long ...... 1 blow.
1 inch diameter by ½ inch long ...... 1 blow.
1¼ inches diameter by ½ inch long ... 1 blow.

This represents a sample of every kind of copper cylinder used at Arlington as well as the second and third blows on the same cylinder. It will be noted from these tables that the equivalent static load as shown by deformation of the copper cylinders agrees with two-thirds of the maximum force as obtained from the space-time curves by the above computation within about 5 per cent. This would seem to indicate that there is a definite relation between equivalent static load and force produced by impact blows.

It must be remembered that this investigation of the impact blow was carried on only for the purpose of determining the equivalent static load in the absence of the cushioning effect of the copper cylinder. The close agreement of the above results has been accepted as justification of the use of the no-cylinder curve to represent the values with the effect of copper cushion eliminated. It must be pointed out, however, that these conclusions and the results are neither final nor absolute. They are accepted only because nothing better has been offered. There are several possible sources of error in the curve computations. First, the time can not be considered as accurate. Autographically, the time intervals are recorded only in seconds, while the computations deal with hundredths of seconds and even smaller intervals. The average time as shown on the graphs in which one second is represented by from 6 to 9 inches horizontally might not be exact for the interval of contact. Again, it is impossible to enlarge the small curves with the degree of accuracy necessary for exact solution of velocities. The slightest variation in the enlargement means a large error in the computed velocity. This explanation and the details of the procedure used are given so that the results can be taken for what they are worth.

What can be said then from the above results is that the maximum force at the tip of the curve computed by the mass-acceleration method, as shown, produces the same effect upon a copper cylinder as a static load of approximately two-thirds the magnitude. Knowing this, then these curves become valuable for measurement of force.

ENERGY-WORK RELATION GIVES SIMPLEST CURVE SOLUTION.

By far the simplest solution of the curves secured during the slab tests is that making use of the energy-work relation. When the plunger of the impact machine or the wheel of a motor truck falls through any distance, a certain amount of energy is developed by the mass acted upon by gravity as well as the spring pressure. This energy must be used up before the wheel can be brought to a stop. In other words, the total energy must be balanced by the resistance of the rubber tire, copper cylinder, slab, etc., acting through the distance of total deformation. Referring to the enlarged space-time curve (Fig. 8) showing the movement of the unsprung weight it is noted that the total energy of the blow is equal to total drop (h) times the weight of the plunger plus the average spring pressure exerted on the plunger falling through the distance (h). This energy is expended on an average resistance acting through the distance (d). The average resistance is obtained from

$$R = \frac{(W+f)\,h}{d}$$

In which,

R = Average resistance.
W = 1,800 = Weight of plunger.
f = Average spring pressure acting through distance (h) which value is obtained from figure 10.
d = Total depth of deformation.
h = Total height of fall.

In this case as in the preceding one the average resistance is of value only when its effect can be expressed in static terms. An examination of the results indicated that the equivalent static effect on the copper cylinder was expressed by the relation

$$\text{Equivalent static load} = 2R - P$$

P becomes zero when the height of fall (h) is greater than the cushion (d). When $h = d$ (in small drops with rubber in contact with slab) the value for P is taken from the rubber deformation curve and is equal to the static load necessary to deform the rubber the amount it is deformed at the beginning of a particular blow.

RESULTS OF THE FORMULAE COMPARED.

Tables 7, 8, and 12 show the equivalent static load as given by the copper cylinder and the maximum force as obtained from the above formulae. The comparisons afforded by these tables are exceedingly interesting. It will be noted that the tables show results obtained with the machine loaded in three different ways. Table 7 shows results obtained with a sprung weight of 6,000 pounds and an unsprung weight of 2,000 pounds. In table 8 the sprung weight is 6,000 pounds and the unsprung weight, 1,800 pounds. In Table 12 are shown results when only a freely falling unsprung weight of 3,050 pounds was used. In this table a very close agreement of results can be noted, the average variation being 2.5 per cent. Also it can be seen that in this table the variations are such as might be expected in a series of observations, that is, that the variations are the same for high drops as for low drops. This would warrant the conclusion that the relation expressed above holds good for any amount of copper deformation.

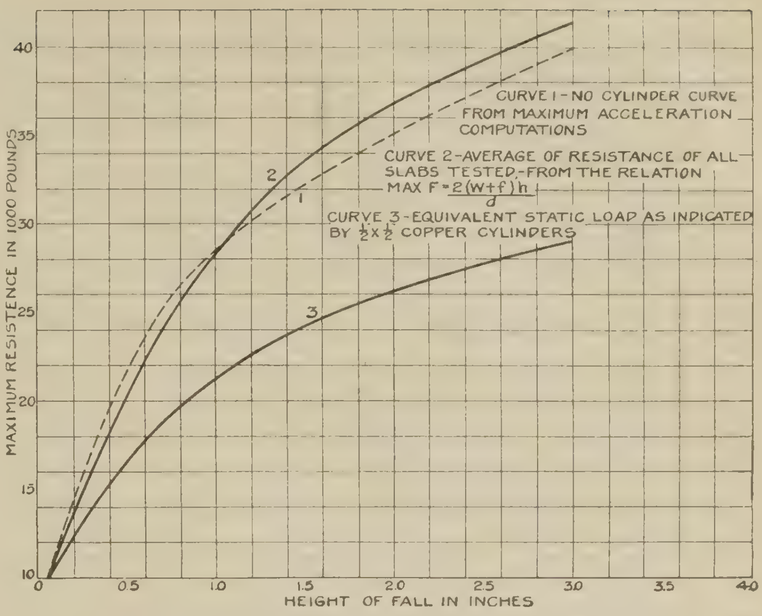


FIG. 9.—CURVES SHOWING THE RELATION OF COMPUTED VALUES OF STATIC EQUIVALENT LOADS AND THE STATIC EQUIVALENTS AS MEASURED BY COPPER CYLINDERS.

TABLE 12.—*Equivalent static load and maximum force for impacts of an unsprung weight for various heights of fall as measured by one-half by one-half inch copper cylinders.*

No.	Free fall (H. F.).	Total height of fall (h).	Total cushion (d).	Equivalent static load.	Maximum force (computed).	Ratio equivalent static load to maximum force.
	Inches.	*Inches.*	*Inches.*	*Pounds.*	*Pounds.*	*Per cent.*
1	1.90	2.42	0.666	22,400	22,150	99.0
2	2.20	2.76	.700	24,400	24,060	98.5
3	3.42	3.004	.724	26,000	25,300	97.5
4	2.73	3.328	.745	27,500	27,260	99.0
5						
6	3.09	3.712	.760	28,600	29,760	104.0
7	3.34	3.980	.780	30,200	31,100	103.0
8	3.59	4.24	.797	32,700	32,450	99.2
9						
01	4.15	4.820	.808	33,000	36,400	110.0
11	2.00	2.512	.650	21,500	23,560	109 0
12	1.73	2.212	.623	20,000	21,640	108.0
13						
14	1.20	1.608	.553	16,500	17,740	107.5
15	1.03	1.424	532	15,600	16,320	104.6
16						
17	.463	.728	.407	11,100	10,920	98.5
18	.286	.472	.328	8,600	8,760	102.0

Unsprung weight (w) = 3,050 pounds. Sprung weight = 0 pounds.
Equivalent static load determined by use of one-half by one-half inch copper cylinders.
Average F is 102.5 per cent of equivalent static load.

Table 7 shows that for low drops there is an average variation of 4.5 per cent and for drops between 1 and 3 inches the variations increase from 10 to 27 with an average of 20.5 per cent. This increase in variation can be accounted for by the fact that as the height of fall increased the falling weights were interfered with by the guides and the beam which lifted the plunger. This interference would naturally reduce the total energy of the blow and consequently the theoretical force would be larger than that indicated by the copper cylinder. No slabs were tested with the machine loaded in either of the above described ways. For the actual tests the unsprung weight was 1,800 pounds and the sprung weight was 6,000 pounds. The results obtained with this loading are shown in Table 8.

From the foregoing results it is apparent that a definite relation exists between the force of impact as com-

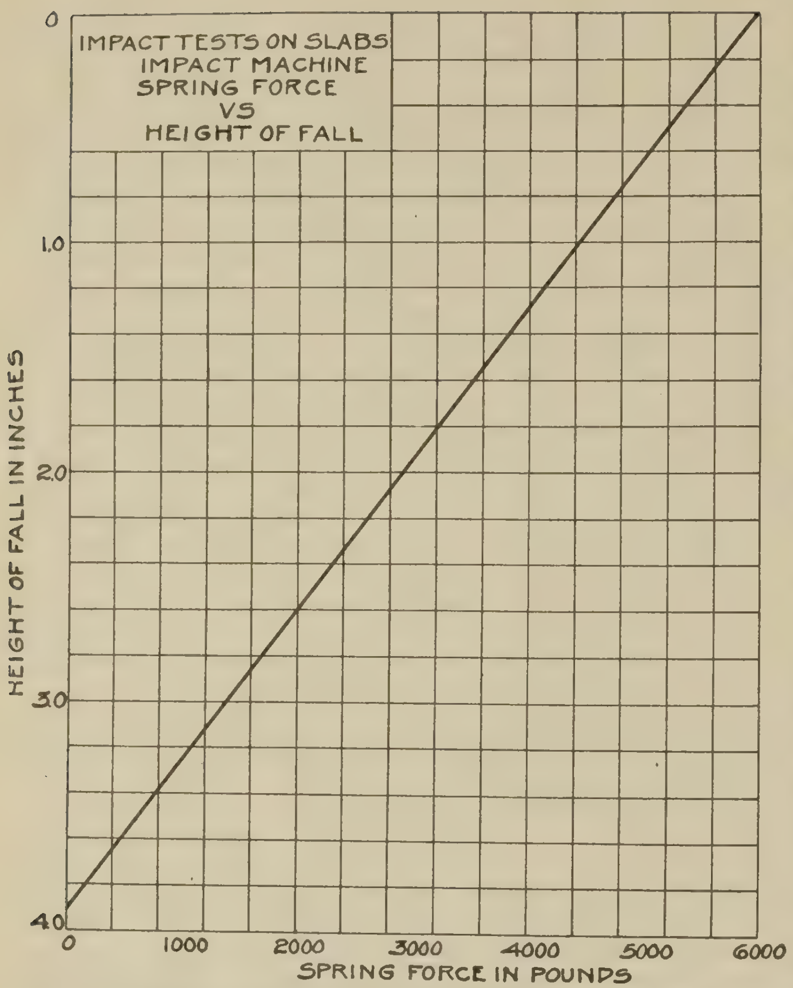


FIG. 10.—AVERAGE SPRING PRESSURE FOR VARIOUS HEIGHTS OF FALL.

puted from the space-time curves and the equivalent static load as indicated by the copper cylinder. It will be noted also that while the impact force, computed by the several methods has different values, a definite relation is shown between each value and the copper cylinder values, thus making the curves of practical use as a means of measurement of force. The indications are that the average force of impact as derived from the curves is one-third the maximum as derived from the tip of the curve, and the static load which produces the same deformation of copper is double the average or two-thirds of the computed maximum.

It will thus be seen that we have been able to express impact in terms of an equivalent static load and through this medium of expression we are enabled to compare the intensity of impact exerted on road slabs tested as already described.

In curve 3, figure 9, the equivalent static load is shown as given by the ½ by ½ inch copper cylinder. Curve 2 is the average curve developed from the space-time curves taken during the tests of different slabs at Arlington. Curve 1 is the curve worked out by the acceleration method for the equivalent static effect of the blow when no cylinder is used, and while there is no relation between the methods used for curves 1 and 2, they agree within about 5 per cent.

The close agreement of curves 1 and 2 furnishes sufficient proof that a definite relation exists between the effect of impact force and equivalent static load. Curve 1 gives the relation between the equivalent static loads as shown by the copper cylinders while curve No. 2 is twice the average impact forces as computed from theoretical formulæ. The difference between curves 2 and 3 represents the effect of the copper cushion. The ½ by ½ inch copper cylinder values corrected by these differences represent the equivalent static loads which could be expected if no cylinder were used. From the foregoing it can be seen that there is ample evidence to warrant the assertion that the force of impact blows as delivered by the road impact machine can be expressed as an equivalent static load and thus is secured a means of comparing the resistances of pavement sections when subjected to impact.

NEW BULLETIN ON MOTOR TRUCK OPERATION.

Department Bulletin No. 1201 just issued by the Department of Agriculture, entitled "Motor Trucks on Eastern Farms," while intended to be of use to farmers in the selection of trucks, contains considerable data useful to anyone interested in the operation of trucks for any purpose. It is largely a compilation of data obtained from 753 owners of trucks used for farm purposes.

Experience has convinced 80 per cent of these owners that trucks between the 1 and 2 ton size are best for their use and less than 3 per cent recommend larger trucks. The average length of haul is 10 miles and 35 to 40 per cent as much time is required to make a haul of a given length with a truck as with horse and wagon. Twenty-nine per cent of the trucks travel usually on dirt roads and can not be used on the average during 10.7 weeks in the year. The average distance traveled per year is 3,820 miles and the average life of a truck 6.7 years, the large trucks lasting somewhat longer than the small ones. Based on present prices it is estimated that the average repair costs covering the entire life of a machine are something like $50 to $150 per year for ½-ton to 2-ton trucks, the cost increasing with the size of the truck. The estimates of 318 men show that pneumatic tires run an average of 4,500 miles and the estimates of 206 men show that solid tires run an average of 8,200 miles.

The average number of miles per gallon of gasoline is about 15 miles for the ½-ton, 11 miles for the 1-ton, 9½-miles for the 1½-ton, and 8 miles for the 2-ton trucks. On the basis of 27 cents per gallon for gasoline and 65 cents per gallon for oil the cost of these items per mile for ½-ton trucks is 2.1 cents, 1-ton trucks 2.7 cents, 1½-ton trucks 3.1 cents, and for 2-ton trucks 3.8 cents.

The average operating cost per mile, including depreciation, repairs, interest on investment, registration, gasoline, oil, and tires is 8.2 cents for ½-ton trucks, 11.9 cents for 1-ton trucks, 19 cents for 1½-ton trucks, and 20.3 cents for 2-ton trucks. These costs do not include housing, taxes, insurance, and labor of the owner in making repairs.

PERMISSIBLE TOLERANCE OF SAND IN COARSE AGGREGATES

By W. K. HATT, Director, Highway Research Committee, Division of Engineering, National Research Council.

IN many gravel deposits there is an excess of coarse sand and a deficiency of pebbles, so that the general use of arbitrary concrete mixes of 1:1½:3, 1:2:4, etc., results in the accumulation at the plant of coarse sand which is wasted, except for limited sale. This coarse sand called "grits" runs from one-eighth inch to one-fourth inch in size. It lends strength to the concrete by permitting a workable mix with less water up to a point where the mix becomes too harsh.

In some pits a division of the fine and coarse aggregate on a one-eighth-inch screen instead of the one-fourth inch would yield concrete of standard quality and conserve a natural resource by the use of a greater portion of the deposit. However, the one-fourth inch as the dividing screen between the fine and coarse aggregate has become so fixed in practice that it would be unwise to modify this standard.

Another factor in the situation is that considerable coarse sand below the one-fourth-inch size clings to and comes through the screen with the pebbles and so lies with the coarse aggregate. By running the screens faster and thus increasing the production of the plant this amount of sand remaining in the coarse aggregate is increased. Specifications in the past have tolerated this coarse sand in the pebbles up to 5 per cent. Can this be increased in the interest of conservation and

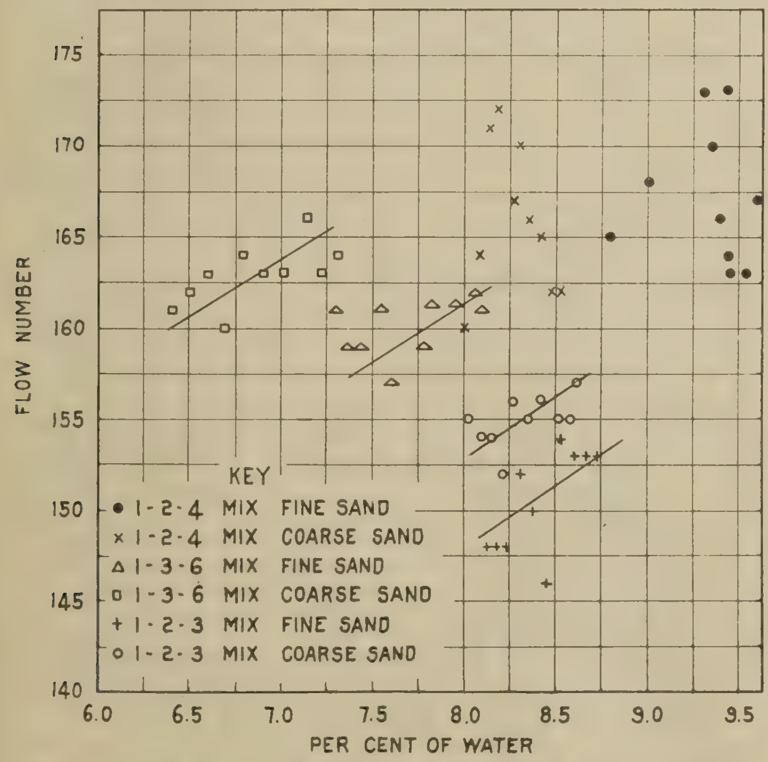


FIG. 1.—CHART SHOWING RELATION BETWEEN FLOW NUMBER AND PER CENT OF WATER FOR VARYING PER CENTS OF TOLERANCE. PER CENT OF WATER EXPRESSED AS PERCENTAGE OF CORRECTED WEIGHTS OF GRAVEL, SAND, AND CEMENT.

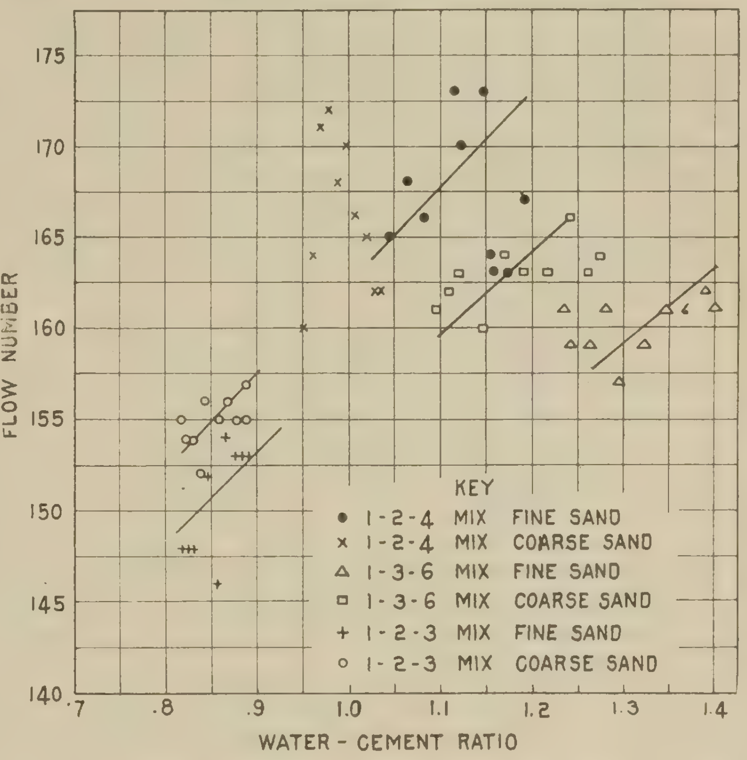


FIG. 2.—RELATION BETWEEN FLOW NUMBER AND WATER CEMENT RATIO FOR VARYING PER CENT OF TOLERANCE.

economy, without diminishing substantially the quality of the concrete or disturbing construction operations on the job? The materials testing laboratory of Purdue University investigated this question in cooperation with the Indiana highway commission and the Indiana Sand and Gravel Producers Association for 1:1½:3 concrete as reported in the proceedings of the American Concrete Institute, 1921.

Later a cooperative agreement was entered into with the Bureau of Public Roads extending the investigation to 1:2:3, 1:2:4, and 1:3:6 concrete, using in each case both a fine and a coarse sand as the fine aggregate. The present paper is an account of these tests.

The indications of the tests are that in the case of the material used for 1:1½:3, 1:2:3, and 1:2:4 proportions, a tolerance of 15 per cent may be allowed without substantially reducing the strength of the concrete and that the difference in the amount of water necessary to bring the various mixes to the same workability is not sufficient to disturb the mixing operations. Concrete of the 1:3:6 proportion became too harsh with such an increase of sand.

Fundamentally, of course, the gravel beds present a graded material ranging from fine to coarse and it might not be expected that an arbitrary division between fine and coarse on a one-fourth-inch screen would meet the technical elements of the situation.

DESCRIPTION OF TESTS AND MATERIALS.

The gravel and sand were obtained from Indiana beds. The cement was a mixture of three brands of Portland cement. The methods of test were those recommended by Committee C–9 of the American Society for Testing Materials in the proceedings for 1920, part 1, page 291, except that paraffined paper molds were used instead of steel molds. The concretes were all brought as nearly as possible to the same consistency as measured by the flow table. (See figs. 1 and 2.) The index of the latter varied approximately not more than 6 per cent, which is very close. The mix was by volume. The following series appear in the results:

Series No.	Mix.	Coarse aggregate.	Fine aggregate.
1	1:2:4	Medium grading	Fine sand.
2	1:2:4	do	Coarse sand.
3	1:3:6	do	Fine sand.
4	1:3:6	do	Coarse sand.
5	1:2:3	do	Fine sand.
6	1:2:3	do	Coarse sand.

The various curves (figs. 3 and 4) exhibit the sizes of the material; and the physical properties of the sand and pebbles are as follows:

Physical properties of the sand.

Property.	Fine sand.	Coarse sand.
Specific gravity	2.62	2.63
Weight in pounds per cubic foot	107.9	110.4
Compression strength, pounds per square inch, 28 days	3,600	4,500
Ratio to Ottawa sand	1.46	1.59
Surface area, square feet per pound	14.08	10.96
Fineness modulus	2.97	3.48

Physical properties of the pebbles.

Property.	Pebbles.
Specific gravity	2.56
Absorption	1.8
Abrasion loss	7.8
Fineness modulus	6.88
Surface area, square feet per 100 pounds	83.8

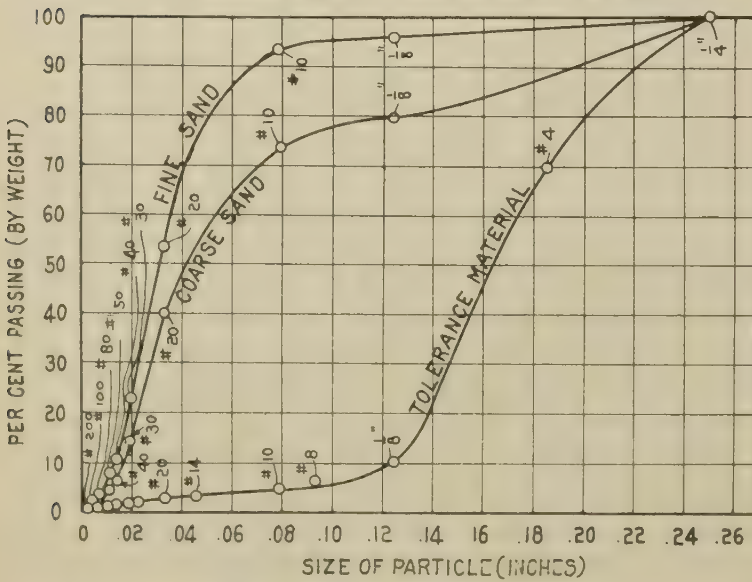


FIG. 3.—SIEVE ANALYSIS OF SANDS AND TOLERANCE MATERIAL.

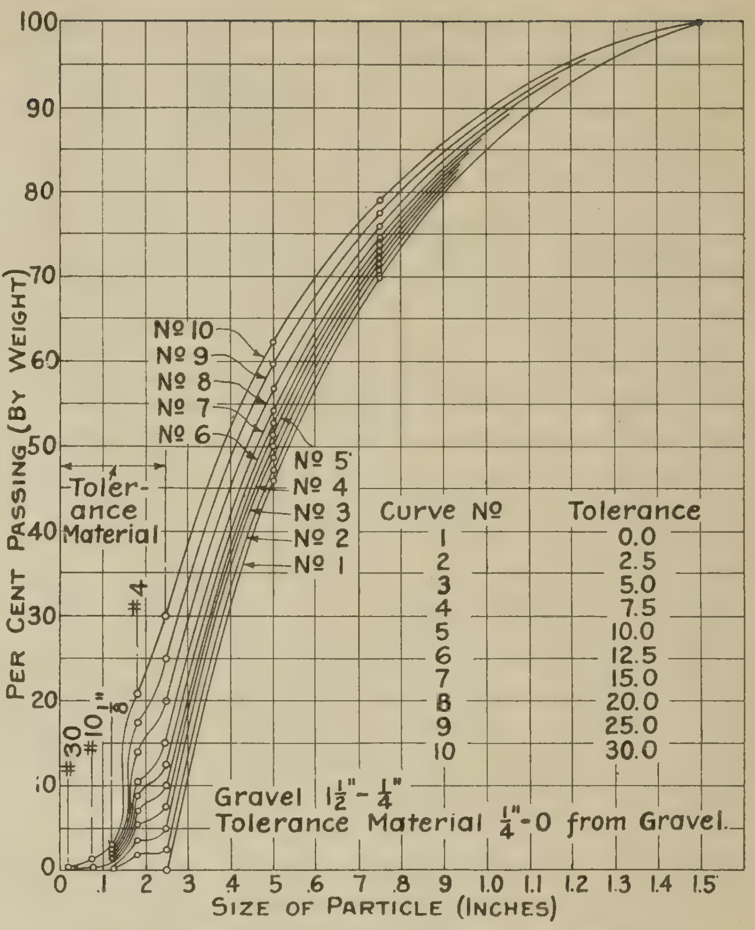


FIG. 4.—SIEVE ANALYSIS OF COARSE AGGREGATE.

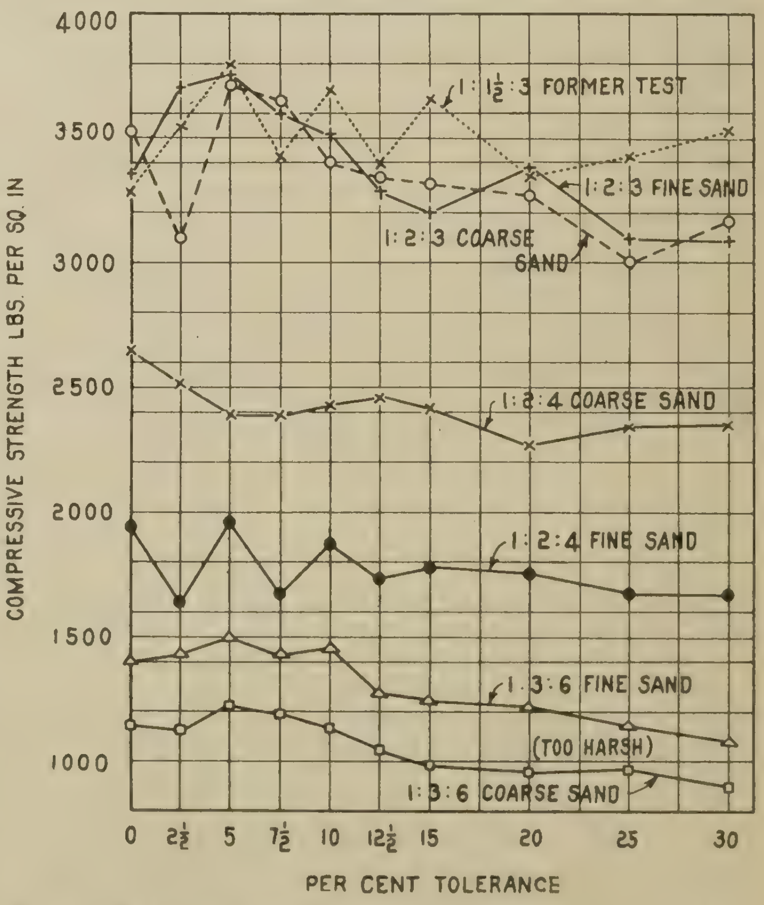


FIG. 5.—STRENGTH OF CONCRETE AS AFFECTED BY INCREASING PER CENT OF TOLERANCE.

The mix in terms of total aggregate is shown in Table 1. The water required to produce the consistency in the cases of the various mixes is shown in Table 2.

RESULTS OF THE TEST.

Figure 4 shows how the strengths of the concrete are affected by an increasing amount of tolerance material. Figure 5 represents these facts on a percentage scale. As shown by these curves the maximum strength is reached with 5 per cent of tolerance material and there is a decrease of strength with increasing tolerance beyond 5 per cent. The following decrease is noted at 15 per cent tolerance from the strength at zero tolerance:

	Per cent.
1 : 1½ : 3	0
1 : 2 : 3 coarse sand	5
1 : 2 : 3 fine sand	0
1 : 2 : 4 coarse sand	10
1 : 2 : 4 fine sand	9
1 : 3 : 6 coarse sand	12
1 : 3 : 6 fine sand	10

TABLE 1.—*Volume of aggregate to one volume of cement.*

Per cent tolerance.	Volume of aggregate to 1 volume of cement in mix.							
	1:1½:3 B concrete.	1:1½:3 C concrete.	1:2:3 with fine sand.	1:2:3 with coarse sand.	1:2:4 with fine sand.	1:2:4 with coarse sand.	1:3:6 with fine sand.	1:3: 6 with coarse sand.
0	3. 87	3. 93	4. 24	4. 38	5. 05	5. 20	7. 67	7. 95
2½	3. 88	3. 97	4. 26	4. 59	5. 10	5. 21	7. 72	7. 96
5	3 90	4. 03	4 30	4. 43	5. 16	5. 25	7. 76	7. 97
7½	3. 92	4. 05	4. 32	4. 44	5. 20	5. 31	7. 81	8. 00
10	3 93	4. 05	4. 35	4. 48	5. 26	5. 32	7. 86	8. 05
12½	3. 96	4. 08	4. 38	4. 51	5. 32	5. 36	7. 91	8. 07
15	3. 98	4 07	4. 41	4. 54	5. 36	5. 41	7. 97	8. 14
20	4. 02	4. 09	4. 45	4. 59	5. 47	5. 45	8. 04	8. 19
25	4. 07	4. 13	4. 46	4. 60	5. 52	5. 49	8. 09	8. 20
30	4. 14	4. 17	4. 48	4. 60	5. 55	5. 49	8. 09	8. 21

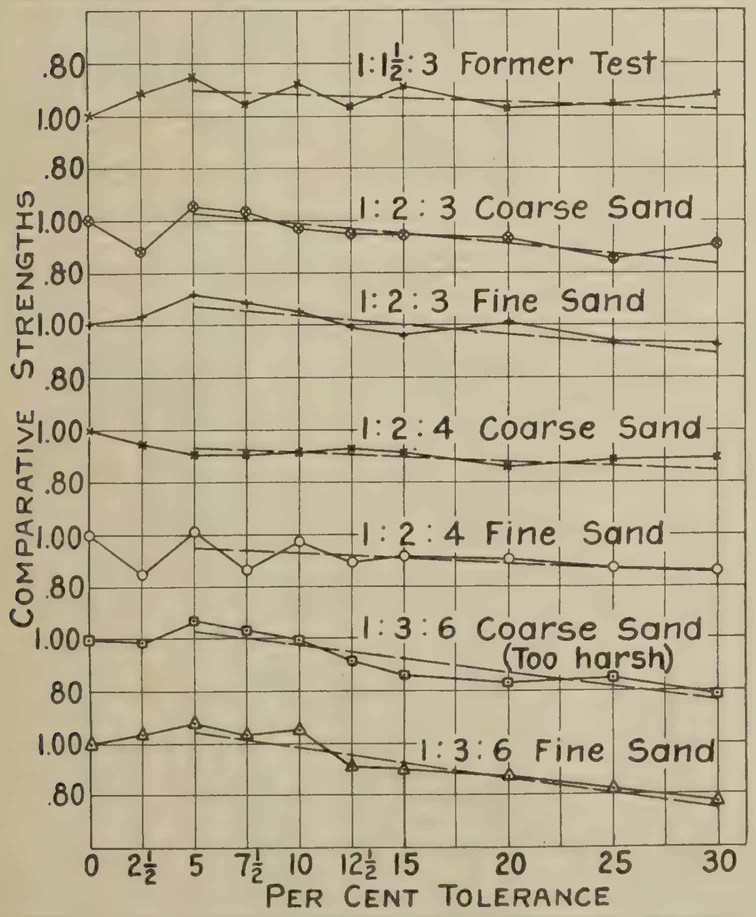


FIG. 6.—CHART SHOWING COMPARATIVE STRENGTHS OF CONCRETE AS AFFECTED BY INCREASING PER CENT OF TOLERANCE. COMPARATIVE STRENGTHS BASED ON STRENGTH AT 0 PER CENT TOLERANCE.

TABLE 2.—*Gallons of water per sack of cement.*

Per cent tolerance.	1:1½:3 B concrete.	1:1½:3 C concrete.	1:2:3 fine sand.	1:2:3 coarse sand.	1:2:4 fine sand.	1:2:4 coarse sand.	1:3:6 fine sand.	1:3:6 coarse sand.
0	5 77	6 11	6. 10	6 10	7. 81	7. 11	9. 22	8. 18
2½	5. 78	6. 18	6. 15	6. 15	7. 96	7. 18	9. 27	8. 29
5	5. 78	6. 30	6 20	6. 20	8. 09	7. 24	9. 43	8. 44
7½	5. 93	6. 25	6. 26	6. 25	8. 34	7. 31	9. 56	8. 58
10	5. 98	6. 30	6. 31	6. 31	8. 37	7 40	9. 67	8. 73
12½	6. 16	6. 37	6. 40	6. 40	8. 58	7. 45	9. 86	8 90
15	6. 03	6. 46	6. 46	6. 48	8. 63	7. 53	10. 05	9. 08
20	6. 25	6 73	6. 55	6. 56	8 70	7. 62	10. 23	9. 27
25	6. 22	6. 87	6 61	6. 64	8. 91	7. 70	10 38	9. 42
30	6. 31	7. 07	6. 64	6. 65	8. 77	7. 70	10. 44	9. 51

(Continued on page 26.)

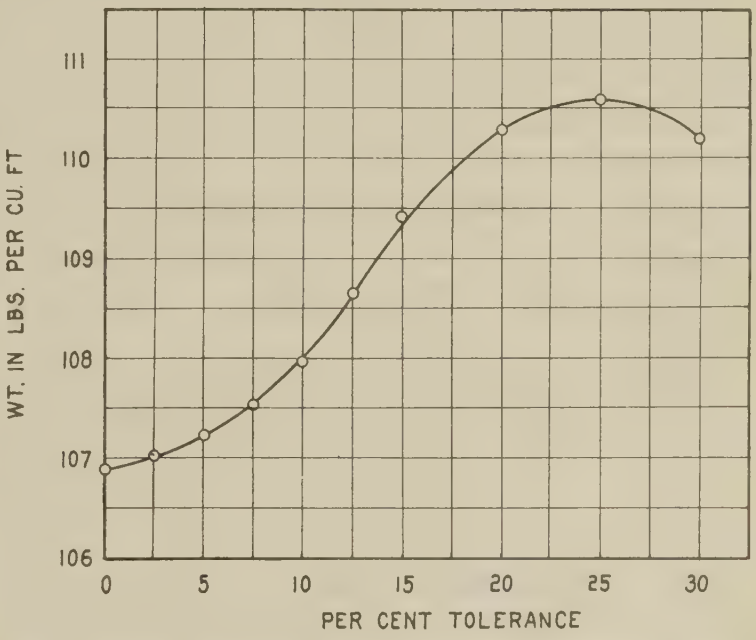


FIG 7.—WEIGHT PER CUBIC FOOT OF COARSE AGGREGATE WITH VARYING PERCENTAGE OF TOLERANCE.

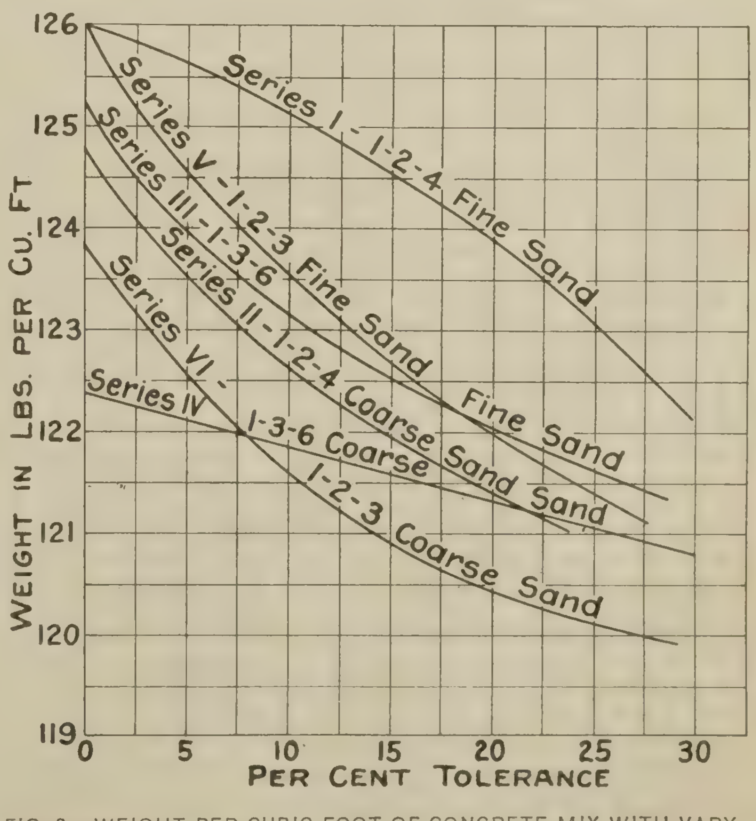
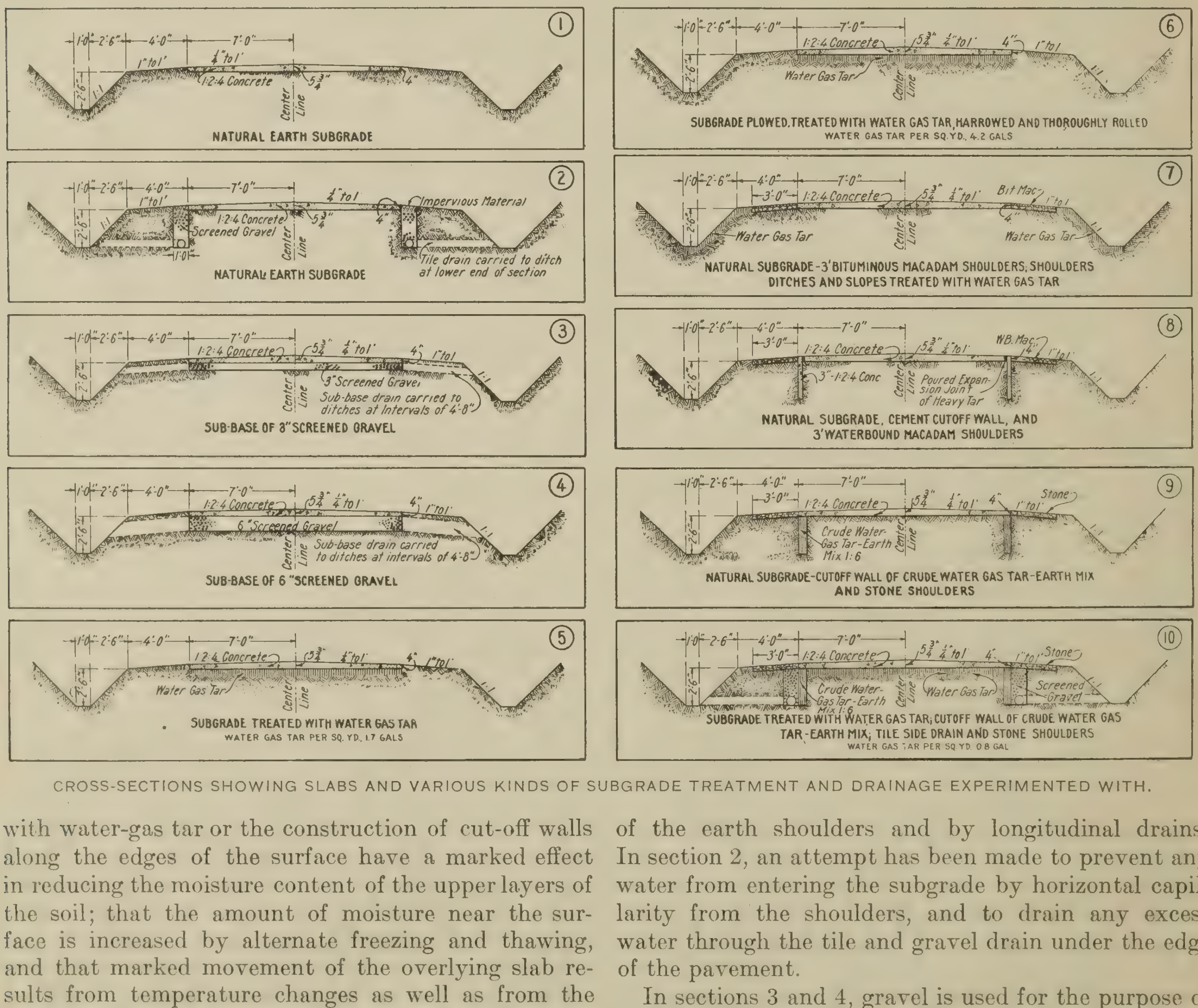


FIG. 8.—WEIGHT PER CUBIC FOOT OF CONCRETE MIX WITH VARYING PER CENT OF TOLERANCE.

SUBGRADE DRAINAGE TESTS YIELD INTERESTING PRELIMINARY DATA

By IRA B. MULLIS, Assistant Testing Engineer, Bureau of Public Roads.

THE subgrade drainage experiments which have been in progress at the Arlington, Va., experiment station of the Bureau of Public Roads since the fall of 1920 are yielding some interesting preliminary data. The more important indications noted to date are that with deep drainage ditches unobstructed the upper layers of the soil contain more moisture than the underlying soil, a condition which is reversed by flooding the ditches; that treatment of the subgrade with water-gas tar or the construction of cut-off walls along the edges of the surface have a marked effect in reducing the moisture content of the upper layers of the soil; that the amount of moisture near the surface is increased by alternate freezing and thawing, and that marked movement of the overlying slab results from temperature changes as well as from the changes in moisture content of the subgrade.



CROSS-SECTIONS SHOWING SLABS AND VARIOUS KINDS OF SUBGRADE TREATMENT AND DRAINAGE EXPERIMENTED WITH.

DESCRIPTION OF THE EXPERIMENT.

For the purposes of the experiment 10 concrete slabs, each 14 feet square, have been laid and surrounded by ditches as shown in the illustration on page 23. Each section was constructed entirely in cut and cutting below grade at any point was carefully avoided, so that the natural earth conditions would not be changed by any filling. The Susquehannah clay soil which composed the subgrade was not rolled, but at the time the pavements were laid it was unusually dry and compact.

As shown by the cross-sections on page 22, the drainage of section 1 is accomplished only by the slope of the earth shoulders and by longitudinal drains. In section 2, an attempt has been made to prevent any water from entering the subgrade by horizontal capillarity from the shoulders, and to drain any excess water through the tile and gravel drain under the edge of the pavement.

In sections 3 and 4, gravel is used for the purpose of distributing any loads on the pavement as well as for draining and aerating the subgrade.

Crude water-gas tar is used in sections 5 and 6 to waterproof the subgrade and thereby cause it to render greater support to the pavement.

Waterproofing has been resorted to on section 7, the attempt being made to waterproof shoulders from rainfall and the insides of the ditches against horizontal capillarity.

Horizontal capillarity is attacked in sections 8, 9, and 10 by the various methods indicated.

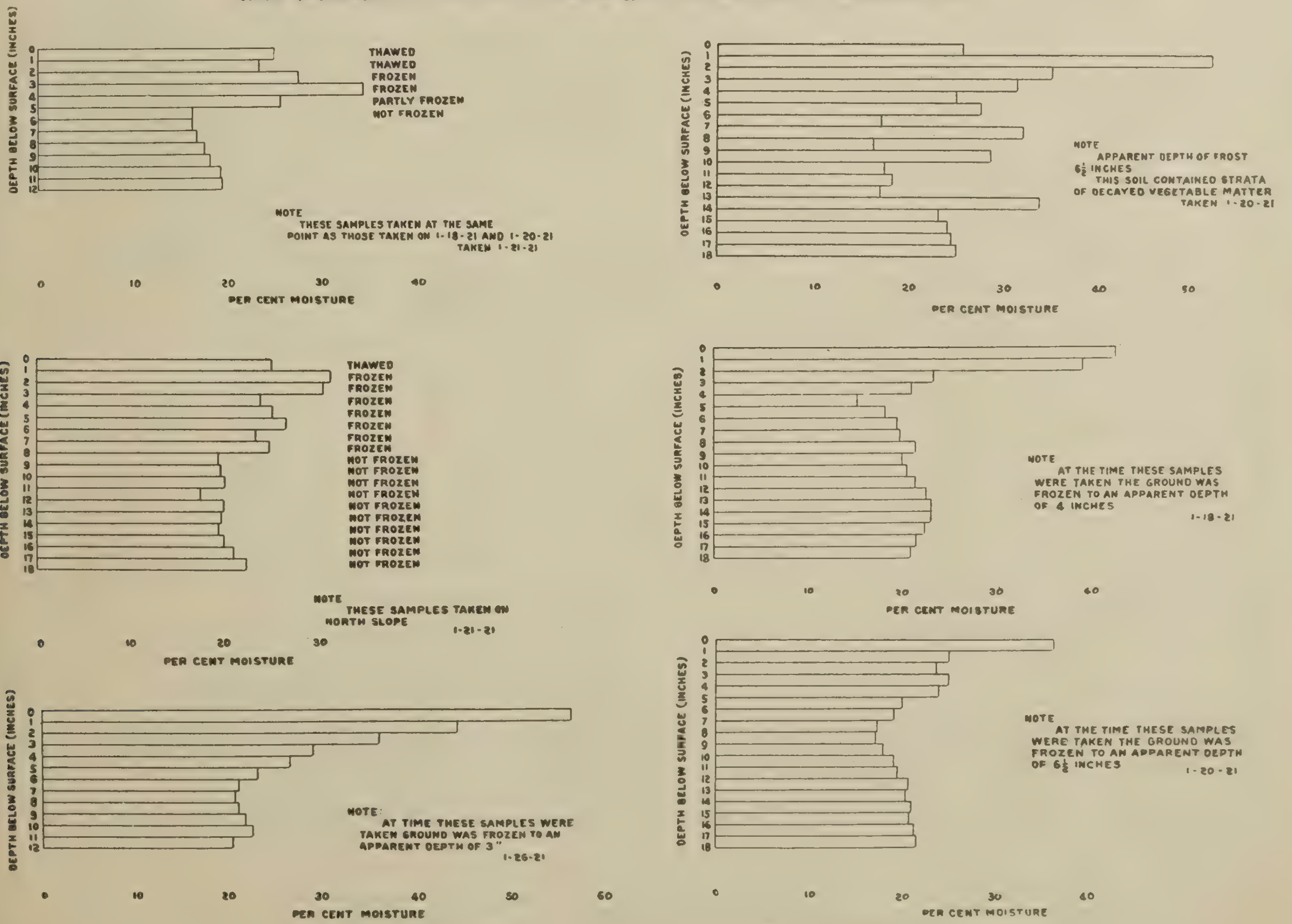
The square plates shown in the illustration on this page are water-tight caps fitted over openings in the pavements which extend entirely through the slabs for the purpose of making examinations of the subgrade, taking soil samples for moisture determinations, etc. The sheet-metal-encased wells, shown in the shoulders, were provided to show the elevation of the ground water. The casings of these wells are perforated below the surface of the ground to admit the water.

GENERAL VIEW OF EXPERIMENT.

The lateral ditches may be drained or flooded for the purpose of studying the effect upon the subgrade. Upon the completion of the studies involving the use of ditches, they will be filled with earth and the experiments continued.

In addition to taking samples of the soil for moisture content determinations, a careful record of rainfall and daily temperatures has been kept throughout the test; and, to follow the movements of the slabs resulting from moisture and temperature changes, precise levels have been taken from time to time on brass plugs embedded in the four corners and center of each slab. The bench mark to which the levels are referred consists of a truncated cone of monel metal in the upper end of a $1\frac{1}{4}$-inch galvanized iron pipe rising from a concrete base about 4 feet under ground. To protect the bench mark from the effects of temperature and frost the pipe was inclosed in a cylindrical casing closed at the top by means of a screw cap, and resting at the bottom on the concrete base, the lower end being waterproofed with 4 inches of heavy asphalt which securely seals the joint with the concrete base.

CHART SHOWING EFFECT OF FROST ACTION ON CAPILLARY MOISTURE AT VARIOUS DEPTHS



EFFECT OF FROST ACTION ON CAPILLARY MOISTURE AT VARIOUS DEPTHS.

OBSERVATIONS OF MOISTURE CONTENT AND SLAB MOVEMENT.

Moisture samples were taken from the subgrades throughout the fall and winter of 1920 but no great amount of water was observed until January 19 when, immediately after a 6-inch freeze, the following observations were made:

Section No.	Well No.[1]	Moisture condition.
1	1	Frosty, free water pressed out.
	3	Ice crystals in auger holes. These holes seem to make this well rather dry in appearance, still frozen.
1	7	Free water one-half inch deep.
	([2])	Frozen and rather dry.
	([3])	Wet, slaked, and contains free water.
2	1	Upper one-fourth inch very moist, still partly frozen.
	3	Ice crystals and slightly upheaved.
	5	Very wet, clay slaked.
3	1	Dry.
	3	Moist, but no free water.
	5	Do.
4	1	Frosty on top.
	3	Drier than perhaps any section in experiments.
5	1	Frost has upheaved surface. No water can be pressed out with thumb.
	3	Ice crystals under subgrade.
	7	Subgrade frosty and heaved.
6	1	Pressure of thumb will squeeze out water.
	3	Clay under surface of subgrade moist. Top of soil not as bad as well 7 of this section. This is probably due to borings which offer greater opportunity for drying out.
	5	Subsoil rather moist, but not wet.
	7	Clay moist and disintegrated by frost.
7	1	Clay slaked, no free water above surface.
	3	Ice crystals.
	7	Free water one-fourth inch deep.
8	1	Ice crystals showing.
	3	Somewhat frozen.
	4	Frosty with ice crystals showing.
9	1	1 inch of water standing on top of subgrade.
	3	Partly thawed, and clay slaked.
	7	1 inch of free water on top of subgrade.
10	1	Clay just under coating of water-gas tar entirely slaked and very wet.
	7	Same as well 1.

[1] The wells referred to are the 6-inch openings through the pavements to permit examination and sampling of the soil.
[2] Well between 3 and 7.
[3] Well to right of 7.

A number of samples taken after the same freeze in an open field and on ditch banks near the experimental sections yielded moisture contents which are shown in the chart on page 23. The chart indicates very clearly that alternate freezing and thawing tends to increase surface moisture. The mild winter offered no further opportunity for the investigation of this phenomenon, but the study is now being continued by artificial methods.

At all times when the ditches were unobstructed the wettest part of the subgrade was observed to be the upper surface. The samples taken to determine the variation in moisture content were first taken at vertical intervals of 6 inches, but later this interval was found to be too great, and samples are now taken at the following depths in inches: $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, 2, 3, 4, 5, 6, 12, 18, and 24.

As noted in the chart on page 25, the natural rainfall was supplemented in the spring of this year by the use of lawn sprinklers placed on each section. On May 30, after about two weeks of sprinkling during which time the artificial precipitation was several times greater than the natural rainfall at any preceding time, the sprinkling was discontinued and moisture determinations were made for the several sections at various depths with the results indicated in the table below.

Percentage of moisture at various depths under several sections.

Depth.	Section No.									
	1	2	3	4	5	6	7	8	9	10
Inches.										
$\frac{1}{4}$	26.4	25.3	26.3	24.3	21.5	20.3	22.1	19.1	20.6	20.3
$\frac{1}{2}$	23.3	21.4	24.3	22.1	21.3	19.8	21.5	18.5	20.4	19.9
$\frac{3}{4}$	20.5	20.4	23.1	21.3	19.7	20.1	19.8	18.5	20.5	19.2
1	19.1	22.7	21.4	19.6	18.5	20.0	20.4	18.3	20.2	18.8
2	18.4	19.6	15.3	18.6	18.8	18.3	20.1	19.0	20.7	19.1
3	14.8	18.6	19.2	18.6	19.0	15.0	20.6	18.5	19.9	19.1

Moisture determinations were not made to a greater depth than 3 inches for the reason that as the depth increased the moisture content was so low that it was considered unnecessary to sample deeper. Before sprinkling was discontinued it was decided that nothing would be gained by further sprinkling, since the subgrade was not becoming any wetter and the percentages of moisture above indicated represent approximately the maximum amount of water which would be absorbed by this particular soil under the climatic condition prevailing at that time and with the construction and drainage shown.

Some idea of the movement of the pavement resulting from changes in moisture content may be obtained from the chart on page 25. At only one time during the period represented by the chart was there a frost which penetrated to the depth of the pavement. The effect of this freeze is shown on January 19. The maximum observed lift on this date was 0.07 foot.

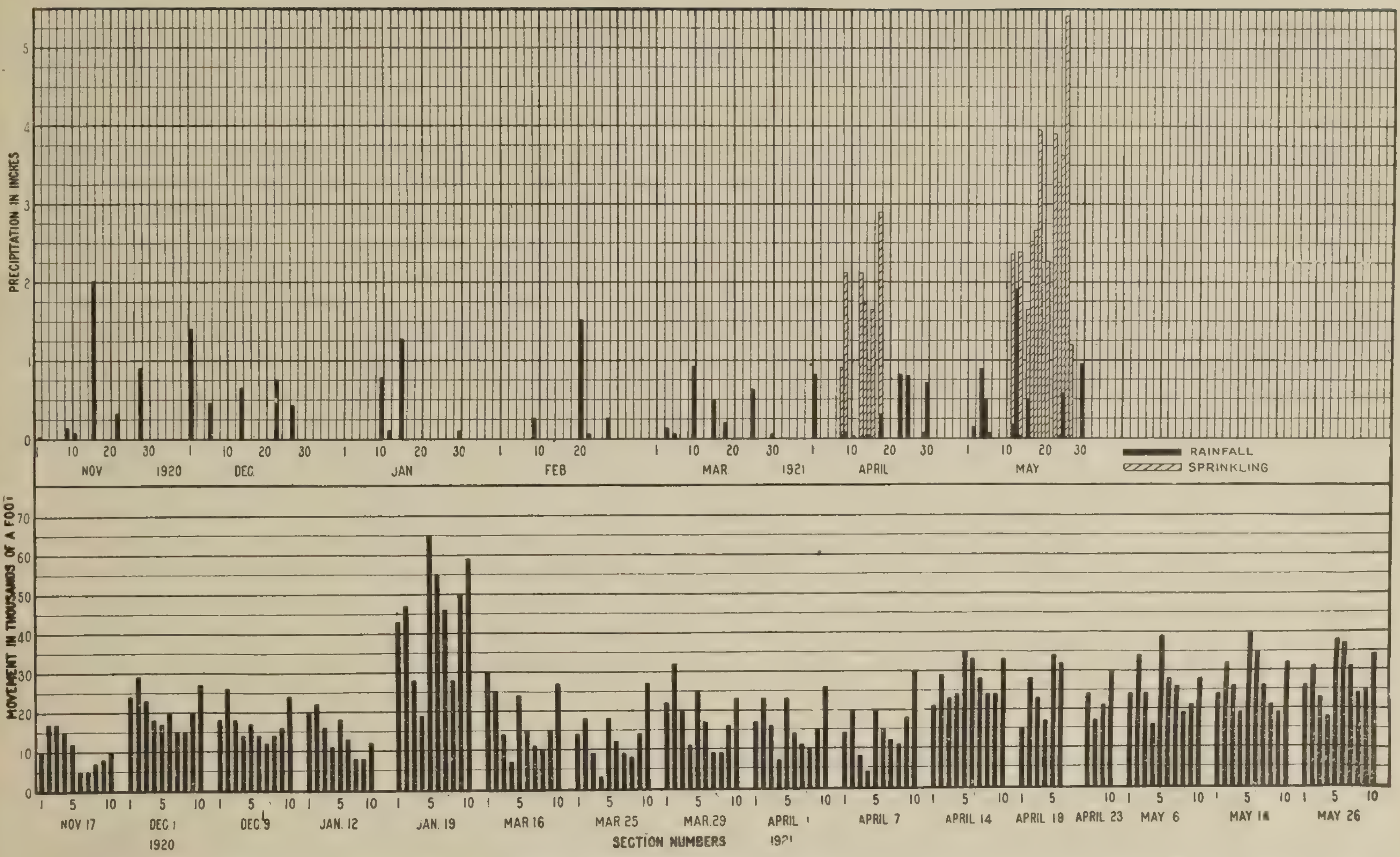
The average movement of the various pavements for the whole period was as follows:

Comparison of movement of various sections.

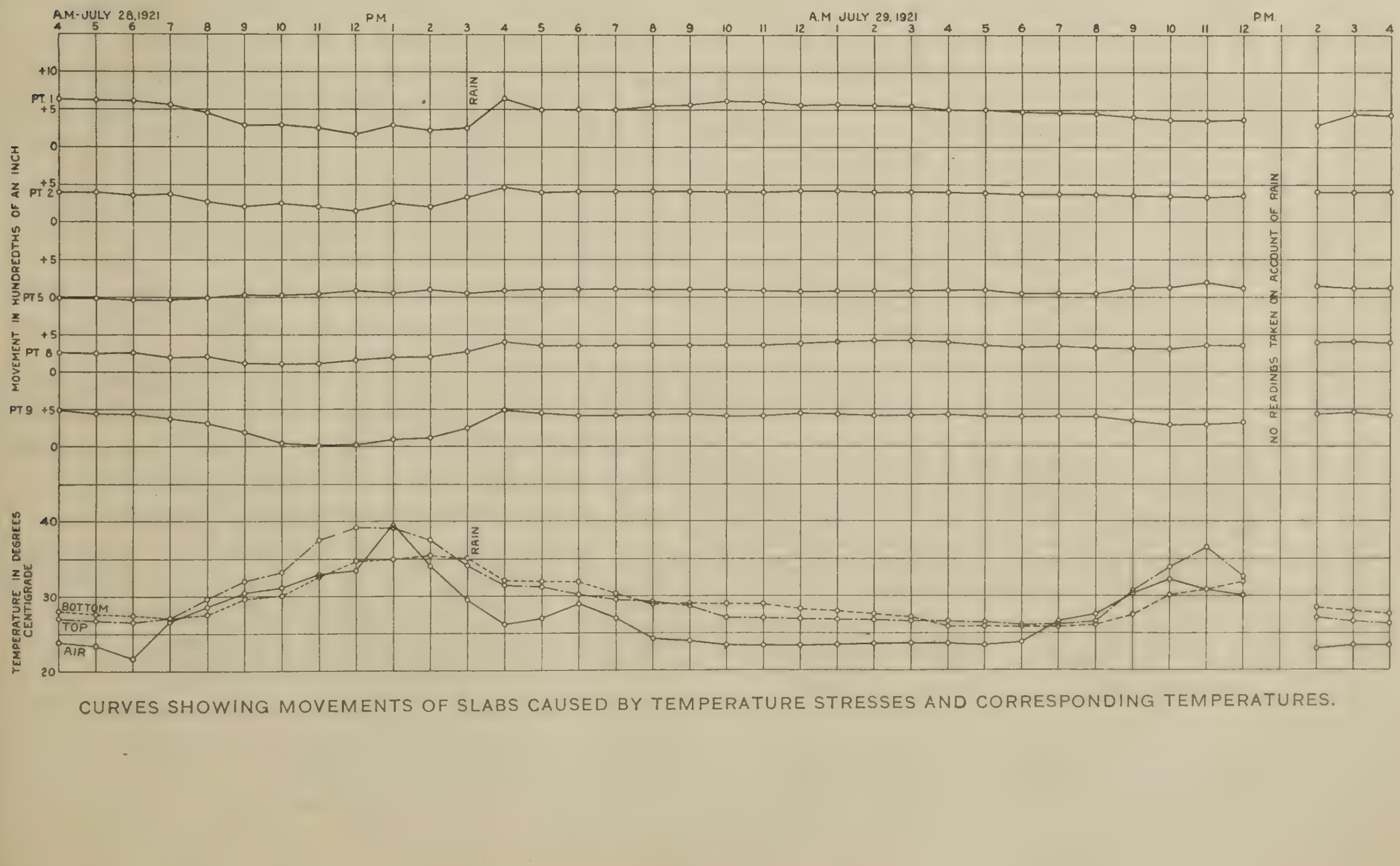
Section No.	Average movement in thousandths of a foot.
4	14.7
8	15.1
7	18.3
3	19.3
1	19.7
9	19.8
6	22.5
5	27.7
2	27.9
10	28.5

THE EFFECT OF STANDING WATER IN SIDE DITCHES.

The effect of standing water in the side ditches has been under observation since July 15, 1921, when dams were built across the lateral drains to such height that the surface of the water in these drains stood approximately 18 inches below the subgrades of the various sections. The height of the water table in



SHOWING HOW SUBGRADE MOISTURE AND FREEZING AFFECT THE HEIGHT OF THE CONCRETE PAVEMENTS AT ARLINGTON.



CURVES SHOWING MOVEMENTS OF SLABS CAUSED BY TEMPERATURE STRESSES AND CORRESPONDING TEMPERATURES.

the ditches has been kept constant as nearly as possible by allowing water to flow in daily except Sunday.

On August 10 the average percentages of moisture at various depths under the several sections were as follows:

Depth in inches.	Section No.									
	1	2	3	4	5	6	7	8	9	10
	Per cent of moisture.									
0 to 3.....	19.2	19.7	18.7	20.8	15.8	14.9	20.5	19.7	19.9	17.0
0 to 6.....	19.9	19.9	18.8	20.8	16.4	14.8	20.5	19.9	19.8	17.3
0 to 24....	20.0	20.0	19.2	20.8	17.0	16.2	21.0	20.4	20.3	18.8
18 to 24...	21.3	21.2	20.6	21.2	19.7	18.3	21.1	22.1	21.1	22.1
24 to 30...	21.9	21.7	21.1	22.2	20.3	19.8	20.4	22.7	21.6	22.4

It will be noted from the above figures that the average percentage of moisture in the subgrade increases with the depth—a condition just the reverse of that which exists when the lateral ditches are unobstructed. The flooded condition of the lateral drains will be continued for several weeks more and other moisture determinations will be made for the purpose of determining what the maximum saturation will be under these conditions.

MOVEMENTS CAUSED BY TEMPERATURE CHANGES.

In the course of the measurement of the movement of the slabs it was noted that the elevations varied from day to day without any corresponding variation of the moisture content of the subgrade. It was thought that such changes might be due to temperature stresses in the pavement itself.

For the purpose of checking this assumption and detecting any movement which might occur very precise measurements were made every hour of the day and night across the center of section 1 and these readings together with the air temperature and the temperature of the upper and lower surfaces of the pavement are plotted on page 25. It will be noted from this graph that the edges of the slab turn downward as the upper surface is heated and upward when the top surface temperature becomes lower than that of the bottom surface of the pavement.

The maximum change noted so far has been slightly more than one-twentieth of an inch. It will be observed that the cooling effect of the two rains which occurred during the period of observation produced rapid changes in elevations. These rather marked temperature-stress changes would indicate the need for more study and research in pavement design as well as in subgrade preparation.

PENNSYLVANIA PAGEANT DEPICTS PROGRESS OF HIGHWAY TRANSPORTATION.

A Conestoga wagon built in 1802, a one-cylinder Cadillac car built in 1902, the famous "Washington Coach" from Valley Forge, a Concord stage coach, a "one-hoss shay" built in the eighteenth century, and dozens of other ancient vehicles of all sorts were the features of a pageant depicting the development of highway transportation, which was held at Caledonia Park, between Gettysburg and Chambersburg, Pa., on October 4.

The pageant included 30 episodes, starting with a lone Indian on his pony to represent the earliest stage of American highway transport. Following were highway scenes of colonial days, and the several later periods, leading up to a representation of modern transport in which a $15,000 passenger automobile was used. Each episode was introduced by appropriately costumed heralds.

During the last two years the State highway department has completed a concrete roadway which extends from Harrisburg to Gettysburg and from Gettysburg to Chambersburg. This road triangle is 113 miles in length. Caledonia Park is midway between Gettysburg and Chambersburg on the Lincoln Highway. On one side of it are 135.5 miles of good road leading to Philadelphia; on the other side 161.2 miles leading to Pittsburgh. The section between Gettysburg and Chambersburg represents the last word in modern highway construction, as does that from Gettysburg to Harrisburg.

Ten thousand persons were fed free of charge at an ox roast held at the park. Five oxen were spitted and roasted in a hollow square composed of 600 feet of tables. The pageant of road development, 1 mile long, formed at Graeffenburg Inn. The speakers' stand was erected over the remains of the old iron furnance built by Thaddeus Stevens and destroyed in 1863 by the Confederates on their way to Gettysburg.

The State police had charge of the immense traffic, which thronged all roads leading to Gettsyburg, Caledonia Park, and Chambersburg. Parking areas were arranged to accommodate 10,000 automobiles. The State department of health had several emergency hospitals between Chambersburg and Gettysburg.

(Continued from page 21.)

It appears, therefore, that the recent action of the joint committee of the several engineering societies in recommending 15 per cent tolerance is reasonable. It is not clear that a gravel plant can deliver material of a uniform percentage of tolerance. However, if this tolerance does vary, the quality of the concrete and the water control in mixing will vary to a minor degree—minor in respect to the unavoidable variations in other elements of construction.

It should be said finally that a laboratory investigation of this kind should be supplemented by a field study to determine if there may be difficulties arising in the handling of materials or from other causes which might qualify the conclusions.

NEW EXPERIMENTAL WORK BEGUN BY THE BUREAU OF PUBLIC ROADS.

THE Bureau of Public Roads is preparing to undertake a number of new experiments which should develop information fully as interesting and important as the impact and wear tests which have attracted such wide attention. The new studies include an investigation to determine the cause of wavy road surfaces, a study of the warping of concrete road slabs as a result of temperature changes, an experiment to determine the effect of slab vibration upon the movement of moisture in the subgrade, a study of impact stresses in bridges and other frame structures, and a large scale experiment to test various designs of concrete surface sections.

CAUSES OF SURFACE CORRUGATION TO BE STUDIED.

The study of the cause of wavy road surfaces will be made on a circular track 15 feet wide and 180 feet in diameter, which is being built at the Arlington Farm. The circumference of the circle will be divided into sections, each of which will be surfaced differently with various kinds of tar and asphalt pavement, some of them on concrete bases. The "traffic" to which these sections will be subjected will be supplied by a driverless motor truck, which will be held to the circular path by means of an arm extending from a circular guide rail mounted on concrete posts at the edge of the track. By a simple device the course of the truck will be altered from time to time so that the entire width of the roadway will be traveled over. At this time the subgrade has been prepared, and the construction of the bases and surface courses will follow immediately. It is not likely that the actual experimental work will be begun until next season.

The astonishing vertical movement of concrete slabs has already been observed in connection with other tests. The edges of such slabs have been found to curl up and down, depending upon the relative temperatures of their upper and lower surfaces. When the top surface is warmed the edges move downward; when the top cools the movement is in the opposite direction. The extreme movement observed so far is about one-tenth of an inch. A new slab has now been constructed and special observations of this phenomenon will be made.

To test the accuracy of the common assumption that vibration of road surfaces increases the moisture content of the upper layers of the subgrade soil, two new concrete slabs will be constructed. On one will be mounted a gasoline engine with an unbalanced flywheel, the revolution of which will set up vibrations in the slab. The other slab will not be vibrated. The effect of the vibrations will be studied by comparative observations of the moisture content of the soil underlying the two slabs. If it is found that the vibrations do increase the moisture at the top, the gasoline engine will be used to accelerate the tests which are being made to determine the effect of subgrade moisture.

INGENIOUS DEVICE TO STUDY BRIDGE IMPACT STRESSES.

The study of impact stresses in bridges will be made with a new instrument devised in the bureau and now practically perfected. Attached to any member of the bridge the instrument makes a photographic record of the effect of a moving load. The deformation resulting from the impact is represented by a fine line on the photograph. From the preliminary tests which have been made it appears that the results of the quickest blows are measured by the instrument. It is now being calibrated and will shortly be put into use to obtain experimental data.

EXPERIMENTS WITH VARIOUS CONCRETE ROAD SECTIONS.

The experiments on concrete sections will be made on the Columbia road in Arlington County, Va., and the cost of the construction will be shared by the county. Only a part of the road will be used for experimental purposes. Various sections will include surfaces with different kinds of joints, some with longitudinal joints and some without. Some will be built with gravel subbases; others will be built over especially treated subgrades in which the soil will be mixed with cement for a depth of 6 inches, using 1 part of cement to 20 parts of earth. Of special interest will be the various forms of ribbed sections and the various arrangements of different kinds of reinforcing material. The road is now under construction, but it will not be completed until next season. This experiment differs from the others previously described in that the various surfaces will not be subjected to artificial wearing or stressing devices. They will be actual road sections and will be subjected to normal road traffic, the weight and volume of which will be determined by careful traffic counts.

FEDERAL AID ALLOWANCES.

PROJECT STATEMENTS APPROVED IN AUGUST, 1921.

State.	Project No.	County.	Length in miles.	Type of construction.	Project statement approved.	Estimated cost.	Federal aid.
Arkansas	142	Sevier	6.500	Gravel	Aug. 23	$173,468.28	$10,000.00
California	81	Trinity	10.610	do	Aug. 6	290,004.00	145,002.00
	82	Inyo	8.370	Bituminous macadam	do	164,807.50	82,403.75
	83	do	11.660	Earth	do	118,195.00	59,097.50
Colorado	130	Arapahoe-Douglas	1.004	Concrete	do	37,998.71	18,999.35
	136	Jefferson	4.798	Earth	Aug. 9	59,990.81	29,995.40
	139	Larimer	4.023	Concrete	Aug. 15	159,999.18	79,999.59
	141	Logan	1.868	do	Aug. 24	79,997.77	37,360.00
	142	do	2.500	do	Aug. 15	89,980.99	44,990.49
	163	Pueblo	Bridge.		Aug. 6	66,000.00	33,000.00
	169	Bent	do		do	110,000.00	55,000.00
Florida	29	Hillsborough	do		Aug. 23	49,500.00	24,750.00
Georgia	198	Clay	6.00	Sand-clay and gravel	Aug. 5	53,500.00	17,500.00
	211	Spalding	4.899	Bituminous macadam	Aug. 11	123,365.13	1,000.00
	215	Banks	4.800	Top soil	Aug. 5	52,286.00	26,143.00
Indiana	29	Gibson-Knox	Bridge.		July 28	544,500.00	272,250.00
Kansas	77	Hamilton	5.672	Earth	Aug. 6	35,640.00	16,250.00
	86	Shawnee	4.029	do	Aug. 10	50,517.16	12,000.00
	87	Doniphan	2.500	Concrete, bituminous, or W. B. macadam.	Aug. 6	111,016.40	37,500.00
Kentucky	35	Boyd	[1] 0.690	Brick and bituminous	Aug. 9	[1] 64,977.22	[1] 32,488.61
	37	Breckenridge		Earth	Aug. 20	[1] 687,782.29	[1] 343,891.14
	51	Henderson	[1] 16.400	do	Aug. 23	[1] 531,080.00	[1] 265,540.00
	52	Pike	10.000	do	Aug. 20	408,017.50	200,000.00
	56	Lawrence	18.500	do	do	330,000.00	165,000.00
	62	Union	8.900	do	Aug. 23	78,815.00	39,407.50
Maine	30	Androscoggin	3.098	Gravel	Aug. 6	74,139.62	37,069.81
Maryland	31	Charles	[2] 3.340	do	July 28	[2] 15,368.86	[2] 2,536.88
	36	Anne Arundel	1.860	Concrete	do	[2] 71,576.11	[2] 7,157.61
Massachusetts	63	Essex	4.552	Bituminous macadam	Aug. 27	211,090.00	91,040.00
	65	Berkshire	1.638	Concrete	Aug. 5	100,430.00	20,000.00
	66	Worcester	1.168	do	Aug. 27	74,800.00	23,360.00
	69	Essex	2.675	do	do	153,670.00	53,500.00
Michigan	49	Cass-St. Joseph	12.700	Concrete or bituminous concrete	July 28	634,623.00	294,000.00
	63	Bay	8.800	do	do	338,470.00	169,235.00
Minnesota	100	Steele		Brick, concrete, or asphalt	Aug. 23		[1] 45,000.00
	205	Todd	16.520	Gravel	Aug. 17	157,773.66	1,000.00
	206	Sherburne	17.420	Concrete, brick, or asphalt	do	635,462.25	10,000.00
	211	Pope and Stevens	15.220	Gravel	do	179,578.24	10,000.00
	217	Sherburne	9.960	do	do	133,462.61	10,000.00
	221	Ormsted	10.680	do	Aug. 15	56,390.40	5,000.00
Mississippi	102	Leake	[1] 8.650	do	Aug. 12	[2] 12,232.98	[2] 6,116.49
	112	Noxubee	9.750	do	Aug. 5	134,421.38	67,210.69
	118	Clarke	18.000	Earth and gravel	Aug. 10	128,141.20	57,663.54
	119	Lauderdale	4.150	Gravel	Aug. 6	36,133.90	18,066.95
	123	Jasper	14.200	do	Aug. 8	128,469.00	64,239.50
	124	Pearl River	8.900	do	Aug. 9	104,417.50	52,208.75
	125	Wayne	6.400	do	do	68,769.25	34,384.62
	127	Jones	9.400	Gravel	Aug. 1	109,758.00	54,879.00
Nebraska	178	Sarpy	2.000	Earth	Aug. 16	11,550.00	5,775.00
New Mexico	69	Lea	11.500	Earth and caliche	July 28	41,569.00	20,784.50
	70	do	14.000	Earth	do	23,925.00	11,962.50
	74	Valencia	7.000	Stone surface	Aug. 6	53,328.00	26,664.00
New York	132	Orange	.600	Bituminous macadam or concrete	July 28	77,000.00	17,135.00
	139	Suffolk		Bituminous macadam	Aug. 8	[1] 100.00	[1] 135.15
	159	Otsego	.500	Bridge (railroad crossing)	July 28	100,000.00	24,000.00
North Dakota	47	Barnes	7.000	Gravel	Aug. 1	39,270.00	19,635.00
	116	Walsh	15.000	Earth	Aug. 29	47,300.00	23,650.00
Ohio	120	Darke	4.376	Brick or concrete	Aug. 8	237,000.00	41,000.00
	148	Mercer	6.006	Concrete or Kentucky rock asphalt	Aug. 12	266,000.00	80,000.00
	210	Fulton	3.359	Concrete	July 28	136,500.00	65,000.00
	214	do	3.009	do	do	122,900.00	40,000.00
	216	Lucas	2.156	do	July 30	79,000.00	20,000.00
	218	Tuscarawas	3.342	Concrete or brick	Aug. 8	161,000.00	15,000.00
	222	Medina	3.612	Concrete	do	148,000.00	70,000.00
South Carolina	108	Abbeville	19.534	Top soil	Aug. 6	76,942.06	38,471.03
	129	Greenville	1.000	Concrete or bituminous concrete	Aug. 9	39,275.88	19,637.94
	134	Abbeville	2.350	Top soil	Aug. 15	6,917.60	3,458.80
South Dakota	77	Yankton	19.920	Earth	Aug. 26	86,790.00	43,395.00
	78	Tripp	18.026	do	do	104,029.20	52,014.60
Texas	211	Travis	9.150	Gravel	Aug. 10	249,107.49	50,000.00
	254	Houston	15.710	Sand clay	do	119,135.06	30,000.00
West Virginia	33	Preston	[1] 1.560	Bituminous macadam	July 28	[1] 18,560.00	[1] 9,280.00
	77	Greenbrier	[1] 3.010	Earth	do		
	82	Gilmer	[1] 5.000	do	do	[2] 10,150.00	[2] 5,075.00
Wisconsin	106	Crawford	8.900	Top soil	do	176,002.20	63,854.67
	180	Iowa	4.340	Mine tailings	do	63,481.00	20,000.00
	200	Dane	7.350	Earth	Aug. 6	74,046.50	30,000.00
	251	Washburn	2.100	Top soil	Aug. 1	21,125.29	9,000.00
	261	Wood	2.000	Concrete	Aug. 10	65,577.52	29,000.00
	262	Dodge	.850	do	Aug. 6	26,000.00	9,920.91
Wyoming	111	Lincoln	2.321	Earth	Aug. 10	32,670.00	16,335.00

[1] Revised statement. Amounts given are decreases over those in the original statement.
[2] Revised statement Amounts given are increases over those in the original statement.

Correction: New Jersey Federal-aid project No. 32, reported as approved in the August number is a concrete road and not macadam as reported.

ROAD PUBLICATIONS OF BUREAU OF PUBLIC ROADS.

Applicants are urgently requested to ask only for those publications in which they are particularly interested. The Department can not undertake to supply complete sets, nor to send free more than one copy of any publication to any one person. The editions of some of the publications are necessarily limited, and when the Department's free supply is exhausted and no funds are available for procuring additional copies, applicants are referred to the Superintendent of Documents, Government Printing Office, this city, who has them for sale at a nominal price, under the law of January 12, 1895. Those publications in this list, the Department supply of which is exhausted, can only be secured by purchase from the Superintendent of Documents, who is not authorized to furnish publications free.

REPORTS.

*Report of the Director of the Office of Public Roads for 1917. 6c.
Report of the Director of the Bureau of Public Roads for 1918.
Report of the Chief of the Bureau of Public Roads for 1919.
Report of the Chief of the Bureau of Public Roads for 1920.

DEPARTMENT BULLETINS.

Dept. Bul. *105. Progress Report of Experiments in Dust Prevention and Road Preservation, 1913. 5c.
*136. Highway Bonds. 25c.
220. Road Models.
*230. Oil Mixed Portland Cement Concrete. 10c.
*249. Portland Cement Concrete Pavements for Country Roads. 15c.
257. Progress Report of Experiments in Dust Prevention and Road Preservation, 1914.
314. Methods for the Examination of Bituminous Road Materials.
347. Methods for the Determination of the Physical Properties of Road-Building Rock.
*348. Relation of Mineral Composition and Rock Structure to the Physical Properties of Road Materials. 10c.
*370. The Results of Physical Tests of Road-Building Rock. 15c.
*373. Brick Roads. 15c.
386. Public Road Mileage and Revenues in the Middle Atlantic States, 1914.
387. Public Road Mileage and Revenues in the Southern States, 1914.
388. Public Road Mileage and Revenues in the New England States, 1914.
*389. Public Road Mileage and Revenues in the Central, Mountain, and Pacific States, 1914. 15c.
390. Public Road Mileage in the United States, 1914. A summary.
*393. Economic Surveys of County Highway Improvement. 35c.
407. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1915.
414. Convict Labor for Road Work.
*463. Earth, Sand-Clay, and Gravel Roads. 15c.
532. The Expansion and Contraction of Concrete and Concrete Roads.
*537. The Results of Physical Tests of Road-Building Rock in 1916, Including all Compression Tests. 5c.
555. Standard Forms for Specifications, Tests, Reports, and Methods of Sampling for Road Materials.
583. Reports on Experimental Convict Road Camp, Fulton County, Ga.
586. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1916.
*660. Highway Cost Keeping. 10c.
670. The Results of Physical Tests of Road-Building Rock in 1916 and 1917.
*691. Typical Specifications for Bituminous Road Materials. 15c.
704. Typical Specifications for Nonbituminous Road Materials.
*724. Drainage Methods and Foundations for County Roads. 20c.
*Public Roads, Vol. I, No. 11. Tests of Road-Building Rock in 1918.
*Public Roads, Vol. II, No. 23. Tests of Road-Building Rock in 1919. 15c.

DEPARTMENT CIRCULAR.

No. 94. TNT as a Blasting Explosive.

FARMERS' BULLETINS.

F. B. *338. Macadam Roads. 5c.
505. Benefits of Improved Roads.
597. The Road Drag.

SEPARATE REPRINTS FROM THE YEARBOOK.

Y. B. Sep. 727. Design of Public Roads.
739. Federal Aid to Highways, 1917.

OFFICE OF PUBLIC ROADS BULLETINS.

Bul. *45. Data for Use in Designing Culverts and Short-span Bridges. (1913.) 15c.

OFFICE OF PUBLIC ROADS CIRCULARS.

Cir. *89. Progress Report of Experiments with Dust Preventatives, 1907. 5c.
*90. Progress Report of Experiments in Dust Prevention, Road Preservation, and Road Construction, 1908. 5c.
*92. Progress Report of Experiments in Dust Prevention and Road Preservation, 1909. 5c.
*94. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1910. 5c.
*99. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1912. 5c.
*100. Typical Specifications for Fabrication and Erection of Steel Highway Bridges. (1913.) 5c.

OFFICE OF THE SECRETARY CIRCULARS.

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*52. State Highway Mileage and Expenditures to January 1, 1915. 5c.
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*Vol. I, No. 11. Automobile Registrations, Licenses, and Revenues in the United States, 1918. 15c.
*Vol. II, No. 15. State Highway Mileage and Expenditures in the United States, 1918. 15c.
Vol. III, No. 25. Automobile Registrations, Licenses, and Revenues in the United States, 1919.
Vol. III, No. 29. State Highway mileage, 1919.
Vol. III, No. 36. Automobile Registrations, Licenses, and Revenues in the United States, 1920.

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH.

Vol. 5, No. 17, D- 2. Effect of Controllable Variables Upon the Penetration Test for Asphalts and Asphalt Cements.
Vol. 5, No. 19, D- 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.
Vol. 5, No. 20, D- 4. Apparatus for Measuring the Wear of Concrete Roads.
Vol. 5, No. 24, D- 6. A New Penetration Needle for Use in Testing Bituminous Materials.
Vol. 6, No. 6, D- 8. Tests of Three Large-Sized Reinforced-Concrete Slabs under Concentrated Loading.
Vol. 10, No. 7, D-13. Toughness of Bituminous Aggregates.
Vol. 11, No. 10, D-15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.
Vol. 17, No. 4, D-16. Ultra-Microscopic Examination of Disperse Colloids Present in Bituminous Road Materials.

*Department supply exhausted.